Sustainable Habitat for Developing Societies: Choosing the way forward

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Session 6E: Material technology
Carbon dioxide emissions of green roofing – case study in southern Brazil ................................................................. 311
Design & Testing out of an Insulating Floor Element, composed of recycled rubber and inert demolition waste ........................... 319
Design Interventions to Encourage Pro-environmental Behavior: An Action Research Study on Waste Diversion in a University Residence Hall ... 326

Session 7 (Day3, December 18, 10:25 - 12:05)

Session 7A: Passive design
From Romance to Performance: Assessing the Impacts of Jali Screens on Energy Savings and Daylighting Quality of Office Buildings in Lahore, Pakistan ................................................................. 334
Concept, Design and Performance of a Shape Variable Mashrabiya as a Shading and Daylighting System for Arid Climates ................ 344
Energy Efficient Hospital Patient Room Design: Effect of Room Shape on Window-to-Wall Ratio in a Desert Climate .......................... 352
Study on the microclimatic conditions and thermal comfort in an institutional campus in hot humid climate .................................... 361

Session 7B: Performance evaluation and design feedback
The Ability of Current Rating Tools to Guarantee Sustainable Successes: Balance and Perspective .................................................. 369
Numerical study: How does a high-rise building affect the surrounding thermal environment by its shading ? ................................. 377
Potential for net zero energy neighbourhoods in the Ahmedabad urban and solar contexts .......................................................... 385
Bioclimatic architecture as an opportunity for developing countries ...................................................................................... 393

Session 7C: User behavior, thermal comfort & energy performance
Occupant Feedback in Energy-Conscious and Business as Usual Buildings in India ........................................................................ 402
Assessment of Air Velocity Preferences and Satisfaction for Naturally Ventilated Office Buildings in India .................................. 411
Learning energy systems: An holistic approach to low energy behaviour in schools ................................................................. 419

Session 7D: Tools and methods/ framework
The study of sky view factor in urban morphologies: computational tools and methods of analysis .................................................. 427
Investigation of methodologies for artificial lighting performance simulations with the presence of shading devices in residential buildings ................................. 435

Session 8 (Day3, December 18, 14:10 - 15:50)

Session 8A: Material technology
Possible Application of Seaweed as Building Material in the Modern Seaweed House on Læsø .............................................................. 443
Design best practice methods to minimize the impact of building materials on urban microclimate .................................................... 451
Re-evaluation of Passive Design measures in the BASF house in recognition of Uncertainty and Model Discrepancy .......................... 459
Life cycle assessment as a tool for material selection - A comparison of autoclaved aerated concrete and VSBK brick wall assembly .... 467
First monitoring results of three straw bale buildings in Belgium ............................................................................................. 475

Session 8B: Innovative construction technology
Microclimatic effects of individual trees with their transpiration ................................................................................................. 483
Assessment of the double-skin façade passive thermal buffer effect .............................................................................................. 491
Low-Energy Industrial Buildings for Climates of Emerging Countries .......................................................................................... 499
Flexible and environmentally responsive mass housing in Bangalore, India .................................................................................. 507

Session 8C: Building reuse and refurbishment
A Multi-Stage Approach to Low Carbon Housing Renovations ................................................................................................. 515
Strategies for Environment Friendly Low Energy Retrofitting of a Health Care Facility in Hot Climate of UAE .................................. 524
Relating Sustainability Indicators to the Refurbishment of the existing Building Stock .............................................................. 532

Session 8D: Integration of renewable energy
Development of Multivalent PV-Thermal Collectors for Cooling, Heating and Generation of Electricity ........................................ 550
Parametric analysis method for urban energy transformation projects .......................................................................................... 559
Multifunctional Glazing System-Solution for Modern Smart Glazing .......................................................................................... 567

Papers in absentia
Environmental Performance of Adaptive Building Envelope Design: Urban housing in Seoul, Korea .................................................. 575
Establishing Energy Efficient Building Codes in Developing Nations: An analysis of window characteristics suited to hot-dry climates through a study of the residential byelaws of Lahore, Pakistan .................................................. 583
Session 5A : Lessons from vernacular architecture

PLEA2014: Day 2, Wednesday, December 17
11:30 - 13:10, Auditorium - Knowledge Consortium of Gujarat
Comparative Thermal Performance of Vernacular Houses at Lucknow: A Quantitative Assessment & Dominant Multiple Strategies

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ABSTRACT

This study focuses on the comparative thermal performance of a selection of cases from three distinct generic types of vernacular houses at Lucknow, a culturally & architecturally renowned city in the Gangetic plains of Northern India. The objective of the study has been to evaluate the core urban courtyard houses, colonial adapted bungalows and semi-rural mud houses at Lucknow to ascertain which type(s) have responded to the prevailing climate better than others and what factor(s) or strategies may be contributing for its (their) improved performances. Most significantly it has aimed to search for emergent energy efficient principles applicable to the region’s composite climate characterised by hot-dry summers, cold winters and intermediate warm-humid monsoon season. This has been pursued firstly by an in-depth study of deviant cases within each generic house type with respect to Lucknow’s composite climate assessing their anticipated performances. Later simultaneous monitoring of indoor temperatures and humidity in identified periods of each season has been analysed among these cases followed by their testing against the adaptive model of thermal comfort prescribed by Nicol and Humphreys. Moreover their simulations on Ecotect software have been examined and calibrated making them suitable for extended research. Conclusively, this study has acknowledged the significance of a combined chemistry of varied strategies & sub-strategies functioning together in each house for effective thermal response in this region. Furthermore, it has given a range of multiple tactics to fall back upon instead of a myopic view of just orientation or thermal mass or others & more importantly it has substantiated the role of ventilation & air movement for the favourable thermal performance of a built envelope. As a whole this research has been useful in deriving inexpensive passive strategies useful for Lucknow also resulting in principles and recommendations suitable for the composite climate of the region.

BACKGROUND

The significance of learning from the vernacular has been corroborated by a number of scholarships that have also ascertained that, their responses to prevailing climatic conditions have been favourable. These lessons are even more meaningful in the contemporary Indian context with low energy resources and the unremitting escalating needs of an exploding population. Moreover learnings from the Indian vernacular have also established their effective thermal performances with respect to existing environments especially the hot-dry and warm-humid climates. Lucknow, is a culturally and architecturally rich North Indian city located in the Gangetic plains, experiencing a composite type climate that necessitates varied responses from a built form all through the year. Furthermore the city fabric consists of broadly three vernacular house types comprising of the core urban courtyard type, bungalow type and the semi-rural mud house type, within its precincts, that have not yet been examined for their thermal responses. It is interesting to note that all these generic house forms are distinct and varied from each other and yet seem to be thermally comfortable in the varying composite climatic conditions of the region.
THERMAL COMFORT: SELECTED MODELS & METHOD:

A review of previous scholarships has acknowledged the role of thermal comfort as most significant within a built form that could be defined as a condition expressing satisfaction with the thermal environment. Moreover, the scientific interventions for assessment of thermal comfort have included various models like the steady state (ASHRAE 55), PMV (Fanger) beside other empirical & analytical indices. These have led to the significance of adaptive model of thermal comfort which relates the outside prevailing conditions to the indoors, thus establishing that people have remained comfortable approximately to the average indoor temperature they encountered. Equations for the same have been derived by Humphreys & Nicol as $T_n = 12.1 + 0.534 \times T_m$ and $T_n = 17 + 0.38 \times T_m$ respectively, where $T_n$ was the predicted indoor comfort temperature directly determined by the outdoor temperature of a place, and $T_m$ that was the monthly mean outdoor temperature (Auliciems). These models gave a flexible thermal comfort band of 5°C to 7°C in which a person could become comfortable by short term actions or long term acclimatization validating their utility in the diverse tropical climate of the Indian Subcontinent simultaneously reducing the energy demands created by uniform steady temperature standards. Furthermore, the recognised most controllable factors affecting the thermal performance of a building envelope within the architectural premise include its Siting, Location, Orientation, Form and Massing, Spatial Organisation, Open Built Distribution, Material and Construction Techniques besides special elements responsive to existing climatic conditions. Accordingly they shall assume a significant role in selection of cases for study and the subsequent extrapolation of passive strategies.

LUCKNOW: CONTEXT CLIMATE & SELECTED STUDIES:

Lucknow city is regarded as one of the “finest cities of North India both in the architectural and cultural context” (Siddiqui 27). As a spontaneously accretive grown city, it is more a consequence of the various layers of development added to it by the diverse rules and colonisations due to which the city’s morphology is an amalgamation of organic & geometric parts. Broadly three types of house forms have developed, the most significant of them being the city courtyard houses, inhabited both by Hindus and Muslims; the bungalows that have been colonial adaptations by British; and the semi-rural mud houses present on the fringes of the city. While most of the courtyard houses are introverted and situated in the old city areas accessed by winding streets among mohallas, some later ones have formed part of newly well-defined settlements. The bungalows on the other hand have constituted of more formal well-defined spaces with extroverted arrangements set amidst large secure compounds within well-maintained cantonment or similar precincts. In contrast the semi-rural mud houses have existed as semi-introverted courtyard houses in informal clusters with an agrarian population of informal usage patterns.

All these house types have evolved in diverse contexts and conditions but have co-existed in the city for more than hundred years. Furthermore they have been built after numerous checks and balances making them vernacular in the true sense of the word. The core urban courtyard houses with shared walls have one or two courts with a single bay of rooms around it opening to narrow shaded streets within dense built contexts. Distinctly the Muslim houses have had two courtyards segregated for both men and women while the Hindu houses possessed a single courtyard both utilized for similar informal activities. Of introverted centripetal organisation, with thick lakhori brick, surkhi lime construction their roofs have been made of timber joists or jack arches. Within these, four variations were selected for the study namely Farangi Mahal house, Jannat Ki Khirki, Kaiserjahan house and Narhai house. The colonial adapted bungalows being detached monolithic units have centripetal extroverted configurations well lighted and exposed to the large open environment around them. These are made of thick walls of brick, surkhi, lime mortar and are usually single storied with flat jack arch with varied heighted roofs and verandas in strategic directions. Within these, three variables in form of Majithia house David house and Rachna house have been selected as cases for examination. The semi-rural mud houses were semi-detached houses in clustered formations on large vegetated sites. Consisting of singly banked rooms around courtyards with transitional verandas the selected cases consisted of the Pradhan house, Rumesh house, small mud house & Rajmahendar house. It is to be reiterated here that while the three types of
house forms at Lucknow were already generically different in terms of organisation & siting the
variables amongst each case varied in terms of shared walls; orientation; fenestration percentage;
Courtyard proportions and massing. The objective of the selection of the cases was to ascertain the role
of specific factors in the varying thermal performances of houses within one generic type and among
diverse types.

TOOLS & TECHNIQUES:

An in-depth critical review of utilised procedures and techniques for assessment of thermal
performance of buildings all over the world was done to arrive at a comprehensive methodology for the
study. These included theoretical studies without on-site documentation by Nevins & Dabaieh;
extensive site analysis with some numerical simulations by Ford & Associates, Vinod Gupta, Ashok Lall
and Campos among others; on-site monitoring with extensive site- study by Brian Ford, Kotharkar,
Ahmad and Fanchiotti; simulations & site studies by Kanika Agrawal, Antarikananda, Avlokita
Agrawal, Haschem and Alanz; on-site monitoring with simulations by Arvind Krishan, Young and
Summers Francoise among others. The simulating software was selected after assessing the reviews of
Crawley, Ling and Summers amid others. Subsequent to the systematic analysis the methodology
devised for this study was all inclusive, incorporating a detailed recording of the selected houses being
variables of each generic type of house form at Lucknow. The expected thermal performance of each
study was evaluated for each case against theoretical parameters after which an onsite simultaneous
monitoring by Hobo Data loggers was conducted in the living rooms of all the houses for similar periods
all over the year. These results were plotted on the predicted comfort equations by both Humphreys and
Nicol for the assessment of recorded data of all selected cases. Concurrently Ecotect models were
developed for all cases with simulation for critical discomfort periods and tested for varying parameters.
Later the results from monitoring & Ecotect were put together and analysed to assess the performance of
each case to establish principles useful for this region.

ANALYSIS OF DATA & DISCUSSION OF RESULTS:

The comparative analysis of the on-site monitoring data of all studies was conducted with
respect to the predicted comfort bands by both Humphreys & Nicol formulated on the basis of Lucknow
meteorological data. On basis of Aulliciens a comfort band of 7 ºC width was considered as these
houses utilised an adaptive informal lifestyle. The scrutiny showed that in summers the variable cases
within all generic types of houses lay within the band with a difference of just 3.5°C within the closest
and farthest cases. However in this season as per the afore-mentioned analysis, the city courtyard houses
(Narhai house closest) generically performed better than the bungalows & mud houses. Furthermore in
winters the bungalows as a type showed improved performances (Rachna house closest to desirable
comfort temperature) while the city houses with larger courtyards achieved lower thermal performances
& the mud houses were even worse. In monsoons generically the city courtyard houses (Narhai house
followed by Jannat house) performed better than mud houses & even more so than bungalows.

On a finer analysis of the temperature data of variables within one type it was gathered that there
was significant deviation within the thermal performance of one generic type meaning that in the same
season one case within the same generic type performed best while another was one of the poorest
amongst all cases. Notwithstanding the above, the most important inference was that within all cases the
temperature variation was not great while the difference in the indoor relative humidity readings was
even more minimal. In summers and winters the difference in maximas & minimas was less than 5°C
while in monsoons the variation was limited to only 3°C. It was also observed that the bungalows
recorded the lowest diurnal variations among all cases. Relative spot readings within the same house
indicated a difference of up to 2°C in the temperatures. On close observations it was found that Narhai
house- a core urban courtyard house recorded lowest indoor temperature in summers while the Rachna
bungalow experienced higher internal temperatures in winters whereas in monsoons Narhai and Jannat
courtyard houses noted best inside conditions. These outcomes also led to the understanding that all the
selected cases of vernacular houses were thermally comfortable although the superiority of one type over
the other could not be distinctly established in any season. In fact it was realised that each house utilized
a combined chemistry of varied strategies and sub-strategies for effective responses to varied seasons.

The Ecotect simulations for each case was calibrated on basis on existing data and the
comparative assessment of their cooling, heating loads, monthly discomfort hours & temperature
distribution was made. After which these models were also simulated with varying factors of orientation,
material properties, and fenestration, shared walls, changed massing & varying shading systems. The
implications of analysis by Ecotect revealed that the maximum heating loads were required by the Small
Mud House while Rachna Bungalow and Narhai House needed minimum heating loads. Alternately
maximum cooling loads were used by Pradhan House and minimum by Majithia, Narhai and
Rajmahendar Houses. The living areas of all houses exhibited more constant hourly temperature profile
than the other rooms. Variations in the simulation models also revealed the change in loads with
modifications in upper floors, shared walls, orientation, fenestration, shading and materials that have
been summarised in the coming paragraphs.

CONCLUSION

The most significant inference of the study was that all the generic vernacular house types of
Lucknow were found to be thermally comfortable in the varying seasons of the region due to diverse
multiple passive strategies adopted by them to counter the extremities of outdoor conditions. While the
superiority of thermal performance of one generic type over the other could not be distinctly established
in any season it was evident that the combined chemistry of varied strategies & sub-strategies were
utilized by each case for effective thermal response to the existing climatic conditions of Lucknow. The
architectural study of the selected cases within each generic type and across types revealed the passive
strategies and sub-strategies utilised by the variants for effective response to prevailing climatic
conditions. The core urban city courtyard houses employed siting amid narrow mutually shaded dense
winding streets with minimal fragmented spaces whereas the bungalows comprised of siting in large
open airy heavily foliaged sites. The mud houses on the other hand used a combination of the above
with dense clusters amid large open sites. Furthermore the city houses had multiple shared walls with
staggered massing of over floor to counteract heat gain & provide shade while the bungalows employed
a minimised envelope with shaded verandahs and trees on periphery for the same. The mud houses on
the other hand used partial shared walls and shading from adjoining large trees. Moreover the city and
mud houses have used introverted courtyard plans with minimal outside fenestrations for preventing heat
gain while bungalows have utilised large fenestrations opening into shaded verandahs and high ceilings
with ventilators for enhancing convective cooling & ventilation. The use of high thermal capacity
materials with high thermal lag in all the houses has contributed to constant temperatures all day and
over the year.

It was also quantified by simulations of the selected cases that, the use of high thermal mass in
building elements could improve the performance of the envelope to 70% but would prove detrimental
without night purge ventilation validating the role of ventilation versus insulation. Furthermore it was
observed that the strategy of orientation of vertical facades with respect to sun has been largely overrated
in this region for structures below 3 stories. It contributed to a deviation of only 5 to 10% whereas the
influence of effective mutual shading could improve the performance up to 30%. This study also
substantiated that although solar radiation assumed maximum significance within the tropical Indian
climate the role of wind and air movement had to be taken into account for favourable thermal
performance of built envelope. Moreover Roof shading has shown to be extremely effective in this
climate while effective massing improved the performance of lower floor up to 45%. Effective Shading
of walls & fenestration have shown to reduce heating & cooling loads by 30% while presence of small
courtyards has also indicated usefulness in all seasons. Verandahs as shading devices have exhibited
significance & have a larger role to play built forms at Lucknow to articulate facades provide shading &
prevent thermal shock in extreme outdoor conditions. The recommended Fenestration proportions have
seen to work more effectively in combination of ventilators & doors reducing loads by up to 32%. The study also showed that a non-parochial view of materials was to be required and their role in a combined assembly system should be assessed.

Furthermore Simulative modelling techniques have made visualisation and subsequent design much easier but the study resolves that the unrestrained use of simulation software’s without an assessment of real conditions are a cause of concern because despite multiple configurations they underestimate the role of wind and air movement. Furthermore in simulative models insufficient credence is given to adaptations due to physical actions in actual environments leading in inaccurate results. Especially in the case of naturally ventilated buildings in the Indian climate their role has to be examined more closely and thus selected with extreme care that would need to be calibrated with actual on-site data. India is fast becoming a global phenomenon as a result of which modern living comparatively has become more inflexible with minimal space reallocation even in the extreme conditions. In an age of fast depleting resources and power crisis learning from the adaptive and flexibility principles of the vernacular makes sense to restrict reliance on active systems of cooling and heating loads.

REFERENCES

Assessing Sustainable Retrofit of the old Dwellings Stock in Brussels Capital Region

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ABSTRACT

In the framework of the research project “B³RetroTool”, a typology of existing dwellings, built before 1945, has been made, based on a literature review of main steps of the urban and building development of Brussels area. This old part of the Brussels dwellings stock has been chosen because it represents 60% of the dwelling stock but moreover, it gives to Brussels its identity, its architectural and its historical legacy.

This contribution presents the methodology to identify typology, to structure a representative database of existing dwellings stock (with spatial distribution in Brussels area) and to define criteria to assess retrofitting strategies for each dwelling type in order to enhance heritage value and to combine it with relevant energy and environmental performances. The originality of this research is to consider energy, environmental and heritage aspects in a non-compartmentalized and complementary way, in order to help designers to reach their objective of a greater sustainability.

INTRODUCTION

The dwellings stock built before 1940 in Brussels has a great heritage value for Brussels Capitale. It also represents 60% of built areas and is responsible for 62% of the region’s energy consumption. This fact has prompted Brussels to invest in strong support for reducing energy consumption in buildings through systems of subsidies. These include subsidies for insulation, replacement of windows, boilers ... So as to target the strategic policy actions in terms of reduction; the Brussels Capital Region has also invested in targeted studies on the state of the existing building stock and opportunities for improvement. All of these studies, mainly based on statistical studies have rarely considered both the heritage and historic value of the buildings and the improvement potential related to buildings components and design principles.

The research’s objective is to achieve important improvements in the energy performance of existing Brussels dwellings stock while preserving heritage value and reducing environmental impact.

The research focuses only on the dwelling stock built before 1940 for three main reasons. First, this is the largest share of the Brussels dwellings stock. Secondly the different types of dwelling could easily be identified. Thirdly, this dwellings stock requires urgent improvements in terms of energy performance and inhabitancy. It should also be noted that dwelling demand is very strong in Brussels. So the retrofit of this dwelling stock could meet this demand by densifying some dwelling types.

This contribution presents identification of dwelling typology built before 1940, proposition of retrofitting scenarios and definition of energy, environmental and heritage value criteria in order to
enhance heritage value of the Brussels dwellings stock and to combine it with relevant energy and environmental performances but also suitable materials and systems. It describes in details the methodology used for identification, repartition and spatial distribution of dwelling typology. Retrofitting scenarios and assessment criteria are subsequently presented.

This research is still ongoing and the results of scenarios assessment are not yet known. The overall results: dwelling typology, its repartition and spatial distribution as well as improvement scenarios and their assessment through case studies will be incorporated into a pre-assessment tool to retrofit the dwellings in an integrated multi-criteria and multi-scale approach.

**HISTORICAL RESEARCH: URBAN DEVELOPMENT OF BRUSSELS, FROM THE 10TH TO 20TH CENTURY**

The first step of the research was to study the historical processes [1, 2, 3, 12] that have influenced the development of the city of Brussels and the Brussels-Capital Region in order to understand the urban characteristics and specificities but also to know the origin of the development of certain types of city blocks and dwellings. Brussels-Capital Region, as it is today, was formed mainly during the last two centuries. But some key elements are older. They are, as example, the topographic or hydrographic elements that were at the origin of the spatial and social differentiation between high side (east and more aristocratic) and low side (western, most popular and industrial) of the city. This spatial and social differentiation is still present today, although less pronounced than originally. It is also the work of fortifications that gave the city center of Brussels, a specific and still visible form. It is also major infrastructure projects such as the creation of the boulevards on the second enclosure, the creation of Willebroeck and Brussels-Charleroi canals, the creation of large avenues, the creation of the North-South Train Junction... All those elements must still be reconsidered in strategies for urban renewal of the region through different scales: neighbourhoods, city blocks and buildings.

This historical research focuses mainly on morphology, demography, urban planning, architecture and types of dwelling.

**DEFINITION OF DWELLING TYPOLOGY**

The study of the dwelling typology before 1945 has been established from the late 17th century for two main reasons. First, dwellings built before 1700 are mainly wooden buildings. In 1695, those wooden buildings were almost destroyed (as the entire city) by the French bombing. The Brussels rebuilding was made with bricks and stones, on the track of the old wooden dwellings. Secondly building permits and the various regulations standardizing construction spread in the 18th century.

Dwelling types were defined according to the historical research of Brussels urban development but also to the changes in lifestyle of Brussels citizen as well as changes in construction methods and materials used. Three main periods of urban development have been identified.

*From 1700 to 1890: urban development of Brussels.* Period characterized by the first great works of urbanization and development of the future Belgian capital city (1830).

*From 1890 to 1914: transition period.* Period characterized by hesitation between the nostalgia for the past and the desire for modernity and a new architectural trend, the “Art Nouveau” launched by Victor Horta, with the construction of Hotel Tassel in 1893.

*From 1920 to 1945: modern period.* Period characterized by a strong demand of housing but also new ways of thinking architecture and urban development.

Regarding the types of dwelling, the research distinguished two key periods:

*From 1700 to 1914.* Period characterized by a predominance of individual housing (modest, bourgeois and aristocratic), whose spatial organization will be based on the spatial organization of the “maison bourgeoise”;

*From 1920 to 1940.* Period characterized by the emergence of new types of dwellings, mainly worker house in the garden cities and apartment building but also new constructive processes and new materials, especially concrete.
Based on archival and/or historical documents, each type of dwelling has been studied according to the methodology including a general description of the type (description of dwelling situation, spatial organization, internal circulation and stair case, building systems and materials, roof, façades and building materials), a description of the main characteristics (relation with public space, size of the plot, size of the building, volume, number of floors, presence of annexe, height and width of the main façade…) and description of type variations if they exist.

**Dwelling typology from 1700 to 1914 [4, 5, 11, 14]**

The single family row house is the most common form of dwelling in Brussels until 1914. For this period, there are three main types of dwelling: the “maison bourgeoise”, the modest or worker house and the “hôtel de maître”. These types are the evolution of the Brussels wooden row house and are thus characterized by the same spatial organization, construction principles and materials that can be presented through the “maison bourgeoise”:

**Spatial organization.** It reflects the lifestyle of the bourgeoisie in the 19th century and it is organized in three modes: reception, family spaces and services or domestic spaces. Internal spaces are divided into two parts: a main part including the reception and living spaces and a secondary part, narrower, including services, stairs and corridors. The plan is organized with a succession of two or three rooms with a depth of 4 to 4.5 meters. Reception and living spaces have high ceilings, large width and are largely lit.

**Construction system, principles and materials.** The construction system is mainly governed by the rules of protection against urban fire. It is based on the constructive system of the Brussels wooden row house. Party walls are made of brick locally sourced and are not structural. The wooden floors are perpendicular to the street façades and partition walls. The wooden beams are spaced between 35 and 40 cm. The thickness of the bearing brick walls is also codified by the regulations of buildings to ensure stability. It varies between 28 cm and 48 cm depending on the type and height of walls. Recovery of floors charges and load-bearing walls is ensured by a combination of discharge vaults and metal lintels scattered throughout the façade and load-bearing walls. Only the structure of the roof is based on party walls, wooden beams ranging from wall to wall. The floors of the ground floor are partly made of hard materials. They are tiled or covered with marble. Floors of the upper levels are in wood. The ground cellars are usually performed in clay. The two façades are narrow (6 m) and high (12 to 18m) but there is however a big difference in composition between the two façades. Back cover: brick facade, sober and coated. Only a few metal lintels and sills are apparent. Main façade composition depends on different styles: neoclassical, eclectic,... Materials used are brick, natural stone and oak for window frames. The level of the street façade decoration shows the social level of inhabitants.

**Dwelling type variations.** The type “maison bourgeoise” could be divided into three variations according the construction date: “maison bourgeoise” built before 1800, “neoclassical maison bourgeoise” and “maison bourgeoise bel étage”. Those three variations have the same spatial organization and same internal plan but show variations at the level of groundfloor and stairs installation.

The same construction systems and materials are found in the modest house and in the “hôtel de maître”. Only the location, the size of the plot, the width of the main façade, the surface area, number of floors, the appearance of the street façade and interior finishes are different. Modest or worker row houses were mostly located in the popular and industrial districts. Maisons bourgeoises were located in residential districts of the pentagon, mainly in the top of the city. Hôtels de maître built for the upper bourgeoisie and aristocracy, after 1830, were located along large avenues and in some districts extensions. In addition to these three types, there are also houses with shop and apartment houses that show a lot of similarities with the “maison bourgeoise”. Those types of dwelling were located on the corner plots and near train stations and infrastructure.
The beginning of World War I, in 1914, traditionally marks the end of a period both in Western Europe in Brussels. Mentalities as well techniques evolve significantly: the car is spreading, domesticity disappears, the role and place of women change. Changes also appear in the ways of life of the bourgeoisie and the working population. These changes have an impact on the spatial organization of dwellings, on the urban development of Brussels and on the types and styles of dwellings whether individual row house remains predominant. Garden cities are built for the workers at the extremities of the city. By 1930, after the financial crisis of 1929, apartment buildings for middle class - back in town - are growing in Brussels. For this period, we can distinguish three types of dwelling: evolution of the “maison bourgeoise”, worker row house in garden-city and apartment building (social and standard). If the evolution of the “maison bourgeoise” still presents many spatial similarities with the “maison bourgeoise” built before 1914, the two other types show a new spatial organization [figure 2]. All three types also were built with new construction systems, principles and new materials, especially concrete.

**Case studies of dwelling types**

For each type of dwelling, a case study sufficiently representative has been searched. With this objective, various Brussels databases and information sources [15] have been consulted and various architects working with old buildings and dwellings have also been contacted. Each case study will be analysed based on original plans, sections and detailed quantity survey.
Figure 3
Pictures of “neoclassical maison bourgeoise”, “maison bourgeoise bel étage”, “hôtel de maître”, apartment house, evolution of maison bourgeoise 1, evolution of maison bourgeoise 2, standart apartment building and social apartment building.

Building stock analysis – Dwelling type repartition

Based on the description of each dwelling type, a simplified characterization has been proposed to fit the data given in the Brussels cadastral matrix (©Administration Generale de la documentation patrimoniale) and to associate each lot to one type. As we can see in the figure 4, the characterization is limited to three factors: date of construction, floor area, number of dwellings per building. There is a total of 159825 buildings and 498819 dwellings registered in the Brussels cadastral matrix.

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Figure 4
Characterization of dwellings types

The figure 5 confirms that more than 60% of the buildings were built before 1945. This analysis shows that "maison bourgeoise" (type 2 in the figure) outnumbers all other types and that many post-war buildings are apartments.

Then, with ArcGIS software, the resulting database can be used to analyse spatial distribution of each type. The left map [figure 6] shows that type “maison bourgeoise” was mainly built close beyond the first encloser. The right map [figure 6] shows that after 1918 the type “evolution of maison bourgeoise” (type 5) was built further out the centre, beyond the second encloser.
ASSESSMENT OF POTENTIAL IMPROVEMENTS OF DWELLINGS STOCK

Based on the description of each dwelling type, various scenarios of retrofitting were proposed. They focused mainly on improving the energy performance of each dwelling type but also on creating opportunities for dwelling densification, function diversity and inhabitancy improvement. Scenarios proposed for each dwelling type will then be applied to the specific case study and assessed according to three criterias (heritage value, energy and environmental impact) and compared with the initial situation.

Climatic data of Brussels Capitale Region

The reference Belgian external climate is a relatively cold, humid and rainy temperate climate. The data presented below, were measured by the Belgian Weather Royal Institute in Uccle (Longitude: 4.36°E, Latitude: 50.80°N; Altitude 100 m): average temperature (9.9°C), average relative humidity of the air (80%), average wind speed and orientation (3.6 m/s, south-west), average global solar radiation (108 W/m² with min:0 - max 889) and average precipitation (930 mm per year).

Assessment criteria

Each assessment criteria - energy, heritage value and environmental impact - contains a series of indicators presented in the table on the next page.
Potential improvements of dwellings stock – retrofitting scenarios [9, 14, 15]

Various scenarios were proposed with the objective to improve significantly the energy performance of the dwellings. Those scenarios focused first on the envelope and then on the technical services. The envelope retrofitting scenarios were defined based on a trend analysis performed on the renovation of housing awarded at Exemplary Buildings initiated by Brussels Environment. They are proposed by phases, knowing that today, only few Brussels owners can finance all of the retrofitting works in one phase. The retrofitting steps are proposed in a hierarchical manner, taking into account the state of the dwelling, the influence on the energy performance and the extent of work required. As an example, the envelope retrofitting scenarios for the “maison bourgeoise” are the following:

1. **Roof insulation**: the insulation could be done from inside or outside. Insulation from inside preserves the structure and the covering. Insulation from outside requires a new covering and sometimes a new structure. Insulation from outside also requires a special attention to specific elements and ornaments and could be linked with integration of renewable energy system.

2. **Roof insulation + Floor slab insulation**
In case of “maison bourgeoise bel étage” with a raised ground floor and cellars naturally lit, the floor slab could be insulated from inside. In case of “neoclassical maison bourgeoise” with a ground floor at street level and cellars without natural light, the floor between ground floor and cellars could be insulated (cellars side).

3. **Roof insulation + Floor slab insulation + Frame replacement (back cover façade)**
In many dwellings, frames are still equipped with single glazing. Those should be replaced by double or triple glazing frames taking into account the possible installation of solar protection (orientation) and increase of the airtightness.

4. **Roof insulation + Floor slab insulation + Frame replacement (back cover façade) + back cover façade insulation**
Back cover façade could easily be insulated from outside. The most common technique is the coating on EPS insulation but wood-based materials will also be assessed.

5. **Roof insulation + Floor slab insulation + Frame replacement (back cover façade) + back cover façade insulation + Glazing and/or frame replacement (main façade)**
The main façade being highly ornamented and the frame strong, the replacement of the frame and/or glazing therefore requires a detailed study. Several solutions can be considered: preservation of existing chassis and replacing single glazing by double glazing or replacement of all.

6. **Roof insulation + Floor slab insulation + Frame replacement (back cover façade) + Back cover façade insulation + Glazing and/or frame replacement (main façade) + Main façade insulation**
The main façade being highly ornamented, insulation from outside is really not possible. Insulation by inside means to pay attention to thermal bridges between façades and wooden beams and requires a detailed study [10].

The technical services retrofitting scenarios are proposed taking into account the existing technical services and the possible densification of the dwelling. The scenarios propose improvement strategies for
existing techniques but also for integration of ventilation systems, renewable energy systems (solar thermal and PV), rainwater infiltration systems and acoustic insulation (in case of dwelling densification). They presented, for each dwelling type, solutions for ducts implantation.

The densification retrofitting scenarios analyse the possible way to increase the number of dwelling, especially into the “maison bourgeoise” characterized by a very large surface area available (up to 400 m²). Some scenarios propose a diversity of functions by integrating professional spaces into the dwelling.

CONCLUSION

The paper presents the methodology used to analyse and characterise the Brussels existing dwellings stock. The data will be used to develop a tool to help improving global performance of this urban area. A definition of dwelling typology was detailed and each building from cadastral database was associated with one type. Using ArcGIS tool, a map of each type can be drawn. For each type, refurbishment scenarios were proposed, as well as three set of criteria to assess energetic, environmental and heritage value in parallel. Developing tool should thus allow assessing simultaneously these three aspects and their interactions. This methodology can be applied in other contexts to provide any user with data at different scales, from the building to the entire city, helping to take sustainable decisions.

ACKNOWLEDGMENTS

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Passive House Elements of Traditional Bosnian Town House:
Towards Contemporary Passive House in Bosnian Context

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ABSTRACT

Bosnia-Herzegovina, a country going through the process of development, has many challenges to overcome in order to achieve satisfactory energy efficiency of its built structures. In the last couple of years, activities to increase energy efficiency of residential buildings have gained momentum in order to align with the European Union energy efficiency legislature. The majority of those activities consist of building stock refurbishment by simply adding thermal insulation onto existing architecture.

Considering the climatic conditions, of warm summers and cold winters, decreasing heat loss is important aspect in striving to achieve thermal comfort and energy efficiency of the buildings in Bosnia-Herzegovina. Other means to achieving thermal comfort could be found in Bosnian vernacular architecture, especially when considering thermal comfort in the summertime. Vernacular architecture offers original passive architectural design solutions that are waiting to be utilized in contemporary design.

Although comprehensive research on many of the aspects of the traditional Bosnian town house have been done in the past, its passive-design elements have not been recognized as such nor systematically studied. This paper aims to introduce passive architectural elements, passive cooling and ventilation techniques to a broader public.

Excellent house performance could potentially be achieved by the integration of the vernacular design traditions, of the Bosnian town house, into contemporary passive-house designs.

Thermal performance of a traditional Bosnian town house is tested through computer aided simulations and site measurements. The results of the study should provide convincing arguments, for the local architects and policy makers, to steer the often misguided and overly provisional trends in house designs, to the sustainable path.

INTRODUCTION

In efforts to achieve sustainability it is up to each country to select solutions suitable for their specific conditions and environment. In Bosnia-Herzegovina, where privately owned, individual housing represents a popular lodging solution, finding a sustainable solution for this particular architectural category is already overdue. Some of the housing that was already built inadequately is now going through refurbishment process of adding thermal insulation, to increase thermal performance. Domestic
households take up 52% of final consumption of energy (ESSBIH 2008) and in general buildings mainly have a poor thermal insulation which causes energy loses of up 30% (CPU 2010).

The study of vernacular housing solutions in a particular environment is an excellent venue for revealing design solutions that can be replicated in the same environment but in a contemporary context. This is particularly suited to passive architecture, which makes use of its surrounding natural environment as much as possible. Beside the natural environment, a significant part of passive housing efficiency is based on the occupants’ behaviour. One can argue that vernacular architecture is the original passive architecture. Making the contemporary passive architecture possible are several inseparable elements: the natural environment, the lifestyle and the architecture design itself. This paper aims to explore specific passive-architecture elements of a traditional town house in Sarajevo, Bosnia-Herzegovina through the case study of Svrzo’s House in Sarajevo.

2. THE TRADITIONAL BOSNIAN TOWN HOUSE - BACKGROUND

The house chosen for the study is a two-storey house with elaborate ground and upper floor plans. It is known as “Svrzo’s house” and is located on the hills of the old part of the town overlooking the city of Sarajevo. It dates back to the 18th century when it was owned by a wealthy local family. It was later donated to Sarajevo City Museum to be converted into a museum itself during the 20th century. This house is particularly suitable for study since it contains a variety of the typical architectural design elements of Bosnian town house and is kept close to its original state.

![Figure 1](image1.png)

**Figure 1** a) Svrzo’s house (2014), view on the front courtyard and open terrace space - *divanhana* on the upper floor clearly distinguished in wood works (Bajramovic, 2014) b) Typical configuration of Bosnian town house, cantilever architecture: ground floor masonry, and upper floor’s timber framework with brick infill (Grabrijan & Neidhardt 1957)

![Figure 2](image2.png)

**Figure 2** The Ground and Upper Floor plans of traditional Bosnian town house: Svrzo’s House in Sarajevo, Bosnia-Herzegovina, renovated to original form and turned into a museum. (Grabrijan & Neidhardt 1957, graphic editing by author)
2.1. Lifestyle and occupants’ behaviour

Traditionally, parts of the house were classified according to their functions, into four groups: habituation, recreation, domestic activities, circulation (Grabrijan & Neidhardt 1957), but the rooms themselves were used very flexibly. The furniture is also flexible, there is the sofa encircling the room on 3 sides and *Musandra* (a walk in closet consisting of a stove, a shower space and a closet), while the rest of the space of the room is free to be used in different ways.

The number and use of the rooms is set according to the needs of the family, flexibility being the key. The same room can be used as living - dining room that transforms into bedroom during the night, other rooms can be children, study or guest rooms. The house is typically a two-story where the ground floor is used as winter quarters, and the upper floor is used as summer quarter. Depending on the house configuration the upper floor is sometime used additionally for winter quarters (Grabrijan & Neidhardt 1957). Such use of the house is a result of the climate, hot summers and cold winters. Winter quarters are connected to the outside through *verandah* (Figure 2), and summer quarters open to outside through *divanhana* (open terrace space – Figure 1&2). Common use of the house by its tenants could be categorized in the following way: 1. Summer and winter use and 2. Private and semi-private use. Front part of the house, adjacent to the main gate courtyard, is considered semi-private, since the guests are greeted there, but second part of the house is completely private.

Several unique architectural elements allow for comfortable summer and winter habitation. The occupants’ behavior is adjusted based on the season.

2.2. Passive-architecture features of the house

![Images of architectural features](photos by author)

**Figure 3** a) Divanhana – open-air terrace space, under deep eaves  b)mushebak , c)doksat (photos by author)

*Divanhana.* (Figure 3.a ) an open-air terrace on the first floor settled under deep eaves which provides a comfortable place to reside in hot summer days. All of the rooms adjacent to it have a direct access through massive wooden doors, and with windows looking onto it. Divanhana, together with narrow open hallway, connects pavilions of the house and enhances the airflow throughout the first floor of the house. It is accessible from the ground floor courtyard directly by stairs allowing for quick access to the rest of the house. With its built-in bench and attractive views it is mainly used for recreational activities such as reading, talking, enjoying the scenery, as an outside summer living room. It is even used even as sleeping space in warm summer nights (Grabrijan & Neidhardt 1957).

*Mushebak* crossing wood lattices in the windows providing enormously valued privacy. It enables cross ventilation of divanhana and hallways (Figure 3.b)

*Doksat*, a prism with window jutting out in the height of the upper floor of the house, overhanging the street (Figure 3. c). It is a standard architectural element that appears on all typical town houses. Since it provides 180 degree view, it is primarily used to overlook over the surrounding neighbourhood. It additionally plays an important role in house’s cross ventilation; windows on all 3
sides which gives room for creating draft and ventilating the room more efficiently (Grabrijan & Neidhardt 1957).

*The Garden and courtyards* (Figure 1&2) are places where one enjoys nature, where decorative and edible plants were planted and taken care of. Summer quarters of the house are oriented onto the garden, which increases the cooling off effect in the hot summer days.

The construction of the house is favourable in terms of thermal mass. The ground floor consists of massive walls, made out of unbaked brick or stone, while the Upper floor consists of wood frame filled in with unbaked brick. The timber frame is resting on the masonry wall. Ceilings are supported by the wood frames and the roof is a heavy wood construction protected by roof tiles.

### 3. PASSIVE COOLING, VENTILATION, AND HEATING FEATURES

A traditional Bosnian town house (further in the text referred as a TBT house) is, among the locals, recognized as comfortable dwelling in the summer, while at the same time having an adequate thermal mass to sustain the heat in winter months. This study aims to test those qualities on one of the TBT house’s pavilions, which is a representative of typical volumes, materials, and layout.

#### 3.1 Climate conditions

According to The Köppen Climate Classification the subtype for Sarajevo’s climate is "Dfb" (Warm Summer Continental Climate) or a medium continental climate with average winter temperatures of -1.3°C in January, and average summer temperature of 19.1°C in July. The average annual temperature is 9.5°C. The coldest month is January with the lowest recorded temperature of -26.1°C and the highest in July with 37.2°C (Weather Base 2014).

Summertime temperatures fluctuate drastically during the day where the average temperature difference between the early morning, afternoon, and evening can reach up to 10 to 15°C, with even more drastic differences between maximum and minimum temperatures. On average winter temperatures are fairly steady throughout the day, with slight decrease during the night, but with drastic maximum and minimum temperature differences across days (FHMI 2013). Humidity is also changing during the day, going from high in the morning (up to 80% yearly average in the morning), going down to 50% around midday and again getting higher in the evening hours. Prevailing winds are a result of complex geographical features, so there is a huge variety of wind directions and speeds. Prevailing directions are ESE and WNW. Dominant winds are SSW and ESE (FHMI 2013).

Although humidity rises during the night, these kind of climate conditions allow for effective night-time cooling because of the large drop in temperature during the night. The traditional lifestyle comprises night-time cooling as a part of the daily routine in summer period. The prevailing wind directions suggest that the orientation of the house openings towards South and West is indeed favourable for natural ventilation. The selected TBT house has the optimal South and West facing openings.

#### 3.2. Cross-ventilation and vertical ventilation

In addition to acting as an outdoor living room in the hot summer days, aforementioned *divanhana* settled under the deep eaves, is a structure that represents a buffer zone, “a layer of air between the hot outer and cool inner spaces which gives rise to air circulation. The rooms behind the *divanhana* are connected to it by windows and doors and open into the side facades so that the ventilation around the corners is also possible” (Grabrijan & Neidhardt 1957)
Figure 4. a): GROUND FLOOR: Cross ventilation through the ground floor openings enabled by the openings’ positioning and the difference between the interior temperature and exterior temperature of the courtyard and the garden. B.: UPPER FLOOR: Openings on the both sides of the rooms allow for cross ventilation. Divanhana plays an important role in the summer months, creating a buffer zone between outside and inside spaces. (Grabrijan& Neidhardt 1957, graphic editing by author)

The rooms that are placed in the central parts of the house, with no horizontal ventilation possible, are ventilated vertically through other rooms and the opening in the roof, as shown in the sketch (Figure 3.). It is clear why the house has been given an attribute of an “airy house” (Grabrijan& Neidhardt 1957) since it is ventilated in both the horizontal and vertical direction.

Figure 5. The airy house, an archetype layout and section of BTB house (Grabrijan& Neidhardt 1957)

3.3. Indoor thermal comfort – A computer simulation analysis

The thermal comfort of the TBT house was examined Using SolarDesigner simulation software (validation of software demonstrated in the article done by authors; see references: Kodama&Takemasa 1991). The pavilion of the house chosen for the computer simulation, represents a typical two-storey architecture of the area. The Ground floor is constructed through massive stone masonry, while the lighter Upper floor is constructed using the bondruk system – a timber framework with unbaked clay brick infill. The performance of the house pavilion Ground floor and Upper floor volumes (Figure 4. a&b) were examined according to different simulation scenarios: summer daytime and nighttime ventilation scenario, and winter all day closed mode ventilation scenario. Simulation was conducted for three consecutive days, in winter time, as well as the summertime. Day 1 is considers as sunny with bright skies, day 2 as partly cloudy and day 3 as cloudy. The temperature values represent the maximum and minimum amplitudes recorded in July and January (consecutively the warmest and coldest month of the year).

3.3.1. Summertime ventilation and passive cooling effects

The TBT house, with ample thermal mass, is expected to benefit from the passive nighttime cooling effect in the summer. The computer simulation tested this on the Ground and Upper floor quarters (Figure 4 a&b). Room air fluctuation during July, the warmest month in this climate, is shown in Figure 7. There are noticeable differences between the Ground floor, and the Upper floor air temperature fluctuation. Traditionally utilized the most in the summertime, the Upper floor quarters, if kept closed all day, can provide a fairly steady temperature throughout the day. At this time of the year nighttime ventilation is the optimal ventilation mode. The optimal passive cooling effects are attained in the nighttime ventilation mode from 7 am to 9 pm, (Shown in Figure 4) with indoor temperatures dropping
up to 15°C, and which allowing the interiors to stay significantly cooler than the outside temperature. Similarly, summer nighttime ventilation on the Ground floor is the optimal ventilation mode, with temperature values going from 12°C up to 21°C in the interior spaces. All day closed mode is providing good thermal comfort, with steady temperatures up to just 19-21°C even when the outside temperatures are around 34°C.

<table>
<thead>
<tr>
<th>ventilation mode</th>
<th>day (8-18) times/h</th>
<th>night (18-8) times/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>daytime ventilation</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>nighttime ventilation</td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td>all day open</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>all day closed</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 1 Ventilation modes (room air changes per hour)

Figure 6. Nighttime ventilation effects on a clear sunny day in July

3.3.2. Winter heating mode

The winter outdoor temperature fluctuations between possible maximum and minimum temperatures values can be significant (Figure 8). Ground floor’s high thermal mass, as well as the First floor’s, provided heating throughout the day (at 21°C), secures the constant comfortable temperature of the interior spaces.

Comparing the thermal performance of the Ground floor and First floor, better performance in winter months has been observed on the Ground floor. Very thick masonry walls, from 44 to 65cm, with significant thermal mass, unsurprisingly, provide good insulation quality. When kept closed all day, without heating, Ground floor quarters keep the temperature between 2°C and 8°C even when the outside temperatures are at extremes (Figure 8.a).

Figure 7.a) Ground floor, summertime room air temperature fluctuations according to different ventilation modes b) Upper floor, summertime room air temperature fluctuations according to different ventilation modes

Figure 8. a) Ground floor heating modes b) Upper floor heating modes
Since the thermal performance of the house in its original state provides relative thermal comfort only in the case of constant heating regime, there was a need to test possible thermal performance improvements of the house by adding thermal insulation. Two additional performance scenarios have been simulated for both of the floors. These scenarios include adding insulation on the outside or inside of the existing wall structure, consecutively (Figure 9&10).

Thermal performance simulation for either of the floors, as well as comparative analysis of the results, showed that the most favorable scenario, among multiple combinations of heating hours and insulation positioning, is the case where the thermal insulation has been installed on the outside of the existing structure (Figure 9). In afore mentioned case the drop of room temperature, in the non-heating hours, is not as drastic as in the case of non-insulated (Figure 8) or inside insulated existing structure (Figure 10). Better thermal performance, due to high thermal mass, also implies decrease in heating load. This study can be used as a reference in efforts to improve energy efficiency and thermal comfort of the existing housing.

![Figure 9. Ground floor: Winter heating mode with additional thermal insulation outside of the existing structure](image)

![Figure 10. Ground floor: Winter heating mode with additional thermal insulation inside of the existing structure](image)

### 3.4. Site measurements

A field survey was conducted throughout the TBT house the using Mother Tool-LM-8000 measuring device. Measurements of indoor and outdoor temperature, humidity and wind speed were taken on two winter days, with extremely different conditions: 23rd of January, an unusually warm day with partly cloudy skies and observed outside temperature of 12°C and 25th of January, cloudy skies with snow and the outside temperature slightly below 0°C.

Since the house is used as a museum, some of the rooms are kept open and some are kept closed during most of the day (during working hours) so that the effects of all day closed or all day open ventilation modes could be observed. On a warm day, inside recorded temperatures in all day closed - no heating mode were slightly lower (8.7 to 10.7°C) than the outside 12°C, and on the cold, snowy day the opposite was true, with inside recorded temperatures (4.5 to 8.5°C) were higher than the outside temperatures (-0.7 to 0.2°C) by 4 to 8°C.

Although similarities between site measurements and software simulations are evident, the site measurements conducted are not to be considered as a final and cogent evidence of the house’s thermal performance since they were executed in an only limited time frame. They can instead be taken as an encouragement for future filed measurements and studies.

### 4. CONCLUSION

The analysis of the architectural elements of the traditional Bosnian town house as well at the computer-aided simulation of possible scenarios in terms of achieving optimal thermal performance, showed positive results. The house indeed demonstrates good performance in the wintertime, similar to that of appropriately insulated contemporary housing. It was discovered that in the summertime, the
combination of different architectural elements (divanhana, deep eaves, pavilion type of layout, gardens and courtyards, massive walls) and techniques (cross ventilation, night-time cooling) contribute to the thermal comfort of the house. These architectural elements and techniques have the potential to change the face of contemporary Bosnian architecture, if utilized properly. Seeking the lost connection with vernacular architecture means re-establishing the most natural way of living, the one in tune with the natural environment. Including vernacular passive elements into contemporary designs is expected to contribute in achieving more energy efficient and comfortable lifestyle while paving a new way to sustainable architecture in Bosnia and Herzegovina.

5. ACKNOWLEDGMENTS

Conducted research and study wouldn’t have been possible without the advice, support, and kindness of professors and other professionals that have provided essential advice and made the access to much needed data possible. Many thanks go to friends and family for all the encouragement of efforts made by authors while conducting this and other research. The authors would like to thank to all the staff of Svrzo’s House Museum, Federal Meteorological Institute in Sarajevo and Commission to Preserve National Monuments of Bosnia-Herzegovina that facilitated their time and efforts in order to provide much needed information and access to facilities.

6. REFERENCES

Solar Control in Traditional Architecture, Potentials for Passive Design in Hot and Arid Climate

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ABSTRACT

This paper is a part of a research work that targets the evolution of traditional architectural features to develop a passive design strategy for contemporary buildings. It counts on the building as a self-climate modifier in hot and arid climate. The traditional house demonstrates awareness of solar geometry and heat transfer mechanisms as basic physical principles which govern the heat gain/loss process within the building. The work in this paper is confined to examining the effect of traditional solar controls and shading mechanisms. Discussed features are the resulted cross shading in narrow street canyon and window screens. The suggested features were introduced as shading devices to an existing contemporary building within consecutive simulations using TRNSYS 17. The climatic data for Cairo as a case study was considered. The simulation model was tested against indoor temperature and validated by comparing results to measured data. The model then was modified by introducing suggested features which found to be comparatively effective in lowering the indoor temperature.

INTRODUCTION

An abandon of studies showed that the basic principle of traditional building was to accomplish a couple of goals; fulfill privacy; and achieve comfort. These purposes were fulfilled through a passive design strategy applied within urban setting, building form, and building envelop. The analysis identified some key components and other subsidiary elements. The main common aspect is the duality of nature of these key elements through which both thermal comfort and privacy were achieved. This paper focuses on the role of shading systems; street cross shading; and window screens, on reducing indoor air temperature in hot and arid climate regions with reference to the Egyptian capital Cairo.

Cairo is located on 30.0566° N, 31.2262° E in the North East side of the African continent. As most of the countries in its region, Cairo is characterized by a typical hot and arid climate that receives an average annual sum of 3000 hrs. Air temperature exceeds 40° C in the summer, as shown in figure 1. The climate in general is characterized by large diurnal temperature differences which allow intense solar radiation during the day and quick cooling down at night. These characteristics impose special considerations upon building design and the urbanization process in general, especially with regards to the solar geometry. The direct solar radiation intensity is up to 814-930 W/m² on the horizontal surfaces. Solar radiation is direct and strong during the day, but the absence of clouds permits easy release to the heat stored during the daytime, in the form of long-wave radiation towards the sky during night-time (Fathy, 1973). The solar radiation on horizontal surfaces reaches the highest range in June; 7.45 KhW/m²/day in Cairo. Egypt receives an average between 5.4 and 7.1 kWh/m² of annual daily direct solar radiation, as shown in figure 2, from north to south (Robaa, 2006).
Determination of the daily and annual sun path is essential to calculate the solar intensity of radiation hits the building (Hausladen, de Saldanha, & Liedle, 2006). It also helps to predict the resulted shadows and hence the placement of shading devices (Datta, 2001). A stereographic projection of the sun path shows both angles of altitude and azimuth as a diagram for the sun path which can be applied to each latitude. Figure 3 shows the sun path diagram for Cairo, the sun position at 15:00 hrs. in April 24, the period during which measurements took place for this study. The old town is characterized by almost narrow urban canyons with aspect ratio, height to width H/W = 2, as shown in figure 4. As the street width is proportional to the building height, the percentage of overshadowing one building by the other, obstruction angle (θ), remains constant for different building heights (Bansal, 1994).

Some recent studies focused on the influence of cross shading, orientation, and proportions of the street canyon on temperature differences. The following results were observed: a study focused on street canyon cross shading concluded that air temperature in the narrow urban canyon (H/W = 2) decreases by 4 °C compared with the wide urban canyon (H/W = 0.5) because of the lower solar gain in summer. A latitude of 33°N, EW street orientation can achieve shading of about 30% for an 8-month period in a year, with aspect ratio, H/W 2:1 or higher. The ratio 0.5:1 is least effective even with NS street orientation, less than 35% street shading (Bourbia, Awbi, 2004)

In 2006 Georgakis and Santamouris showed that ambient temperature above the canyon is found to be higher than the temperature inside the street with maximum of 5°C (Georgakis, Santamouris, 2006) The duration of solar radiation incident on both the east and west facades simultaneously was less than 3 hours in a traditional narrow canyon. The NS street orientation for H/W = 1.5:1 and higher can result in street shading between 40 to 80% of street area, whilst diagonal street orientations NW–SE (S2, S3) and NE–SW (S5, S6), can only manage street shading between 30 to 50% of street area throughout the year.

Studies have proved that incorporating overhangs depending on the different mean azimuth angles for summer and winter direct sunshine decreases the thermal gain through the building. For vertical glazing shaded by horizontal overhangs facing south, the rate of heat transfer into the building was 75 Wm² lower than unshaded windows, for June 21 (Askar, Probert, and Batty, 2001). It has been proven that the use of window screens in hot climates reduces the cooling loads and the perforation ratio of the
screens influences the inside temperature. Simulations were applied to screens on west, south, east and north facades and an ultimate ratios were proved as achieving the highest rate of energy saving. Proposed ratio between the width and depth was 1:1 with an 80% perforation in the west and north orientation and 90% in east and south. In comparison with non-shading windows, the energy savings resulted from the use of these screens reached 30%, 30%, 25% and 7% for the west, south, east, and north orientations. (Sherif, El Zafarany, and Arafa, 2012).

**METHODOLOGY**

The methodology of implementation of this paper was to test the indoor air temperature of an existing contemporary building which adopts the modern construction method prevailing in Cairo. The selected case study was intended to compromise the major opposites to the suggested features which would be introduced to the simulation package in TRNSYS to compare results with those of the base case and hence determine the extent to which those features can influence the indoor temperature. In order to validate the model generated in TRNSYS, in-site measurements took place within a certain timespan, which were then compared to the simulation results that found to be quite identical.

**Case Study**

The selected case is located on the eastern borders of Cairo within a residential quarter in the district of Heliopolis called the Sheraton Housing Area. **Figure 5** shows a satellite image of the site. The monitored case exists in the first floor of a nine-story residential building on a ground floor area of 310 m². Each floor consists of two identical apartments with an area of 135 m². The main façade is south-west oriented on a main street with 75 m. and a central green area, shown in **figure 6**. The building is a concrete structure and its walls are of hollow red bricks with density of 1790 kg/m³, thermal conductivity 2.1 kJ/hm.k, and specific heat 840 J/kg.C according to the Egyptian code for Buildings. Windows are 6mm. single clear glass with aluminum frames and all doors are made of wood. Parquet timber flooring is applied to the monitored case. The monitored room, shaded in the floor plan, **figure 7**, is the main living area of the western apartment in the first floor. The room is overlooking the main street through a relatively wide window 6 m², about 54% of the wall with no shading device. The case shows a lack of any cross shadings from opposite buildings except for the building facing the north east façade.

<table>
<thead>
<tr>
<th>Table 1. Building description</th>
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</tr>
<tr>
<td>Building type</td>
<td>Residential</td>
</tr>
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<td>Ground floor area</td>
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</tr>
<tr>
<td>Windows</td>
<td>6 mm. single clear glass</td>
</tr>
<tr>
<td></td>
<td>with aluminum frames</td>
</tr>
</tbody>
</table>
Measurements

Filed measurements took place for indoor air temperature of the selected room for one week long from the 18th to 25th of April using temperature data loggers hanged from the ceiling of the space on a height of 1.7 m. To get more plausible results, two data loggers were installed in the room, one facing the window directly overlooking the street and the other facing the balcony as shown in figure 8. A temperature data logger was as well placed outside in the balcony to get real ambient temperature records. The data loggers used are HOBO U12-012. According to the manufacturer, the measurement range of the loggers are -20° to 70° C and 5% to 95% RH. The accuracy of the loggers is ± 0.35° C from 0° to 50° and ± 2.5% from 10% to 90% RH. The loggers were set to continuously take readings each 10 minutes. The space was vacant and totally closed during the measurements periods and no cooling system operated. The results of the field measurements are shown in figure 9.

Although the selected period is not the best to represent the hot climate of the region, it was quite adequate for validation of the simulation model that should be tested against real measurements. Moreover, a comparatively high temperatures which reached a maximum of 38° C were recorded, which closely matches the hottest summer days. The weather data for Cairo was obtained on daily basis during the measurements period and a week before from the NOAA (National Oceanic and Atmospheric Administration). The obtained data included hourly records which were subsequently used to create a weather data file that was given to TRNSYS to run the simulation. Some differences were traced between the values of the measured ambient temperature, especially for the minimum values, and those of the obtained weather data which found to be 4° C less in average as shown in figure 10. This could be attributed to the differences between both sites of measurements as the weather data is obtained from the weather station that installed in Cairo Air Port in a totally open spacious and un-urbanized area. This is quite different from the site in which the readings were recorded; within relatively dense urban fabric in which the measured temperature should be influenced by the heat island effect and the heat released from the buildings during night-time cooling.

Figure 8  (a, b, c) Data loggers installation

Figure 9  Real Measured Temperatures

Figure 10  Measured outdoor temperature against real weather data
Simulation Package

As the main concern of this stage was to validate the capacity of the simulations by comparing their results to those of the real in-site measurements, a model of the selected case has been created and all related data was given to TRNSYS 17. A 3D model was created by TRNSYS 3D, as shown in figure 11, and the previously mentioned construction materials and their thermal properties, as shown in tables 1 and 2, were entered in TRNSYS Build. Simulation has run for the selected timespan and five days before upon the created weather data file. Initial values for indoor temperature was set to 21°C and relative humidity to 50%. A comparison then was carried out between the simulation results for indoor temperature of the selected room and the measured values.

![Figure 11 Model of the case study created by TRNSYS 3D tool](image1)

![Figure 12 Simulation results for indoor temperature against measured data](image2)

The results, shown in figure 12, demonstrate remarkable conformity between both profiles of measured and simulated indoor temperature which reaches a maximum of 30°C and a minimum of 25°C in both cases. As described above, the space was closed all along the measurements period and hence no ventilation or infiltration rates were applied. This might explain the relatively narrow gaps between maximum and minimum temperatures as it limits the chances for the occurrence of effective night-time cooling. Ventilation and the role of wind velocity can be discussed within subsequent paper that focuses on the role of the courtyard, as the work of this paper is confined to discussing the shading devices and the response to the solar factor.

Experiments

The main objective of this paper is a preliminary examination of the effect of the traditional shading methods on indoor air temperature in hot climate. As long as simulation results for the basic case were found to be similar to the measured data values, experiments could take place by incorporating the suggested features into the created model and hence results could be compared to those of the basic case to assess potential influences. Two major experiments then took place as follows:

**Narrow Street Canyon, Cross Shading.** The old traditional city was always characterized by dense urban fabric and narrow streets that generally form deep narrow canyons with average width of 7 cubits. This formation resulted in subsidiary streets which are almost east-west oriented being shaded along the day. The case studied in this paper represents an extreme opposite to this situation with a street width of 75 m., which supposedly played a significant role in the relative high indoor temperature. According to the west-south orientation of the main façade, it would be then exposed to the direct solar radiation especially from the middle of the day on.

This experimental step proposed a building opposite to the main façade and as the same height as the monitored building, leaving a street width of 6m, which creates a relatively deep narrow street canyon with aspect ratio much over 2. Although the case of adding a building in front of another is unlikely to happen within existing urban settlement, this experiment is applied to demonstrate the effect of narrow street canyon cross shading if being considered within urban development that take place in
the future. It was added as a shading device in TRNSYS 3D model, as shown in figure 13. An updated shading matrix was then generated in TRNSYS Build and the simulation has run as the same as the basic case in terms of period, material properties and other parameters. The results showed a significant decrease in indoor temperature that averages 4° C when compared to the values taken from simulation of the base case, as shown in figure 14.

Window Screens. Another shading device was added which is a window screen. The screen was incorporated to the window on the south-west façade. The window occupies an area of 6 m², about 54% of its wall. The screen was designed with modular sections of 5x5 cm. with proposed ratio between the width and the depth 1:1 and 50% perforation, as shown in figure 15. The resulted exposed glazing surface was then 19%. The simulation has run with new shading matrix generated and without opposite building. The results showed also decrease in maximum indoor air temperature with average value of 2.5° C, as shown in figure 16.

DISCUSSION

It is quite relevant that the first case in which an opposite building exists is found to reflect better thermal performance, as shown in figure 17, this could be attributed to a couple of factors. First is that the entire façade is shaded by the opposite building not only the shaded proportion of the window. Hence the transmitted solar radiation into the space would be significantly reduced, as shown in figure 18. The second factor is the role of resulted reduced outdoor temperature of the street and hence the façade temperature. In this case when the sun hits the surface of a building in a street canyon, convective current results as the air density changes the hot air moves to the upper level and be replaced with cooler air which has greater density, as shown in figure 19. The exposure of gap to the night sky enhances the night time cooling since the heat radiates up to the sky. The street is cooled down during night and daytime unless the sun is coming on a vertical angle. However, this could be discussed within a following paper.
To predict the performance of the suggested features during the hottest summer days, simulations have run for the base case to a year time span, figure 20. The same experiments were applied upon yearly weather data and a relative differences were found for maximum temperature in both cases within summer days in July and August, as shown in figure 21. In winter days however, the case of cross shading condition showed comparatively dramatic decrees in indoor temperature during January, as shown in figure 22. As the length of shadow on a wall surface can be determined, in relation to solar geometry, by horizontal and vertical shadow angles, as shown in figure 23. The decrees of indoor temperature could then be attributed to the position of the sun being too low in the sky and the opposing building that would almost block the radiation that would not reach the lower floors which remain shaded all the time, as shown in figures 24 a-b. However the window screens would be less effective in winter due to the limited shading resulted by the angle of the sun beam, as shown in figures 24 c-d.
CONCLUSION

Solar control was achieved within the old city on both levels of urban density and building envelop. The orientation of main roads in the old town is north-south; however the secondary streets of the residential quarters are east-west oriented. The buildings as a cluster therefore are shading each other. The amount of shading depends mainly on the morphology of the street canyon which results in decrease in the canyon temperature and hence the façade temperature and subsequently the amount of heat transferred by conduction through the walls. The incorporation of window screens also contributes to lower the indoor air temperature in hot and arid climate. The screen acts as a baffle zone between the interior and the exterior, so the glare of sunlight is broken up by the lattice that provides a dark area. By introducing both techniques to a contemporary building by running simulations using TRNSYS it is found to be relatively effective in reducing maximum indoor temperature in hot weather. However, the suggested features can be more efficient when applied within future researches considering convective current resulted in narrow street canyons and the role of cross ventilation in night-time cooling.

REFERENCES


Kampong Ayer: A Community Living on Water in Brunei Darussalam

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University of Nottingham University of Nottingham University of Nottingham University of Nottingham

ABSTRACT
Land scarcity and rising population in developing countries, particularly in the urban parts of Asia, has led to limited livable floor area for domestic mass housing. Developing countries with similar climate and cultural background face common challenges with their comparatively larger population resulting in high-rise housing. While this may be a solution to accommodating the increasing density in many cities, issues relating to cultural preservation, vernacular architecture conservation, social structures, environmental comfort and sense of community are often in contradiction with this urban solution. In particular, with for a rural community with different characteristics to an urban intent, the transition might prove stressful. In Brunei Darussalam, encouraging living both on water (in Kampong Ayer) and on land is what is being currently proposed. However, as its population is rapidly increasing and living on land is becoming increasingly popular, in this paper, the authors question if the housing developments on the water in Kampong Ayer, promote a sustainable community. The authors explored if waterside housing development, modelled on traditional settlement patterns, can provide a viable solution for rural housing in parts of Brunei. Domestic and communal relationships of its inhabitants were defined to identify sociospatial patterns of a sustainable community. Findings include the correlations between the formal and spatial organization of the home and patterns of occupation.

INTRODUCTION
The modernisation of rural communities into the urban ones may have many benefits in theory, but over time and with population growth, this tends to develop limitations. This is largely due to incompatible solutions imposed on these communities, resulting in their inability to adapt to them. To move forward, it is necessary to take a few steps back and examine vernacular architecture for a better understanding of how communities lived independently and built their own houses (Oliver, 1969). In as much as vernacular architecture in housing has often been associated with squatters and illegal settlements such as the favelas in Brazil, these self-built houses frequently offer insights into community spatial requirements. Indeed, learning from the past can encourage a stress-less human adaptability process (Roaf, 2010).

The Kampong Ayer, or ‘Water Village’, located in Brunei’s capital city Bandar Seri Begawan, houses around 39,000 people in self-built homes on stilts that form a unique architectural heritage that has been occupied for over 1300 years. Thirty years ago, the ‘discovery’ of the urban poor’s ingenuity in building their own houses generated a significant amount of research interest and subsequent literature (Ward, 1982). Similarly, studies that covered the technical performance of this type of housing, such as thermal comfort, were undertaken separately. However, it is suggested that a combination of both technical and socio-cultural issues would be more effective (Evans, 1980). For instance, while the performance studies into technology developed to combat climate change have been successful, the technological capability of
the community to fully utilise such technology is questionable (Hyde, 2008). It is suggested that the compatibility of technical and social solutions with regards to managing the urban poor needs to be in accordance with the local habits and preferences of the people (Labaki and Kowaltowski, 1998). Often we are unsure of what these local habits and preferences are. Nonetheless, a typical place that reveals such information is the house. As such, perhaps the first step towards understanding rural communities is to examine the role of the house and appreciate its significance to the community (Waterson, 1990). Gaining a deeper appreciation and understanding of the meaning and perpetual variables encapsulated in the house by examining patterns of daily domestic activities can give a clearer explanation of how it came to be rather than the end product itself (Rapoport, 1969).

Developing countries with similar climate and cultural values face common challenges with their comparatively larger population and often resort to high-rise housing. Brunei Darussalam, with a relatively small population of fewer than 400,000 people, has a less urgent agenda but equal concern for the sustainability of its future housing. In 1910 the attempt to relocate some residents of Kampong Ayer (around 10% of the total population) into housing estates on land began. However, as its population continues to grow and living on land becomes increasingly popular, a tailored sustainable housing approach for communities living on water may be needed to preserve and sustain Kampong Ayer. As the majority of the residents who reside there are low-income earners, it is of even more importance to resolve its housing issue (Sullivan and Ward, 2012).

In this paper the authors present an investigation into the evolution of spaces, from the 1950’s to the present day, of six houses in Brunei Darussalam, by analysing the daily life patterns registered on the floor plans of each house using a system developed by the authors. As there is limited detailed evidence of the daily activities, which occurred in the houses historically, it was not be possible to make any definite comparisons. Therefore, most of the work described in this paper was based on the actual findings from the field investigations.

Background

According to the Brunei Malay Technology Museum, 1989, there are five basic house types found in Kampong Ayer. Of these, the plan layout of two houses, ‘Tungkup’ and ‘Berlanggar’, best showed similarities to the case study houses, as they bore a strong resemblance to the current houses (Fig. 1). These simple open plan layouts suggest a communal use of gathering space as is typical of Malay houses found in the Malay Archipelago region. Typical characteristics of this house type were considered to create a datum for this discussion. In reference to a typical Malay house (Fig. 2), it is suggested that the floor plans demonstrate its multi-functional purpose, influenced by the time of day and year, minimal physical partitioning and furniture, and with most activities utilising the floor (Lim, 1987). Physically, the interior spaces are not defined by walls and are instead distinguished by differences in floor levels, varying floor sizes, orientation and location.

![Figure 1 Two Houses types, Tungkup (left) and Berlanggar (right) in Kampong Ayer, Brunei Darussalam as recorded by the Brunei Museum (Redrawn by authors).](image-url)
METHODOLOGY

The houses were randomly selected and the house owners’ were each required to sign a study participation agreement. Of the houses investigated, house 1, 2, 4 and 6 were found to have more traditional layouts, whereas house 3 and 5, built in the last four years, were found to have a ‘modern’ layout (Fig. 3). A summary of the characteristics of each house is given in Table 1. The investigation involved having the house occupants mark occupancy charts for each room in their houses, so as to map the frequency of and time when the rooms were occupied. The information marked on these charts showed the most commonly used rooms in the house as well as the number of people occupying the room at hourly intervals throughout the day, for period of 4-6 weeks.

Additionally, using Tinytag data loggers, the recording of internal temperature and relative humidity of the four most occupied rooms in each house was conducted simultaneously. To shed more light on the results of the occupancy investigation, interviews (partly based on findings from initial results of the study) with the house owners were undertaken. In addition to this, a survey was carried out with the intention of giving a general view on the living conditions of the people in Kampong Ayer. Some results from this survey as related to the selected houses are discussed later.

Figure 3 House plans of six houses (Source: House 1, 2, 4 & 6 from authors; House 3 & 5 from Public Works Department and Housing Development Department, Brunei Darussalam, respectively).
Table 1: Brief Descriptive Comparison of the Six Houses

<table>
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<tr>
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<th>4</th>
<th>5</th>
<th>6</th>
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<tbody>
<tr>
<td>Number of people living in the house</td>
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<td>14</td>
<td>15</td>
<td>6</td>
<td>4</td>
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<tr>
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<td>3</td>
<td>4</td>
<td>8</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Total floor area (m²)</td>
<td>211</td>
<td>194</td>
<td>203</td>
<td>336</td>
<td>122</td>
<td>105</td>
</tr>
<tr>
<td>Number of families Living in the house</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**OBSERVATIONS**

Sleeping arrangements were found to depend on the number of people living in the house and number of bedrooms available. For households with sufficient bedrooms, everyone was assigned to a group sleeping area. For instance, for a typical family living in a three-bedroom house, the parents shared a bedroom, while groups of the male children and female children each had a room each. Babies and younger children often share a room with their parents whereas young male and female children can share a room only if there is no other room. Segregating the children at an early age is partly influenced by the Islamic religion - the main religion practiced in Brunei Darussalam. Often, in deciding who gets a bedroom, female children are given priority over male children. Such was the case in House 3 where a family of fourteen living in a four-bedroom house allocated rooms in the following manner: Bedroom 1 – parents; Bedroom 2 – three daughters; Bedroom 3 – eldest daughter, her husband and their two young children; Bedroom 4 – second eldest daughter who is engaged to be married (her future husband will share the room with her); Living Room - three sons (one son sleeps in the communal space in the bedroom lobby at night). It was found that an insufficient number of bedrooms compelled families make use of other rooms in the house for sleeping, commonly the living room or family TV area. The bedrooms have beds while the living room or family room will have mattresses on the floor, which are rolled up and put away during the day.

Areas for sharing meals varied in all six houses. House 1 had a dining area next to the kitchen area, used for the main meals. On the other hand, House 5 had a dining table in an area separate from the kitchen, which was also used for main meals. House 2, 3, 4 and 6 each had a small table in the kitchen where the families could gather at mealtimes. Sometimes this involved moving furniture to accommodate everyone. Occupants of House 1, 5 and 6 had all their meals at their table at regular times of the day, whereas occupants of House 2, 3 and 4 had irregular meal times with some meals taken in different parts of the house such as the family TV room. With the exception of House 3 where the head the family occasionally used meal times as an opportunity to hold family discussions, it was noted that meal times were viewed mostly as a time for eating instead of dialogue. In addition to providing space for informal dining, the kitchen was used for cooking and as such its floor area is sufficient to accommodate just this. Also, the kitchen is usually modified to accommodate kitchenware storage and large freezer units. As fresh meat is not readily available, families bought in bulk to store until the next shopping trip in the city.

Common to all six houses was the popularity of the family TV area as the main gathering zone for family members. This took place mainly in the evening, after dinner and the last prayer of the day, at around 8.00PM. Rarely used for informal family gatherings, the living room is mostly used to receive guests. During special occasions and events involving many guests, all the communal areas in the house are occupied to accommodate everyone - including in the corridors. Furniture is moved to create more open spaces and carpets are rolled out on the floor for guests to sit on. As with the sleeping arrangements, females and males tend to group separately further highlighting gender segregation in spatial use, as is influenced by Islam.

Traditionally, the front of the house has an outdoor area, the veranda, which is used for less formal gatherings or as an introductory area before entering the house. Usually, this is the first area to be
renovated so as to extend the living room area. As a small roof or a large over-hanging roof already covers this space, it requires only three external walls, windows and a new entrance to do so. This newly extended room is commonly utilised as a living room or small shop (Fig. 4). In House 4, the existing living room is large enough to accommodate a small shop indoors (Fig. 4). However, the extension option was found to be more common possibly due to occupants wanting to keep indoor areas inaccessible to the public.

Figure 4 Left: House 3 before and after conversion of the veranda into a shop (a) December 2012 (b) January 2014. Right: Showing the living room in House 4 that has been modified to accommodate a small shop (Source: Author).

RESULTS FROM THE OCCUPANCY INVESTIGATIONS

Tables 2 and 3 show some results of the occupancy investigations. Table 2 reveals the bedrooms and the family TV room to be the most frequented spaces. Specifically, a large duration of the time spent in the bedrooms is spent sleeping (between 9.00PM and 5.00AM) but is also occupied for short afternoon naps and performance of daily prayers during the day. As was highlighted earlier, the family TV area is occupied more frequently than the living area as it is less formal and allows the families to gather there to rest, watch TV and carry out a variety of activities. Also shown is the amount of time spent in other areas in each house where/when each family conducts other daily activities.

Table 2: The Most Frequently Occupied Rooms in Each House

<table>
<thead>
<tr>
<th>House</th>
<th>Three Most Occupied Rooms in Each House with Percentage of Occupancy (On average in a day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Family TV 71%</td>
</tr>
<tr>
<td>2</td>
<td>Bedroom 1 92%</td>
</tr>
<tr>
<td>3</td>
<td>Bedroom 1 100%</td>
</tr>
<tr>
<td>4</td>
<td>Living 100%</td>
</tr>
<tr>
<td>5</td>
<td>Bedroom 2 100%</td>
</tr>
<tr>
<td>6</td>
<td>Bedroom 1 100%</td>
</tr>
</tbody>
</table>

To get an indication of the thermal comfort conditions in the houses, the temperature and relative humidity measures of selected rooms in each house was recorded. As the houses are located within the warm-humid climate zone, discomfort is more likely to be as a result of relatively high temperatures and relative humidity levels. More often than not, the main means of relief for occupants in this climate is air-movement for physiological cooling (Koenigsberger, 1974). As is typical of the Malay House, the more traditional houses were found to be structurally responsive to the climate through the provision of lightweight construction (to prevent storage of heat in the fabric), large window openings to enhance cross ventilation and air-movement as well as wide overhangs/eaves that act as sun shading elements. Some of the bedrooms had air-conditioners - only used occasionally during the night. Thermal discomfort during this time was suggested to be due to the increased number of occupants within the spaces. While the more recently built houses feature fewer passive cooling controls, it is suggested that structural modifications,
such as indoor partitions have contributed to inefficiency in maintaining comfort naturally. Also, as these houses were more compact in plan, their layouts have significantly reduced the opportunities for, and efficiency, of natural cross-ventilation. Additionally, the results from the recordings were matched against the CBE Thermal Comfort Tool for ASHRAE Standard 55-2010 to determine whether any of the readings were within the predicted thermal comfort zone. Table 3 presents a snapshot of recordings taken a selected typical day – temperatures that fall within the standard are highlighted.

<table>
<thead>
<tr>
<th>House (on water)</th>
<th>Rooms</th>
<th>Internal Temperature °C and Relative Humidity %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2.00 AM</td>
</tr>
<tr>
<td>1</td>
<td>Family TV</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Bedroom 2</td>
<td>-</td>
</tr>
<tr>
<td>Dining</td>
<td>30°C / 63.9%</td>
<td>27°C / 77.1%</td>
</tr>
<tr>
<td>2</td>
<td>Bedroom 1</td>
<td>22°C / 71%</td>
</tr>
<tr>
<td>Family TV</td>
<td>25°C / 86%</td>
<td>25°C / 86%</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>25°C / 87%</td>
<td>25°C / 92%</td>
</tr>
<tr>
<td>3</td>
<td>Bedroom 1</td>
<td>19°C / 59%</td>
</tr>
<tr>
<td>Bedroom 3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Family TV</td>
<td>25°C / 64%</td>
<td>26°C / 77%</td>
</tr>
<tr>
<td>4</td>
<td>Living</td>
<td>-</td>
</tr>
<tr>
<td>Family TV</td>
<td>25°C / 86%</td>
<td>27°C / 77%</td>
</tr>
<tr>
<td>Kitchen</td>
<td>25°C / 88%</td>
<td>26°C / 85%</td>
</tr>
<tr>
<td>5</td>
<td>Bedroom 2</td>
<td>-</td>
</tr>
<tr>
<td>Bedroom 3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>27°C / 73%</td>
<td>27°C / 78%</td>
</tr>
<tr>
<td>6</td>
<td>Bedroom 1</td>
<td>27°C / 79%</td>
</tr>
<tr>
<td>Living</td>
<td>26°C / 83%</td>
<td>28°C / 73%</td>
</tr>
<tr>
<td>Family TV</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Although most of the readings shown fall outside of the thermal comfort zone of ASHRAE Standard 55-2010, it is suggested that the use of structural controls (large fenestration, orientation, space volume, floor area and in some cases mechanical ventilation) and self-adjustment mechanisms helps to make existing conditions tolerable. At first glance, the readings from the houses located in the water have lower temperature readings than the houses on land. It is suggested that this is as a result of the micro-climate conditions. As the surrounding ‘ground’ area the houses on water is less likely to retain heat, then it is less likely for the houses to absorb heat via radiation/reflection from the ground surface, as might be the case in the houses on land. During the study it was found that external temperature levels taken in both areas showed those on land to be higher than for that of the houses on water. However, the extent to which the comparison of water and land ground surfaces and their influence on the thermal comfort in the houses will require further investigation to reach a more valid conclusion.

RESULTS FROM THE SURVEY

Results from the survey regarding the houses revealed some information about the renovations of these houses (Fig. 5). A majority of the participants taking part in this survey, live in timber houses on water, and have at some point made renovations and extensions to their house - most of which are self-built and constructed with timber. Some have integrated other materials including brick and steel. Employing contractors or foreign labourers to build the extensions is becoming increasingly popular too, which is subsequently diminishing the timber-building skill amongst the local community.
DISCUSSION ON OBSERVATIONS AND RESULTS OF INVESTIGATION

For houses with larger families, limited sleeping areas and gathering areas leave occupants with the need to utilise other areas of the house for these activities. The living and family TV areas are normally used for sleeping by the older single male members of the family with the priority of occupation of bedrooms given to the married couples and female family members. This indicates a type of hierarchy within the families which is distinctly determined by age, gender and marital status.

It is suggested that the nature of ‘gathering’ has evolved due to the size of the kitchen. Traditionally, the open floor plan of the houses accommodated all household activities. All family members would gather in this open area where they would - together or in their own time - rest, sleep, pray, eat and talk. There was rarely any furniture in these houses and everyone sat on mats/carpets on the floor, which also helped to define space. This was useful during big occasions as they were able to fit large numbers of people in the communal areas of the open interior. In contrast to the set up in the houses today, internal walls and furniture have compromised the previously free-flowing nature of house and reduced its flexibility. While bedrooms are off limits to guests and visitors, all communal parts of the house are used; as such, furniture is often shifted to give an open space. The traditional way of gathering is still favoured and practiced in some houses in Kampong Ayer. The daily family gathering space in traditional open layouts was only ever in one space. In the current layouts the gathering area consists of two spaces; the living area (mainly for receiving guests) and the family TV area (for casual family gatherings). How often the living area was used depended on how frequently they had guests. The family TV area is mainly for watching television, meaning less interaction amongst family members.

From a structural viewpoint, traditional houses in Kampong Ayer, with their open plans and minimal internal partitions, were able to enhance the cooling effect of natural ventilation with the light, constant breeze flowing freely through the houses. Nowadays, the houses, and more so those on land, have evolved into complex layouts with more internal wall partitions. Although this gives more visual privacy within the house, opportunities for efficient natural cross ventilation may be compromised. Renovation of the veranda

Figure 5: Results of Part: House; Questions 9, 11, 13 and 14.
into another room may have also compromised the advantage of utilising it as a heat buffer. Nonetheless, despite the results from the internal temperature and relative humidity recordings showing that most of the conditions were outside the prescribed thermal comfort range, occupants still managed to feel comfortable with the minimal help of fans/air-conditioning units as a result of using existing passive controls.

With self-building skills becoming less popular in Kampong Ayer, the locals are seeking expertise elsewhere. Not only is this more expensive, but it also means that the ‘sense of community’ that is tied to self-help/self-build is disappearing. This can have a dramatic effect on the sustainability of the water village, as a huge part of their resilience in the past centuries has been through community cooperation. As most of the houses in Kampong Ayer today are originally self-built, its design intent stems from the house owners own desires and necessities. The contents of the houses and the modifications made to the houses over time are clear indications of the constantly changing life stages of each family. The flexibility of the houses in allowing the house extensions and renovations to suit the families’ changing structure has allowed them to remain comfortable in the same houses for many generations (Friedman, 2011).

As has been suggested in numerous other studies, the design of climate responsive houses is often ignored when developing mass-housing proposals and may be dominated by cost, availability of land and population as is common in the aforementioned high-rise typologies. Also, it has been noted that sociocultural issues tend to influence the occupancy and morphology of their houses. It has been suggested that more suitable approach would be to examine both technical and socio-cultural factors side by side so as to derive an approach that would lead to the future development and maintenance of sustainable communities in Brunei Darussalam effectively.

CONCLUSION

Communities usually survive most environmental challenges they face; as long as the adaptability period and means to adapt is within its capability and that there is cooperation amongst the community members to achieve a joint goal to survive. However, some challenges that prove to go beyond the community’s resilience can result in a defeated end. The people living in Kampong Ayer appear to want to continue living there as they have adapted well despite the challenges imposed on the village, such as scarcity of local materials, economics or employment. Their undeniably strong sense of independence and individuality, apparent in the make up of their houses, shows confidence in their spirit to be sustainable. However, the extent of their resilience is yet to be determined. There are certainly other factors influencing the sustainability of such a community, some of these may be future threats. On that note, this paper opens doors to investigate what the limits are to this community’s sustainability in this context.

REFERENCES

Session 5B: Low carbon cities and neighborhood development

PLEA2014: Day 2, Wednesday, December 17
11:30 - 13:10, Compassion - Knowledge Consortium of Gujarat
How effective are ‘close to zero’ carbon new dwellings in reducing actual energy demand: Insights from UK

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Mariam Kapsali, MSc
OISD, Oxford Brookes University

ABSTRACT

In the UK, zero carbon will be the standard for new homes from 2016 and non-domestic buildings by 2019. However, it is increasingly recognized new buildings use at least twice the energy predicted by energy models and this gap is relatively poorly understood, thereby risking contravention of zero carbon policy. Yet there is relatively little understanding within policy and wider industry of what might be causing this gap.

This paper investigates the actual energy demand reductions achieved in three ‘close to zero’ carbon social housing developments in UK, through a systematic approach comprising building performance monitoring and post-occupancy evaluation of six case study dwellings over 1.5 years. The six case study houses cover a variety of built forms and different types of construction systems with similar occupancy profiles within the same development.

Findings from the first year of monitoring show that the actual energy use in the case study houses exceeds their design predictions by a factor up to 3. CO₂ footprint across the six houses differ by a factor of nearly 2 in some cases despite all the developments being designed to Code for Sustainable homes level 4 or 5. Consistently high indoor temperatures (>25°C) are observed in the majority of the dwellings both in living rooms and bedrooms. Other issues include lack of user comprehension of mechanical ventilation and heat recovery (MVHR) systems and air source heat pumps, resulting from poor guidance during handover and inadequate commissioning of these systems.

To ensure that such low energy houses perform as intended, seasonal commissioning of services and systems is essential. Occupants need to be trained through graduated handover, supplemented by visual home user guides offering advice on using energy systems and controls. Otherwise there is a risk that UK Government’s zero carbon housing policy may get undermined.

INTRODUCTION

The UK government has passed a legally binding framework to reduce the country’s carbon emissions 80% below 1990 levels by 2050 (UKGBC, 2008). Zero carbon will be the standard for new homes from 2016 and non-domestic buildings by 2019. However, there is a growing concern within the housing industry that, in practice, even current energy efficiency and carbon emissions standards are not being achieved (Gupta and Gregg, 2012). It is increasingly recognized that there is a gap between actual energy use in building and the energy predicted by models (Gupta et al, 2013; Bell et al, 2010). This performance gap may undermine zero carbon housing policy and carry considerable commercial risk for the wider industrial sector (Zero Carbon Hub, 2013). Yet there is relatively little understanding within policy and wider industry of what might be causing this gap.

Rajat Gupta is Professor of Sustainable Architecture and Mariam Kapsali is a Research Associate in the Oxford Institute for Sustainable Development (OISD), School of Architecture, Oxford Brookes University, Oxford, England.
Research on the performance gap in the housing sector highlights the need for measuring fabric performance and reviewing the commissioning of services and systems (Wingfield et al, 2011), (Zero Carbon Hub, 2013; Gupta et al, 2013) but also points out the effect of occupant behaviour and understanding (Firth et al, 2008; Steemers and Yun, 2009; Gill et al, 2010).

This paper investigates the performance gap in six case study dwellings across three ‘close to zero’ carbon social housing developments in the UK. A Building Performance Evaluation (BPE) based forensic approach is adopted to evaluate the location and extents of the performance gap for these projects, followed by an in-depth analysis of the empirical findings to reveal the causes of the discrepancies. Findings reveal that fabric performance, installation and commissioning, usability of controls, occupant behaviour and understanding play an important role in influencing housing performance and are the root causes behind the performance gap.

**BUILDING PERFORMANCE EVALUATION METHODOLOGY AND CASE STUDIES**

Building performance evaluation (BPE) is the process of identifying and locating the gas between ‘as designed’ and ‘in use’ performance through a systematic collection and analysis of qualitative and quantitative information related to energy performance, environmental conditions, fabric performance and occupant feedback. The project is part of the National Building Performance Evaluation (BPE) programme funded by the Technology Strategy Board, the UK Government’s innovation agency. The programme involves both domestic and non-domestic buildings and aims to help the construction industry deliver more efficient and better performing buildings (TSB, 2012).

The six cast study dwellings are part of three exemplar social housing developments (A, B and C) located in South East England). The six case studies (two per development – A1, A2, B1, B2, C1 and C2) were selected to represent a variety of built forms and construction systems with similar occupancy profiles. Table 1 presents the background characteristics of the case studies and Table 2 presents an overview of their design specifications and construction details. Understanding the extent and location of the performance gap in these studies helps to identify ways to address the gap.

| Table 1. Case Studies Information |
|-------------------------------|------------------|-----------------|-----------------|-----------------|
| **Case study reference**      | **Development A** | **Development B** | **Development C** |
| **Area**                      | 94 m²            | 88 m²           | 123 m²          | 128 m²          | 146 m²          |
| **Typology**                  | 2 bed, mid-terrace | 3 bed, end-terrace | 4 bed, mid-terrace | 4 bed, mid-terrace | 5 bed, detached |
| **Occupancy patterns**        | 24h              | 15:00-8:00      | 24h             | 13:00-8:00      | 13:00-8:00      |
| **Occupants**                 | 2 adults, 2 children | 2 adults, 2 children | 4 adults, 1 baby | 2 adults, 3 children | 1 adult, 5 children |

| Table 2. Design Specifications and Construction Details |
|--------------------------------|------------------|-----------------|-----------------|
| **Construction type**          | Timber frame with cast hempcrete | Steel frame with pre-insulated panels | Timber frame and brick |
| **Target design rating**       | CSH Level 5      | CSH Level 4     | CSH Level 4     |
| **As designed**                | Walls 0.18       | Walls 0.15      | Walls 0.21      |
| **U-values W/m²K**             | Windows 1.4      | Windows ≤1.2    | Windows 1.3     |
| **Space heating and hot water system** | Exhaust Air Heat Pump (EAHP), underfloor heating, solar collectors | Air Source Heat Pump (ASHP), underfloor heating, immersion heater back up | Gas condensing boiler with radiators |
| **Ventilation strategy**       | MVHR through EAHP | MVHR | MVHR             |
| **Renewables**                 | 4kWpk Photovoltaics | 1.5kWpk Photovoltaics | 1.65kWp & 1.88kWp Photovoltaics |
ACTUAL ENERGY USE

Monitoring data for energy consumption are provided for the period from January to December 2013 as shown in Figure 1. Comparison of actual energy use with ‘as designed’ SAP\(^1\) predictions reveals big discrepancies between them in all cases. These discrepancies are partly due to the fact that SAP does not cover all end uses of energy in dwellings. To overcome this, SAP predictions were extended to include electricity for lighting and appliances and energy used for cooking. Actual annual energy use exceeds the extended SAP prediction by a factor of 2 in Cases A1, A2, B1 and B2, by a factor of 2.5 in Case C1 and by a factor of 3 in Case C2. Actual annual CO\(_2\) emissions are even higher compared to the extended SAP prediction in all cases. Cases A1 and A2 present the highest discrepancies, exceeding the values of the extended SAP model by a factor of 4.5 and 3 respectively. This is due to the houses being electrically heated.

Cases A1 and A2, although designed for CSH Level 5, consume more electricity than Cases B1 and B2 that have been designed for CSH Level 4. This is partly due to the low COP of the EAHPs in Cases A1 and A2 that has been measured to 1.4 instead of the design specification of 2.6. The design COP of the ASHPs in Cases B1 and B2 is 3.13. Cases C1 and C2 have a similar performance to a typical UK house, despite being designed to CSH Level 4.

There is also significant variation in the energy consumption of houses within the same development designed to the same standard and with similar occupancy patterns (Table 1). In Development A, occupants in Case A2 keep their thermostat at 19\(^\circ\)C and are more energy conscious than their neighbours who keep the thermostat between 25-27\(^\circ\)C. Occupant expectations and control over heating resulted in the annual CO\(_2\) emissions and actual energy use of Case A1 being higher than that of Case A2 by a factor of 1.3. In Development B, annual CO\(_2\) emissions and actual energy use in Case B1 are higher than those of Case B2 by a factor of 1.2 as a result of poor occupant understanding of the ASHP that led to reduction of the system’s efficiency. The highest energy consumption is observed in Cases C1 and C2. Annual energy use of Case C2 exceeds that of Case C1 by a factor of 1.5. In both houses occupants set their thermostats as high as 30\(^\circ\)C throughout the day, but in Case C2 occupants tend to leave the windows open day and night even during winter (Figure 4) thus increasing the heat loss and the heating demand.

\[\text{Actual energy use} = \text{as designed SAP} 	imes \frac{\text{actual COP}}{\text{design COP}}\]

\[\text{Actual CO}_2\text{ emissions} = \text{as designed SAP} 	imes \frac{\text{actual COP}}{\text{design COP}} \times 0.445 \text{ kgCO}_2/\text{kWh}\]

\[\text{Actual CO}_2\text{ emissions} = \text{as designed SAP} 	imes \frac{\text{actual COP}}{\text{design COP}} \times 0.184 \text{ kgCO}_2/\text{kWh}\]

![Figure 1](image)

(a) Comparison of actual energy consumption and (b) comparison of actual CO\(_2\) emissions with SAP predictions and Extended SAP prediction across all cases (January – December 2013). Emissions factors: Electricity 0.445 kgCO\(_2\)/kWh, Gas 0.184 kgCO\(_2\)/kWh (Carbon Trust, 2013).

\(^1\) The Standard Assessment Procedure (SAP) is the methodology used by the UK Government to assess and compare the energy and environmental performance of dwellings.
CAUSES OF PERFORMANCE GAP

Fabric performance

The fabric performance of each housing development was forensically assessed using in situ U-value tests, air permeability tests and infrared thermography. The common emerging issues across the three developments are summarized in Table 3.

Table 3. Common emerging issues highlighted by evaluation of fabric performance

<table>
<thead>
<tr>
<th></th>
<th>Development A</th>
<th>Development B</th>
<th>Development C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat loss through party walls</td>
<td>×</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>Heat loss through external walls</td>
<td>×</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat loss through window and door frames</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Thermal bridges (thresholds, ceiling beams)</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Actual U-values higher than design</td>
<td>×</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loft insulation not well distributed</td>
<td></td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Actual air-permeability much higher than design</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

Wall insulation levels were found to be good in all cases. The findings from the in-situ U-value tests showed that in Developments B and C actual wall U-values are similar or even better than those specified at the design stage. However in all cases, thermographic images revealed heat loss and air leakage paths through door and window frames, cold spots in walls and thermal bridges across thresholds. Thermal bridges through ceiling beams and heat loss through party walls were also identified. This has implications for better detailing of joints and juctions by designers and careful implementation by contractors.

Air permeability tests revealed a noteworthy gap between ‘as designed’ and actual air-tightness in all case studies. All dwellings missed their design target (2-3 m³/m².h) with air-permeability in most cases being twice as high as designed as shown in Figure 2. Such high values (5-6 m³/m².h) question the actual need for an MVHR system since these have been specified for more airtight homes usually having air permeability below 3 m³/m².h. Better air-tightness would have resulted from high quality detailing at key junctions, skirtings and service penetrations and careful workmanship around door and window thresholds and seals.

![Figure 2](image)

Figure 2 Comparison of measured and design air permeability.

Installation and commissioning of systems and services

A commissioning review is undertaken to ensure that the services and equipment’s commissioning are complete and the design and operational strategy was capable of creating the desired performance and comfort.

The MVHR system installation and commissioning was found to be the most problematic issue in all six houses due to the developers’ lack of experience with such systems. Improper commissioning and system imbalances were noted in all cases, breakdowns were reported in Cases B1 and B2, noise and cold draughts were reported in Cases C1 and B2 respectively. System imbalance due to poor commissioning and occupant intervention leads to increased heat loss and heating loads, increased
energy use of the MVHR unit, system resistance, noise and cold draughts. In some cases (C1, C2) occupants had completely shut the supply terminals thus seriously undermining indoor air quality.

Commissioning of heating controls and room thermostats was also found to be problematic in Developments A and B. In Development A, commissioning check before the move-in revealed that the room thermostats had not been properly connected. In Development B, the wireless room thermostats had not been properly connected to the heating system resulting in the heating being constantly on leading to energy wastage. This was discovered during the study several months after the move-in following occupant complaints of lack of control over heating and of rooms being too hot. Poor commissioning of heating controls results in increased energy use and makes occupants skeptical of the low carbon technologies installed in the houses.

Usability of control interfaces

A review of the control interfaces investigates the relationship between the design and usability of controls and the potential effect they could have during the dwelling’s occupancy (Bordass et al, 2007). Table 4 summarizes the key issues that emerged from the three developments.

<table>
<thead>
<tr>
<th>Table 4. Common emerging issues highlighted by review of control interfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development</td>
</tr>
<tr>
<td>Conflicting control strategies</td>
</tr>
<tr>
<td>Oversimplified control interfaces</td>
</tr>
<tr>
<td>Overcomplicated heating controls and zoning</td>
</tr>
<tr>
<td>No indication of MVHR failure or maintenance</td>
</tr>
<tr>
<td>MVHR unit inaccessible, located in loft</td>
</tr>
<tr>
<td>Windows and doors intuitive, good fine control</td>
</tr>
</tbody>
</table>

Heating controls and thermostats were found to be problematic in Developments A and B. In Development B the designers’ intention to provide occupants with good levels of control resulted in an excessive use of over-designed thermostats and zones that confuse occupants and complicate commissioning. On the other hand, oversimplified controls like the ones used in Development A, lead to similar results. Unclear, oversimplified or complex control strategies have a negative impact on energy use due to poor occupant understanding and control.

Provision of usable and accessible MVHR controls was an issue for all cases. The MVHR units in Developments B and C are not easily accessible as they are located in narrow loft spaces that hinder maintenance. In most cases, boost buttons do not provide an indication of system response and MVHR units do not give an indication of failure or maintenance. Poor control over ventilation and poor maintenance can lead to increased energy use of the MVHR unit and can also have a negative impact on indoor air quality and occupant comfort.

Handover process and user guidance: communication of design intent

The handover homeowners receive before moving into their new home was observed and the documentation was reviewed to establish whether the information provided is sufficient in communicating the intent and operation of the new home without being overly technical or confusing.

The findings reveal that a phased approach, such as those followed in Developments A and B, is more successful for the handover. However, it would have been more beneficial if the handover also included discussion on the handover documentation (User Guide and O&M manuals) and hands-on application by the occupants. In Development C no phased approach was followed as the handover was completed in a day. Significant risk has been identified regarding the amount of information the occupants can absorb on the day of the handover. The review of Home User Guides showed that the guides generally contain extensive technical details, instead of providing occupants with clear guidelines on how to make better use of systems on a daily and seasonal basis.

Despite the differences in the handover process and guidance documentation, follow up conversation and interviews with occupants revealed that in all three developments some occupants have
failed to understand the purpose and operation of the low carbon systems or have forgotten the information that was provided to them initially. Lack of occupant understanding is one of the reasons leading to higher energy use and poor performance of systems. This raises questions about the quality of the handover and the need for retraining the occupants.

**Occupant expectations and satisfaction**

**Occupant behaviour and expectations.** Internal temperature data (January – December 2013) reveal that demand temperatures in the houses are high as shown in Figure 3. This is closely related to occupants’ high expectations of comfort. Overall temperatures are high with five out of six houses having mean living room temperatures above 21°C and three out of six houses having a mean above 23°C. Peak temperatures above 27°C were also observed in the majority of the houses (five out of six). Bedroom temperatures present a similar trend with five out of six houses having mean bedroom temperatures above 21°C. Cases A1 and C1 have the highest mean temperatures as the occupants use a lot of heating energy by keeping their thermostats around 25-27°C throughout the day. In Case C2 occupants also keep their thermostat very high throughout the day (30°C) but mean temperatures are around 21°C because occupants keep their windows open for many hours during the day (Figure 4), thus leading to the high gas consumption shown in Figure 1. This level of demand is leading to a gap between design prediction and actual consumption in terms of both energy use and environmental conditions.

![Figure 3](image1)

**Figure 3** Mean, minimum and maximum temperatures in (a) living rooms and (b) bedrooms (January – December 2013).

![Figure 4](image2)

**Figure 4** Hourly average temperatures and hourly percentage of window opening across a day (November – April) in Case C1 and Case C2.

**Occupant surveys, interviews and walkthroughs.** Occupant satisfaction surveys were carried out in all three developments using standardized occupant satisfaction questionnaires (BUS). Additionally, semi-structured interviews and walkthroughs were carried out with the occupants of the six case studies using the same templates. Table 5 summarizes the positive and negative occupant feedback from the survey and occupant interviews related to controls, comfort and satisfaction with space.
Table 5. Common emerging issues highlighted by occupant survey and interviews.

<table>
<thead>
<tr>
<th>Positive feedback</th>
<th>Development A</th>
<th>Development B</th>
<th>Development C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satisfaction with space and layout</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Satisfaction with design and appearance</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Satisfaction with light levels (natural, artificial)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Temperatures good overall</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Negative feedback</th>
<th>Development A</th>
<th>Development B</th>
<th>Development C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor control over heating</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Lack of understanding of heating system</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Lack of knowledge about MVHR</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Poor control over ventilation</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot during summer</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Home User Guide considered complicated.</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Energy bills considered high</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

In all developments occupants are fairly satisfied with the appearance, design, layout and space of the houses. Also, daylight levels are appreciated in most cases. Most negative feedback involves the operation and control of the heating and MVHR system. Control over heating is considered problematic in Developments A and B that feature heat pumps and underfloor heating as occupants are not well familiar with such technologies and find the Home User Guide confusing. Control over ventilation is also considered problematic in most cases due to occupant confusion about the operation of the MVHR system. Moreover, energy bills are high in all houses although all three developments designed to reduce energy use. Occupants in Developments A and B are very unhappy with their electricity bills which they attribute to the poor performance of the heating system. In Table 6 actual electricity and gas bills are between 3 to 20 times higher than the SAP estimated energy costs. The combination of many new technologies, unfamiliar to both the occupants and the developers and owners, led to confusion and dissatisfaction in most cases.

Energy use in houses depends heavily on the occupants’ perception of comfort and their attempts to attain comfortable conditions. Thermal comfort satisfaction is closely linked to the level of understanding and control over the heating and ventilation system. Resolving the issue of comfort and control effectively and understanding occupant expectations through follow-ups and training are essential for closing the performance gap and achieving better environmental conditions.

Table 6. Comparison of actual bills with SAP estimated costs and UK typical domestic energy bills

<table>
<thead>
<tr>
<th>Cost (£)</th>
<th>A1</th>
<th>A2</th>
<th>B1</th>
<th>B2</th>
<th>C1</th>
<th>C2</th>
<th>UK typical ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted (SAP) cost</td>
<td>70</td>
<td>70</td>
<td>330</td>
<td>336</td>
<td>259</td>
<td>315</td>
<td></td>
</tr>
<tr>
<td>Electricity bills</td>
<td>1,440</td>
<td>1,200</td>
<td>1,300</td>
<td>1,100</td>
<td>700</td>
<td>960</td>
<td>424</td>
</tr>
<tr>
<td>Gas bills</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>720</td>
<td>1,500</td>
<td>608</td>
</tr>
<tr>
<td>Actual total cost</td>
<td>1,440</td>
<td>1,200</td>
<td>1,300</td>
<td>1,100</td>
<td>1,420</td>
<td>2,460</td>
<td>1,032</td>
</tr>
</tbody>
</table>

CONCLUSION

Using a mixed-methods socio-technical BPE approach, this study has identified the reasons for underperformance of ‘close to zero’ carbon new dwellings. The study has revealed that the actual energy use in the case study houses exceeds design predictions by a factor up to 3. Furthermore, actual energy use across the six case study houses varies by a factor 1.6, despite all the developments being designed to CSH Level 4 or 5 and having similar occupancy profiles. Fabric performance, commissioning of systems, usability of controls and occupant understanding and expectations increase the gap between actual and design performance. Discrepancies in fabric and system performance may result from difficulty of communicating design intentions and expectations, specification error or omissions and construction errors. Such issues could be avoided through rapid diagnostics onsite and better

² Typical UK domestic energy bills and consumption figures based on average household bills (Ofgem, 2011)
communication between all stakeholders. Installation and commissioning is clearly an area where increased training and awareness and checks will have a large impact on improving the performance of dwellings. In order to improve commissioning and maintenance developers and constructors need to ensure that their technicians receive adequate training. Seasonal commissioning also needs to be encouraged for houses with technologies such as heat pumps and MVHR systems.

The study also highlights the need for a detailed and coordinated services layout plan showing location of systems and controls that will help to solve issues of accessibility and will provide the basis for a clear strategy that the occupants need to follow. Combination of clear design intentions, intuitive and responsive control mechanisms and good occupant guidance and training will ensure better use of systems and increase the potential for energy reductions and improvement of environmental conditions. Findings indicate the need for graduated handover that involves hands on application by occupants, supplemented by visual home user guides offering clear guidance on the daily and seasonal operation of systems and controls. Guidance must be customized according to residents’ background and abilities.

Learning from real-world case studies is an insightful way for understanding the reasons behind the energy performance gap in order to achieve low carbon housing in practice. This requires a formalized briefing, commissioning and feedback protocol, such as ‘Soft Landings’ (BSRIA, 2009), that has started to be used in domestic projects. This will help to ensure that these lessons are captured and fed back to the developers, constructors and designers. Otherwise there is a risk that UK Government’s zero carbon housing policy may get undermined.

ACKNOWLEDGMENTS

We are grateful to UK Government’s Technology Strategy Board’s Building Performance Evaluation (BPE) programme for sponsoring these BPE research projects. Our sincere thanks also to occupants, client and project design teams for their help and support during the study.

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Stevenson, F. and H.B. Rijal. 2010. Developing occupancy feedback from a prototype to improve housing production, Building Research & Information, 38:5, 549-563
A quiet revolution: Mapping energy use in low carbon communities

ABSTRACT

Recent Government funding in the UK has enabled 22 low carbon community organisations to work with the private and academic sector to understand and reduce energy consumption in domestic and non-domestic buildings. This has helped communities prepare for policy mechanisms such as the national Green Deal programme which aims to improve existing housing and non-domestic buildings by offering up-front loans to be repaid by energy savings. This paper presents the role and application of a unique carbon mapping approach, which has enabled five of these low carbon communities to rapidly assess on a house-by-house level, the potential for improving the energy efficiency of their housing stock. DECoRuM, an award-winning GIS-based carbon counting model is used to measure, model, map and manage energy use and CO\textsubscript{2} emission reductions from approximately 1,300 houses across five communities, displaying estimates of energy use and carbon emissions before and after community action. Incremental packages of energy saving measures and low carbon technologies are assessed for their impact on CO\textsubscript{2} emissions to reveal further potential for large-scale refurbishment in the local area. Eligibility for the Green Deal is tested to show that on average 72 per cent of homes over all communities are suitable for finance. Through community events, results are visualised and fed back to the householders using colour-coded spatial maps along with thermal imaging. Findings from this study are relevant for policy-making and practitioners engaged in area-based carbon reductions.

INTRODUCTION

The UK is committed to reducing greenhouse gas (GHG) emissions by 80% from 1990 levels. In response to this commitment, the national Green Deal programme has been proposed to offer energy efficiency improvements to homeowners and businesses at little or no upfront cost with payment recouped through customers’ energy bills (DECC, 2012a). The Energy Company Obligation (ECO), proposed to work alongside the Green Deal, will similarly support those experiencing fuel poverty and in hard to treat homes. In addition to the Green Deal, recent Government funding in the UK has enabled 22 low carbon community organisations to work with the private and academic sector to understand and reduce the amount of energy that is used in homes and buildings. One such programme, the Low Carbon Communities Challenge (LCCC), focussed on stimulating energy improvements of homes through capital funding of physical interventions to homes and buildings, behaviour change campaigns and low carbon living activities. The theoretical savings from the 8,206 installed measures and technologies for the entire programme is 3,062 tonnes of CO\textsubscript{2}/yr (DECC, 2012b).

The Department of Energy and Climate Change (DECC) (2012b) provide an overall qualitative review of the LCCC impact. Gupta et al. (2014) applied a measurement, monitoring and evaluation (MME) approach to 88 households across six LCCC communities. Their findings show mixed results in

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terms of energy use across the households depending on a number of factors including the physical and technical interventions, and occupant behaviours and lifestyle. The detailed evaluations also uncovered unintended consequences associated with energy behaviours, such as increased use of washing machines and other such appliances due to 'free electricity' from low/zero carbon technologies.

Geographical information systems (GIS) provide a platform for presenting findings in an aggregated form which can be visually effective in communicating results to householders and community groups. A number of GIS based studies focus on energy use estimations using a top-down approach. These include using remotely sensed anthropogenic heat to serve as a proxy to derive the spatial pattern of energy use (Zhou et al., 2012) or combining location, demographic and end-use data to enable energy consumption to be calculated and mapped (Pereira and Assis, 2013). In contrast to the above, the present study combines a bottom-up building characteristic data collection approach to estimate energy use and carbon emissions of approximately 1,300 dwellings over five communities, Community A, B, C, and D (anonymised as per communities’ request) in England and Wales, combined with a top-down approach to analysis and geographical visualisation. This is demonstrated through the application of urban energy modelling using DECoRuM© (Domestic Energy, Carbon counting and carbon Reduction Model), to rapidly model, map, and measure energy use and carbon emissions on a house-by-house level. The following method calculates the carbon reduction impact of the LCCC and the impact of further carbon reduction measures for the five communities. The work presented in this paper is part of the Evaluating Low Carbon Communities (EVALOC) project which seeks to assess, explain and communicate the changes in energy use due to community activities within selected case study projects under DECC’s LCCC initiative.

METHODOLOGY

The following steps are taken to map and assess the energy consumption, carbon emissions, and retrofit potential for the selected communities:

1. Data collection (e.g. home details, local climate data, etc.), modelling and mapping in GIS
2. Assessment of results, e.g., carbon emissions, before the LCCC and after the LCCC
3. Selected carbon reduction / Green Deal packages are applied to the neighbourhood and the results are calculated and mapped

The communities

Table 1 lists the five communities and some further details.

<table>
<thead>
<tr>
<th>Community</th>
<th>Number of Households</th>
<th>Dominant Built Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>311</td>
<td>1930-49 semi-detached</td>
</tr>
<tr>
<td>B</td>
<td>242</td>
<td>1966-76 terraced</td>
</tr>
<tr>
<td>C</td>
<td>274</td>
<td>Pre-1900s terraced</td>
</tr>
<tr>
<td>D</td>
<td>184</td>
<td>Pre-1900s terraced</td>
</tr>
<tr>
<td>E</td>
<td>275</td>
<td>Pre-1930s terraced</td>
</tr>
</tbody>
</table>

DECoRuM model

DECoRuM is a GIS-based toolkit for carbon emissions reduction planning with the capability to estimate energy-related CO₂ emissions and effectiveness of mitigation strategies in existing UK dwellings, aggregating the results to a street, district and city level. The aggregated method of calculation and map-based presentation allows the results to be scaled-up for larger application and assessment. The background calculations of DECoRuM are performed by BREDEM-12 (Building Research Establishment’s Domestic Energy Model) and SAP 2009 (Standard Assessment Procedure) both of which are dynamically linked to create the model. BREDEM is a methodology for calculation of the energy use of dwellings based on characteristics; it is suitable for stock modelling. It shares some features with the SAP methodology, but allows users to adjust inputs which are fixed in SAP (BRE, 2014). SAP, based on BREDEM is the Government approved method for the assessment of the energy and environmental performance of dwellings. Though not as robust as dynamic thermal simulation, the strength of DECoRuM is in the ability to rapidly process results for many dwellings and present them on
an urban scale. The tool is useful for communicating energy related concepts and identifying potential areas for concern and further investigation, including simulation, house assessment and monitoring.

Some limitations include:

- Time required for data collection and entry; home questionnaires are helpful in reducing this initial effort.
- Behaviour related assessment is limited: occupancy times, heating schedules, window opening schedules, etc. are not available. Different scenarios must be calculated separately and cannot vary within a given timeframe; calculations are static.
- The model does not calculate where specifically a homeowner should insulate walls and whether internal or external insulation is ideal (insulation is simply either solid wall or cavity).

Data collection and modelling. In the DECoRuM model, CO\textsubscript{2} emissions are the result of heat loss calculations from fabric and ventilation, estimated energy use from heating, domestic hot water and electricity use as calculated using BREDEM-12. To inform the model, actual house characteristics are gathered from historic and current maps, on-site assessment, home occupant questionnaires, Energy Performance Certificates (EPCs), and literature describing home characteristics based on age and typology. As examples: occupancy, unless known, is calculated from floor area using the BREDEM-12 method; street-facing windows and frames are directly observed but all other unseen windows are assumed to be the same; wall construction and U-values (unless known, e.g. reported in EPCs) are based on the age of the home where construction methods are well documented (e.g. BREDEM reference tables). Verification is performed by calibrating the aggregated results to DECC’s lower level super output area (LSOA) energy consumption data for England and Wales. LSOAs are zones made up of an average of 1500 residents or 400 households with relative social homogeneity, for which there are gas and electricity consumption figures reported (DECC, 2014a). Use of LSOA data for a similar purpose can be found in Booth and Choudhary (2011) and Williams et al. (2013).

Mapping the results. The results for each household are displayed on a map using GIS software; in this instance MapInfo. GIS allows any variable to be mapped for visual communication, e.g. kWh/year, CO\textsubscript{2} emissions/m\textsuperscript{2}/year, homes in need of cavity wall insulation, PV suitability, etc. Previously, DECoRuM maps have been used by the Grassroots Leads Energy Efficiency community group in Highfield, Bicester to provide residents with energy consumption information and to suggest energy efficiency improvement measures (Gupta and Cherian, 2013), and to present climate change impact and adaptation effectiveness to communities in the SNACC project (Suburban Neighbourhood Adaptation for a Changing Climate (Williams, et al., 2013).

Carbon reduction measures. Previous research by the authors and others has demonstrated the development of mitigation measures and packages, which were found to be effective for similar home typologies (Gupta and Gregg, 2012; DECC, 2014b). This and other research (simulation and building performance evaluation) have demonstrated the effectiveness of specific mitigation measures for CO\textsubscript{2} reduction in homes. These include reduced U-values on building elements, high efficiency boilers, insulating hot water cylinder and pipes, and increased level of heating control. When creating packages, focus on a fabric based package is done to emphasise the importance of implementing fabric first (low tech demand reduction) measures and also due to its (generally) lower capital cost.

MAPPING LOW CARBON COMMUNITIES

Each of the 22 communities, as a part of the LCCC, received grants ranging from £250k - £970k to pay for physical interventions to homes and buildings (90%) and behaviour change activities (10%) (DECC, 2012b). Table 2 lists the physical measures purchased for households against those which were mapped in DECoRuM. Community scale measures or non-domestic measures, e.g. wind turbines (Communities A and B), PV on community centres and schools (Communities D and E), are not listed because the contribution of these measures are not calculated in the household (demand side) energy consumption modelling of DECoRuM; in addition, LSOA, used to validate DECoRuM, only provides consumption values. With regard to household measures, not all households in the communities received
physical measures and not all households that did receive measures are mapped. The impact of behaviour change will likely indirectly come out of the aggregated figure as the aggregated figure is validated by the LSOA, however, the MME method used in Gupta and Barnfield (2013) is essential for measuring the impact of behaviour change activities in detail.

Table 2. Physical Measures Applied to Households in Each Community (DECC, 2012b)

<table>
<thead>
<tr>
<th>Community</th>
<th>LCCC measures (total households)</th>
<th>Measures (mapped)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>(0)</td>
<td>PV (9), solar thermal (2) ASHP (2)</td>
</tr>
<tr>
<td>B</td>
<td>Cavity wall insulation (125), loft insulation (223), PV (12), solar thermal (6), ASHP (4)</td>
<td>Cavity wall insulation (10), loft insulation (28), PV (3), solar thermal (1)</td>
</tr>
<tr>
<td>C</td>
<td>PV (11), solar thermal (4), wood pellet boiler, ASHP (3)</td>
<td>PV (6), solar thermal (4), ASHP (3)</td>
</tr>
<tr>
<td>D</td>
<td>PV (53)</td>
<td>PV (53)</td>
</tr>
<tr>
<td>E</td>
<td>PV (8)</td>
<td>PV (4), solar thermal (1)</td>
</tr>
</tbody>
</table>

Communities before LCCC action

Occupant questionnaires (requesting specifically when measures were installed), EPCs (pre-2010) and LCCC household details were especially helpful in modelling the communities before LCCC implementation. Though occupant questionnaires or EPCs were not available for each household, these tools served to inform the model with regard to what measures did not exist in many households before the LCCC. Since measures were purchased and installed anywhere from 2010 – 2012, the maps of Pre-LCCC implementation are referred to as Pre-2010.

Communities after LCCC action

In the same way, the same tools were used to assess what measures are in place after LCCC implementation. These maps are referred to as 2012. Figure 1 shows the Pre-2010 and 2012 results from Community E. After the interventions made by LCCC programme in Community E, there is a mean annual CO$_2$ reduction of 536 kgCO$_2$/yr/household or 12 per cent in the mapped area in 2012. These results can be attributed to LCCC involvement, but not entirely, as not all mapped households were involved in the LCCC.

![Figure 1](pre-2010-2012-maps-community-e.png)

Figure 1 Pre-2010 and 2012 maps of annual CO$_2$ emissions for Community E.

Table 3 lists the communities and the results from the mapping for these two periods. Aside from other differing factors, Communities A and C are not served by the National Gas Network and are notably higher in annual emissions due to a majority of occupants utilising oil or electricity for heat.
Table 3. Mean annual domestic CO₂ emissions (kgCO₂/year) before and after LCCC programme

<table>
<thead>
<tr>
<th>Community</th>
<th>Pre-2010</th>
<th>2012</th>
<th>2012 City Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5,969</td>
<td>5,286</td>
<td>Not available</td>
</tr>
<tr>
<td>B</td>
<td>4,564</td>
<td>4,046</td>
<td>4,179</td>
</tr>
<tr>
<td>C</td>
<td>9,298</td>
<td>7,111</td>
<td>Not available</td>
</tr>
<tr>
<td>D</td>
<td>5,753</td>
<td>4,889</td>
<td>4,895</td>
</tr>
<tr>
<td>E</td>
<td>4,574</td>
<td>4,038</td>
<td>4,454</td>
</tr>
</tbody>
</table>

Carbon reduction measures and packages

The model filters suitable dwellings for each retrofit measure based on the current (2012) condition of the dwelling, e.g. solid walled homes receive solid wall insulation and insulated cavity walls received no further insulation. Potential energy and carbon reductions are then calculated by the model for each household and then aggregated to realise community level impact. To meet the Government’s carbon reduction target, most UK homes will require a package of measures (DECC, 2014b); therefore, the following typical retrofit measures were tested individually and also incrementally packaged. Table 4 lists the packages that were developed for testing in DECoRuM; all measures are acceptable for Green Deal financing. Lowering the thermostat, a behaviour change measure, was also tested and presented to residents but not packaged. Primarily, the reason for this is that the packages were designed to reflect measures with capital costs so that the packages could be tested for Green Deal finance suitability.

Table 4. Carbon Reduction Packages

<table>
<thead>
<tr>
<th>Package</th>
<th>Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric improvement package</td>
<td>Wall insulation (cavity or solid), loft insulation, floor insulation,</td>
</tr>
<tr>
<td></td>
<td>double glazing, draught proofing</td>
</tr>
<tr>
<td>Fabric and heating upgrade</td>
<td>Fabric package + high efficiency condensing boiler, hot water</td>
</tr>
<tr>
<td>package</td>
<td>cylinder insulation, pipework insulation, heating controls</td>
</tr>
<tr>
<td>Fabric, heating and electricity</td>
<td>Fabric and heating upgrade package + energy efficient lighting</td>
</tr>
<tr>
<td>package</td>
<td>and appliances, photovoltaic system, solar hot water system</td>
</tr>
</tbody>
</table>

An important key driver for refurbishment is capital cost. DECoRuM uses low and high estimates of the capital costs for each measure to indicate a likely range for the cost-effective carbon saving potential (the mean is taken from these two figures). The overall capital cost for community wide implementation of a certain package is calculated, based on the potential of each house within the community. Figure 2 shows the mean capital costs and energy cost reduction potential for each package in the two most common house types in Community E. The Pre-1930s terraced housing represents 28 per cent of the dwellings in the mapped area and 1930-1949 semi-detached represents 18 per cent.

![Fabric improvement Package](image1.png) ![Fabric and heating upgrade package](image2.png) ![Fabric, heating EE and solar energy systems package](image3.png)

**Figure 2** Package capital costs and reductions for Pre-1930s and 1930-49 house types in Community E.

The mean total cost for each home only considers those dwellings which could benefit from a
measure in each package, though not all measures in the package need to be applied to qualify for the package in the model. Immediately as is seen in figure 2, Pre-1930s cost more to retrofit. This is attributed to the solid wall exterior of the house type, which will require solid wall insulation. The cost for solid wall insulation for each home is taken from the mean of external and internal insulation. Due to the nature of the data collection, especially where no questionnaires are filled, the model does not have the capability to assess whether internal or external insulation is a better choice for a particular dwelling. Annual cost reductions are a combination of a reduction in fuel costs and feed-in tariff (FiT) and Renewable Heat Incentive (RHI) (paid from April 2014) payments for PV and solar hot water respectively. Differing FiT payments, as per EPC grade, per house, are calculated into the total figure.

**Carbon reduction packages and the Green Deal**

Each carbon reduction package is then tested for Green Deal finance (theoretical) approval, specifically; will each package meet the *Golden Rule* on a house-by-house level? The Golden Rule is the central mechanism for determining which measures (to complete a package) are able to be financed through the Green Deal. The rule: “Estimated savings must be greater than or equal to repayments.” This, however, is not a guarantee but a calculated intent (DECC, 2012).

DECoRuM has the capability to calculate whether a package will meet the Golden Rule after measures are modelled and energy use reduction and energy cost reductions are calculated. The model calculates whether the annual fuel cost savings are less than the annual payback over the life of the measure(s). *Figure 3* shows the Golden Rule compliance for each package for Community E. As an example, a large portion of the terraced housing in the southeast section of the Fabric Package map do not meet the Golden Rule primarily because the cost of solid wall insulation and new double glazing together is too high in relation to the potential savings. In order to qualify some dwellings will need to consider alternative combinations of measures. It is also important to point out that the cost for solid wall insulation, as mentioned above, is an average fixed cost between external and internal wall insulation; opting for internal wall insulation would likely reduce the capital cost for the overall package. Alternatively, the strip of homes in the northeast section of the Fabric Package map (next to the legend) meets the Golden Rule. Most of these dwellings are 1930-49 semi-detached (*figure 2*) requiring cavity wall insulation, a less expensive measure.

*Figure 3*  Golden Rule compliance for each package in Community E.

DECoRuM modelling demonstrated a fairly wide range of Golden Rule compliance between the communities (*table 5* – the packages are numbered in the order they are listed in *table 4*). Communities A, B and C, as communities, appear to be easier targets for the Green Deal. Communities A and C specifically have more reduction potential, partially due to the size of the dwellings and the majority using oil for heating. Community B, on the other hand, for the Fabric Package, requires little up-front cost whereas all homes are cavity wall (many already insulated – table 2) and many already have double glazing (the second most costly fabric measure following solid wall insulation). Community D,
comprised of 94 per cent solid wall terraced housing, presents a challenge in meeting the Golden Rule for the Fabric Package. Package 3 clearly becomes more difficult due to the cost of PV and solar hot water systems (poor solar orientation is also calculated into the reduction in solar systems impact). FiT and RHI payments do not count toward reduction of savings to calculate the Golden Rule. A dwelling could use the Green Deal finance to install PV and collect the FiT but if a home is performing poorly according to their EPC, e.g. worse than D, their FiT is reduced, thereby encouraging fabric improvement first (or in conjunction). The Green Deal also only covers a portion of the capital cost for PV depending on how much electricity is actually (calculated) used in the dwelling.

<table>
<thead>
<tr>
<th>Community</th>
<th>Package 1</th>
<th>Package 2</th>
<th>Package 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>91%</td>
<td>91%</td>
<td>65%</td>
</tr>
<tr>
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<td>100%</td>
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<td>29%</td>
<td>27%</td>
<td>11%</td>
</tr>
<tr>
<td>E</td>
<td>54%</td>
<td>48%</td>
<td>31%</td>
</tr>
</tbody>
</table>

DISCUSSION

Outputs from DECoRuM, maps of estimated energy use and CO$_2$ reduction potential of individual households, were used to provide energy feedback to householders (on a community level) through workshops, wherein the local community also had access to expert information and advice on taking action to reduce energy use through individual discussions and group presentations. The maps, along with thermal imaging surveys of the houses, used to make energy use visible by highlighting areas of heat loss and potential areas for fabric improvements, gave householders a clear view of the impacts different refurbishment measures and packages have had or may have on the energy performance of their house. The workshops also helped to gather more data from householders (using questionnaires), to further refine the model.

The communities are using the findings from the carbon mapping, along with thermal imaging and the MME studies to inform the householders in the community on effectiveness of work already done and also highlight areas for improvement. The carbon mapping is specifically useful for the community groups to pinpoint areas of high energy use, problem households and promising areas for Green Deal finance. The application of packages, the calculated impact, and costs, as shown through carbon mapping, establishes DECoRuM as a useful tool for Green Deal assessors, local authorities and the low carbon community groups intending to implement large scale retrofits.

It is important to remember that there are many combinations of carbon reduction measures and they do not need to follow the packages as defined in this study. It is likely that many more homes will be able to find a package that will fit their home and meet the Golden Rule. There are also a large number of ‘border line’ cases (houses which almost meet the Golden Rule). This highlights the importance of adopting a holistic approach that includes both technical improvements and behaviour change measures; one which the Green Deal is attempting to provide through energy saving advice (DECC, 2012a). This approach, where effective, would ensure that most of the predicted energy savings are achieved in practice and the Golden Rule will be met.

CONCLUSION

Carbon mapping has emerged as a valuable approach for strategic planning, evaluation and implementation of community and neighbourhood scale domestic refurbishments by rapidly measuring, modelling, and mapping and managing energy use and CO$_2$ emission reductions on a house-by-house level. Bespoke site specific mapping of current energy consumption and visualisation of the potential for energy savings can enable the uptake of carbon reduction measures. The model can help local authorities, community groups and householders to prepare for future change and policy mechanisms such as the national Green Deal programme and the ECO. The specific area-based approach can serve as a tool to scale-up the uptake of low energy domestic refurbishments, by providing Green Deal providers,
local authorities, community organisations and householders with information on the technical and economic feasibility of deploying a suite of best practice refurbishment measures. Findings from this study are also relevant for practitioners and researchers engaged in tracking and assessing impact of large-scale area-based domestic refurbishments and the future effectiveness of the Green Deal after implementation.

Similar work includes the development of DECoRuM-Adapt, a next step for DECoRuM created to assess future climate impact, overheating risk and adaptation measure effectiveness. The assessment of the climate change risk allows for the further evaluation of mitigation measures to optimise the home’s refurbishment to be thermally comfortable now and in the future (Gupta and Gregg, 2013). To further benefit research in this area, future work in urban modelling would include analysis of modelling outputs with socio-economic data to track the effect of refurbishments on fuel poverty.

ACKNOWLEDGMENTS

The authors would like to acknowledge the many residents of the neighbourhoods who returned energy questionnaires and allowed us to install temperature and energy data loggers in their homes. Thank you also to Laura Barnfield, Tara Hipwood, Chiara Fratter, and Bob Irving for assisting in the carbon mapping work, workshop presentations and performing the thermal imaging surveys. The research presented here is part of the EVALOC low carbon communities project [grant number RES-628-25-0012] which is funded under the EPSRC/ESRC Energy and Communities stream of Research Council UK’s (RCUK) energy programme.

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The Impact of Vegetation on Urban Microclimate to Counterbalance Built Density in a Subtropical Changing Climate

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ABSTRACT
The purpose of this paper is to assess the cooling effects of vegetation in urban microclimate, especially during daytime, to counterbalance built density in a subtropical climate. The findings contribute to a land-based mitigation strategy, trying to answer partially what a changing climate will mean for cities facing two mechanisms that can be superimposed: the global warming and the local heat-island effect, in the city of Sao Paulo, Brazil. According to the Brazilian Panel on Climate Change (PBMC), Brazil's climate will be warmer in the coming decades, with a temperature increase in all regions between 1°C and 6°C by 2100, compared to the records at the end of the 20th century. The paper presents a brief review of planning with high-density and urban greening, having in mind that even low-density land use can contribute to urban heating, depending on the infrastructure development. In high-density cities, the most important vegetation effect is to prevent overheating in urban canyons, decreasing solar radiation absorption by shading and increasing evaporative cooling by the leaves and soil coverage. This way vegetation prevents overheating of buildings and other urban surfaces, contributing to better comfort conditions. Parametric studies exploring different scenarios of high-density urban blocks and greening have been carried out to investigate two different distribution of dense trees (LAI=4.6) to ameliorate urban microclimate using ENVI-met model 4 (preview), previously calibrated with field measurements of local climate and vegetation data. Aiming to benefit urban activities, air and mean radiant temperatures at the pedestrian level are compared. None of these will reverse long-term warming trends but, as we move from mitigation to adaptation, combinations of these strategies can slow the pace of warming over time and moderate urban warming, indicating a way forward for urban design in tropical and subtropical cities.

INTRODUCTION
Brazil has recently constituted the Brazilian Panel on Climate Change (PBMC). According to PBMC (2013), Brazil's climate will be warmer in the coming decades, with gradual and variable average temperature increase in all regions between 1°C and 6°C by 2100, compared to that recorded at the end of the 20th century. Brazil has its own voluntary commitments for emission reductions, as part of the National Politics for Climate Change, but adaptation measures for urban areas are still missing, and some local research groups are investigating this, aiming to support the review of the National Plan for Climate Change. Land use as a climate change mitigation measure, especially in urban areas, is underexplored; in this scenario we need more resilient cities and, for that, adaptation is crucial.
Concerning the coupling of global and local warming effects, cities do not cause heat waves, but they amplify them. Because of the greater prevalence of mineral-based building materials, cities absorb and retain substantially more heat than rural areas characterized by more vegetative cover. Because of that the main reason for city warming is not the global warming itself, but the replacement of the vegetation for hard surfaces and the anthropogenic emissions (Stone, 2012).

One of the climate related land use implications is the urban heat island (UHI), which is more diverse than originally suspected (Arnfield, 2003). On the surface UHI is easy to understand and to visualize the results of urbanization. However, UHI is a multi-faceted phenomenon whose proper definition and physical basis is more complex. Proper understanding of the definition and types, dynamics and underlying physical processes of the UHI, however, is key to formulating mitigation measures (Roth, 2013). Besides differences based on the medium sensed (air, surface, even subsurface) and the sensing system employed (Arnfield, 2003), there is growing evidence supporting the existence of phase and amplitude departures in the UHI in tropical cities, in comparison with mid-latitude cities (Marques Filho et al., 2009; Chow; Roth, 2006). The UHI in tropical and subtropical cities is less intense than in higher latitude cities, and it is more pronounced during daytime and strongly regulated by the moisture content of the atmosphere and soil in adjacent rural regions (Roth, 2007). As well as in other tropical and subtropical climates, according to Ferreira et al. (2012), the UHI in the city of São Paulo has a daytime character, with a maximum intensity during afternoon (14:00-16:00 LT) and a minimum during morning time (07:00-08:00 LT) in almost all months monitored in 2004. The maximum UHI intensity varied from 2.6°C in July (16:00 LT) to 5.5°C in September (15:00 LT).

The role of density

Cities differ from their rural surroundings in a multitude of ways, many of them directly related to the surface energy balance and the formation of UHIs. Urban form is affected first and foremost by building dimensions and spacing, but also by the characteristics of artificial surfaces and by the amount of green space. The presence of a dense matrix of buildings promotes the creation of UHIs through a variety of processes, for example, the trapping of solar energy due to multiple reflection and absorption within canyons, the restricted sky view factor of deep and/or narrow canyons and reduction of wind speeds near the ground (Erell et al., 2011).

For several reasons, one of the current needs of urban settlements is a higher urban density, a topic that still causes some debate, but from mobility and urban climate points of view, low-density areas can be even worse. According to Stone (2012), areas of low population density may still effect a significant influence on UHI formation if they have extensive infrastructure development.

The urban climatic issues of heat, humidity, lack of daylight, solar access and urban ventilation is of topical concern to urban planners and governments, so, the need for appropriate designs for high-density cities is clear. Urbanization and higher-density living is an irreversible path of human development. Higher-density living will continue to be developed and will soon be the norm. The environmental dimensions of high-density cities, especially in tropical and subtropical climatic zones, are decisive. Buildings are fighting each other for natural light and ventilation. The provision of light and air can be difficult; a paradigm shift is required, new tools are needed, but high-density living is a definite possibility, although it is not an easy path (Ng, 2010). To increase ventilation, height variation should be considered as much as possible; the stepped height concept can help to optimize the wind-capturing potential as well as the view of sky component for daylight availability. Designed properly, the strategy of tall and thin has a better chance to capture daylight. Given the same building bulk, on average, daylight availability to windows can improve by some 40 per cent (Ng; Wong, 2005).

The role of Green

Planted areas in a city tend to reduce daytime maximum temperatures, reducing radiant exchange at the ground surface. The effect of vegetation on the atmospheric heat island is manifested not only
indirectly, in the form of a reduction of sensible heat flux from the cooler surface, but also directly in the form of evaporative cooling. Most field studies support the argument that a lack of vegetation in the city would tend to result in elevated daytime air temperature, and concomitantly, that a large-scale planting campaign may lead to a reduction of the daytime urban heat island (Erell et al., 2011).

According to Chen and Wong (2010), in a built environment the UHI effect can be described as a conflict between buildings and the urban climate, and considering the positive impact of plants upon this conflict, a conceptual model was proposed by the authors to understand the interactions among the three critical components in the built environment: climate, buildings and plants. In order to uncover the benefits of greenery in a built environment, the microclimatic effects should be quantified. There are some possibilities to reduce ambient air temperature with plants: urban parks, road trees, landscape within the vicinity of buildings and rooftop gardens. In addition, the surface temperatures could be reduced with rooftop gardens or vertical landscaping.

In high-density cities, land is scarce and there is little provision of space for the incorporation of urban greenery such as urban parks and landscaping. The integration of greenery in buildings also faces many constrains (Chen; Wong, 2010), in spite of some cases of success, like in Singapore, with the adoption of Green Plot Ratio by the local legislation (Ong, 2002).

Due to the combined effect of shade and evapotranspiration, air temperature reductions from 1°C to 3°C can be achieved under the canopy in green areas, depending on the climate and soil conditions. According to Wong and Chen (2009), from the planning point of view, it can be found that smaller green areas strategically arranged or grouped around buildings should be largely promoted. This does not mean that large urban parks are not effective in terms of improving urban climate, but they are considered as a luxury to a heavily built-up environment, especially if rapid urbanization is experienced.

Within this context and assuming that the densification is inevitable and desirable from the point of view of urban sustainability, especially in megacities like Sao Paulo, the purpose of this research is to assess the cooling effects of vegetation in urban microclimate, especially during daytime, to counteract an increasing built density in a subtropical climate. The findings contribute to a land-based mitigation strategy, trying to answer partially what a changing climate will mean for cities and aiming for a more favourable energy balance in cities facing two climate-change mechanisms that can be superimposed: the global warming and the local daytime heat-island effect.

**URBAN AND CLIMATIC CONTEXT OF SAO PAULO METROPOLITAN AREA**

São Paulo is located at 23°32’S, 46°37’W, 60 Km far from the sea with altitudes varying from 720m to 850m. The city experiences hot, humid summers with air temperatures varying between 22°C and 30°C and mild winters between 10°C and 22°C. The metropolitan region, the 3rd biggest in the world, with more than 22 million inhabitants, had in 2014 the warmest January since 1943, when climatic data started to be regularly recorded in the city by the National Meteorological Institute (INMET) and the warmest February, with a maximum air temperature up to 36,4°C. In other cities, like Porto Alegre, January 2014 was also the warmest in almost 100 years.

According to PBMC (2013), in the future, besides mean temperature warming, an increase of extreme events is expected. January and February 2014 presented air temperatures above those observed ever and humidity values below those historically found. Whilst the historical climatological averages for these months are respectively 21,6°C and 21,8°C, the mean values recorded in 2014 were 24,2°C and 24,3°C and the highest measured air temperature since the meteorological station of the Institute of Astronomy, Geophysics and Atmospheric Sciences of the University of São Paulo (IAG-USP) recordings started were registered in both months: 31,6°C. While both months are generally characterized by high rainfall amount and average relative humidity of 83%, the 2014 first two months had lower precipitation rates and recorded lower values of relative humidity (75% and 73% respectively). Thus, for this study, the incorporation of these months in the simulation is intended to be representative of an extreme event, characterized by higher temperatures and lower humidity rates.

Megacities like São Paulo are vulnerable to global warming and local warming effects, driven by
urbanization. The PMBC is especially worried about the fast pace of vegetation suppression in Sao Paulo, both in the interspace of buildings as well as in the outskirts of the city.

Comparing the city of Sao Paulo’s population density with other cities in the world (Fig. 1), it is observed that even with an average density of 73.87 hab/ha (IBGE, 2011), similar to other cities, the density of Sao Paulo’s densest district is one of the lowest. As the availability of transport and infrastructure should be directly linked to urban density, it would be possible to think that there is an equitable distribution of these infrastructures throughout the city, which is definitely not true. São Paulo has some areas with reasonable availability of transport that does not necessarily have high values of population density and vice versa.

São Paulo is characterised by a heterogeneous urban structure, resulting from the rapid growth of the city during the 20th century. One of the effects of this growth is the social conflict of high-rise office towers and residential apartment buildings close to poor informal settlements (favelas). In addition, the distribution of vegetated areas is non-uniform in the city. While there are 35 parks, corresponding to 15 million m² (21% of the total area of Sao Paulo municipality), the downtown districts of Bras and Bela Vista are almost devoid of vegetation. Thus, few areas in the city are characterised by large amount of vegetation and street trees, usually in the wealthiest districts, mainly in the west zone of the city.

The central area of São Paulo is formed by various districts, one of those is Bela Vista, chosen for this study due to its population density (the highest in the city) and for the built density (the 3rd higher), compared to a total of 97 districts in the municipality. Bela Vista shows the predominance of vertical residential buildings with heights varying between 10 and 20 floors. It also has one of the lowest green area per inhabitant, almost zero, according to Sao Paulo Environmental Agency.
FIELD MICROCLIMATE MEASUREMENTS

Microclimate monitoring was carried out from March 4th to April 29th of 2013 in the area of Bela Vista to register air temperature, relative humidity, solar radiation, surface temperature, wind direction and speed, aiming to previously calibrate the ENVI-met\textsuperscript{1} preview for the parametric simulations. Figure 3 shows a nine-block area and in the middle of the central and densest block a Campbell Scientific meteorological station was set up in the ground floor of a residential building. In order to avoid obstructions for residents’ circulation and for the equipment’s protection, residents allowed the equipment installation in the building backyard, over grass and under a wooden pergola.

![Figure 3: Location of the meteorological station in the middle of the densest block in Bela Vista. Source: GUSSON, 2014.](image)

CALIBRATION AND PARAMETRIC SIMULATIONS IN ENVI-MET MODEL

The ENVI-met three-dimensional microclimate model was chosen for this study due to its advanced approach on plant-atmosphere interactions in cities. ENVI-met is one of the few models that seeks to describe the major climate processes acting in the urban environment, including turbulence, the turbulent transport of sensible and latent heat, the radiation fluxes within the urban structures and the influence of vegetation. The model simulates aerodynamics, thermodynamics and the radiation balance in complex urban structures with resolutions between 0.5m and 10m according to the position of the sun, urban geometry, vegetation, soil and various construction materials by solving thermodynamic and plant physiological equations (Bruse; Fleer, 1998; Bruse, 2012; Huttner, 2012).

For ENVI-met 4.0 preview, the forcing feature was incorporated and it is now possible to define the diurnal variation of the atmospheric boundary conditions and the incoming radiation. It also allows developing much more detailed weather scenarios for testing purposes and producing results that are in good accordance with field measurements (Jansson, 2006). The input data are shown in Table 1. The solar radiation calculated as a function of the latitude was adjusted to measured radiation by applying 1,4 octas for low clouds cover and 0,4 octas for high clouds cover. The adjustment factor for solar radiation was 1 (100%), in accordance with the measured data. The only additional climate data (not derived from local measurements) was that for specific humidity at 2500m, obtained from the local airport Campo de Marte (ca. 3,3km north of the site).\textsuperscript{2} The soil temperature for the upper layer was measured using Campbell 107 temperature probe and humidity was estimated with Simple Biosphere Model – SIB2.\textsuperscript{3} The model showed close similarity between adjusted and measured data, providing reliable results for the parametric simulations.

\textsuperscript{1} ENVI-met website: http://www.envi-met.com/
\textsuperscript{2} Available at the University of Wyoming: http://weather.uwyo.edu/upperair/sounding.html
\textsuperscript{3} Data provided by IAG Laboratory of Climate and Biosphere, University of Sao Paulo.
For simulations, the starting day was defined based on pluviometric data collected from two fixed meteorological stations: one in the northern and other in the southern part of the city for the same period of Bela Vista measurements, which indicated the longest period with stable climatic conditions between April 26th-28th 2013, during autumn. Besides that, February 2014 was chosen to represent an extreme warm summer, characterized by higher temperatures and lower humidity rates registered in decades.

Initially a Base Case model was created and the input area domain was formed by 9 blocks of 100m x 100m (10,000m²) each, which can be considered an average block size in Sao Paulo. In each block there are nine towers with 45m height (15 floors, average in Bela Vista), 20m x 20m each, representing a plot ratio of 5.4. The tower has a square shape plan that was planned to consider 4 housing units with 58m² each, per floor, and a population density of 3.5 people/apartment (total of 1764 inhab/ha).

Two other scenarios were created with different trees’ distribution: a central park with trees covering an entire central block; and the same green area distributed in rows of street trees located in the perimeter of every block. In both cases, dense trees (LAI=4.6 m²/m²) and a soil type of sandy-clay-loam were chosen. Wind speed was kept constant in 0.5m/s in all scenarios, aiming to minimize convection effects and emphasizes the effect of green and built density.

![Figure 4](image)

**Figure 4**: The three scenarios for ENVI-met model: (a) base case, only towers, (b) towers + central park, (c) towers + street trees

**RESULTS AND DISCUSSION**

All results are shown for 15h LST, coinciding with the maximum air temperature in all cases (Figure 5). As expected, in autumn, April 2013, with a mild climate in Sao Paulo, air temperature differences are minor, up to 0.5°C, comparing the scenarios a and b, in and around the park, and about 0.3°C comparing a and c. Concerning the distribution, the oasis effect is more pronounced in scenario b than c. In February 2014, the extreme warm summer this year, air temperature differences become more significant and the effect of vegetation is slightly more pronounced showing air temperature differences up to 0.6°C comparing scenarios a and b and about 0.2°C comparing b and c. On the other hand, the effects of the mutual shading of buildings and the vegetation contrasts with the warmer surfaces of the streets and the unshaded spaces between buildings, showing mean radiant temperature differences up to 13°C in and around the park comparing the scenarios a and b, even during the mild April 2013. In scenario c, mean radiant temperature is lower along the shaded streets, although inside the blocks, scenario b performs better, configuring an oasis effect. Going to the extreme summer, February 2014, the picture is about the same, but with higher temperatures in the three scenarios, being mean radiant temperature in the scenario b about 10°C lower than the scenario a. In scenario c the benefits of tree shading are evident on the mean radiant temperature along the streets, under the canopies, but the effect is local, and do not spread over the blocks (Table 2).
Figure 5: Air temperature results in both seasons, showing the highest air temperature at 15h LST.

Table 2: Simulation Results for 15h LST

<table>
<thead>
<tr>
<th></th>
<th>Base Case – only towers (a)</th>
<th>Central Park Scenario (b)</th>
<th>Street Trees Scenario (c)</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air temperature</strong></td>
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<tr>
<td><strong>Mean radiant temp.</strong></td>
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</table>

Based on simulation results, an empirical adaptive thermal comfort index developed for local conditions was applied. The Temperature of Equivalent Perception - TEP (Monteiro; Alucci, 2011) was calculated based on the mean values for the central block in the three scenarios for the two periods, at 15h LST. Wind speed was 0.5 m/s, the same adopted for the simulation input.
CONCLUSIONS

In both seasons, air temperature differences are small among the three scenarios, around 0.5°C. In spite of that, the lower mean radiant temperature in the central park (scenario b) provoke an increase in comfort levels according to TEP, around 5°C, characterizing what Erell et al. (2011) called park cool island, an oasis effect even in-between towers in a high-density context. On the scenario c, the effect is noticeable when compared to the base case (scenario a), but localized under the trees’ canopies and the oasis effect do not spread over the blocks. None of these scenarios will reverse long-term warming trends but combinations of these strategies can moderate the extreme of climate events in cities.

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The Life and Death of the Minnesota Experimental City: An Experiment in Utopian City Planning

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ABSTRACT

Sustainability at the macro scale of settlement has been an aspect of the design of cities since our earliest history as urban dwellers (e.g. human settlements in ancient China, Egypt, Greece, India, Asia Minor, the Mediterranean world and South and Central America). The Minnesota Experimental City (referred to by its planners) was imagined initially by a university professor and a newspaper publisher, and was planned by working groups – meeting at the University of Minnesota - which included designers, planners, business people, government leaders, sociologists, educators, theologians, scientists, and economists, and ultimately supported in its early phases by both the federal government and the State of Minnesota. The goal was to plan, develop, and build – through a public/private partnership - a healthy environment for a new city of 250,000 people for northern Minnesota and to be constructed from the early 1970’s to the mid-1980’s. It would incorporate such technological innovations as car-free zones with people-movers, waterless toilets, a power-generating system fueled by both the burning of garbage in pollution-free furnaces and the use of windmills, and partially domed, climate-controlled, city centers. The goals of the city included life-long learning; social integration among and between religious, racial, age-specific and ethnic sub-groups; and values which looked not just forward but back to a feeling of community which emphasized “good food, good friends, and a good relationship to the earth.” In essence, the Minnesota Experimental City embodied the principles of social, economic and environmental sustainability. This paper discusses the salient features of the Minnesota Experimental City and its relevance in the present context.

INTRODUCTION

As urban planners around the world confront the critical issues of the twenty-first century—expanding population, rapid urbanization, limited global resources, increased demand for food production, and protection of a fragile environment - this paper narrates the story of the Minnesota Experimental City (called MXC) – a livable sustainable new city of 250,000 people, planned for northern Minnesota in the central United States, intended to be constructed from the early 1970’s to the mid-80’s.

It’s often the case that great big ideas like the MXC have larger-than-life characters behind them, and the MXC is no different. The story of the birth of the MXC idea is the story of Athelstan Spilhaus and Otto Silha – two men who met at the right time – (1965) - and in the right city and state – (Minneapolis, Minnesota – known at the time for its progressive politics) - each with a history of thinking creatively as they operated in their very different spheres – (Spilhaus, the world of science and education in his position of the Dean of the Institute of Technology at the University of Minnesota; Silha, the worlds of newspaper publishing and civic philanthropy). The MXC was planned by working
groups which included designers, planners, business people, government leaders, sociologists, theologians, scientists, and economists. Their goal was – through a public/private partnership - to plan, develop, and build a healthy, sustainable environment for the city’s inhabitants, which would incorporate such technological innovations as car-free zones with people-movers, waterless toilets, a power-generating system fueled by both the burning of garbage in pollution-free furnaces and the use of windmills, and a domed, climate-controlled downtown area. This paper will examine these forward-thinking technological innovations, but also the human-centered goals of the planners (among them futurist Buckminster Fuller, urbanologist Harvey Perloff, theologian Martin Marty, and economist Walter Heller) which included life-long learning; social integration among and between religious, racial, age-specific and ethnic sub-groups; and values which looked not just forward but back to a feeling of community which emphasized “good food, good friends, and a good relationship to the earth” (TIME, 1973).

It is helpful to understand the planning context in which these initial conversations between Spilhaus and Silha took place. The Housing Act of 1949 had launched the “Urban Renewal” movement in American cities. Neighborhoods considered “blighted” in dozens of cities across the country were cleared at federal and local expense, and land given to developers for redevelopment. The Housing Act of 1954 had made this redevelopment even more attractive to developers by providing FHA-backed loans to build housing. In 1956, the Federal-Aid Highways Act encouraged city and federal planners to construct new highways to provide easy access into central cities, often destroying healthy existing inner-city neighborhoods in the process. These actions, on top of the housing acts of the 30’s and 40’s which served to increase segregation and the growth of government-funded slum housing, along with the growth of suburban areas as city residents fled increasingly more troubled city centers, resulted in the sense that the American urban experience had failed. In 1961, Jane Jacobs in The Life and Death of Great American Cities began to raise strong questions about what had gone wrong at the hands of planners and government officials. There was a deep-felt concern that society was headed in the wrong direction in its ability to address the social issues of the day, e.g. segregation (of age groups as well as races), the environment, and education, but that all the tools were at hand to move in another direction.

By the mid-1960’s, cities and their citizens were in turmoil. Polluted rivers were catching fire, spurring the birth of the environmental movement in the United States. This and the race riots that began in 1965 and continued through the remainder of the decade resulted in the sort of thoughtful – and urgent – discussions that Spilhaus, Silha, and leaders in business and industry in Minneapolis were engaged in, concerning the future of cities.

Add to this milieu the sense – based on evidence such as the successes of the Apollo moon shot program – that technological advances could solve our problems and move us forward. There was the sense also – a sort of World’s Fair type of thinking – that the inventiveness and marketing know-how of the American people had not been applied to the problems of cities and housing (Spilhaus had directed the U.S. exhibit at the Seattle’s World’s Fair, and MXC planners were inspired by Moshe Safdie’s Habitat housing complex built for Expo 67 in Montreal).

The Minnesota Experimental City was never built. The paper will look to answer the question, “why not?” and seek, also, to describe aspects of the city’s design, features, and goals which might find new life in planning the healthy communities and sustainable habitats of today and tomorrow.

NEW TOWNS TO SUSTAINABLE TOWNS

The idea that we could re-imagine or re-invent cities to make them more “uplifting” places of habitation was, of course, not a new idea. Hippodamus (c. 498- c. 408 BC), a native of Miletus, Greece invented the art of planning cities and designed port towns of Piraeus and orthogonally planned towns such as Olynthus, Priene and Miletus. Conscious planning of cities reemerged in Europe during the Renaissance with prime objective to glorify a ruler or a state and partly aimed at improving circulation and providing military defense. From the 16th century to the end of the 18th, many cities were laid out and built with monumental splendor rather than health and comfort provisions for citizens.
The modern origins of urban planning lie in a social movement for urban reform that arose in the latter part of the 19th century as a reaction against the disorder of the industrial city. Many visionaries of the period sought an ideal city, yet practical considerations of adequate sanitation, movement of goods and people, and provision of amenities also drove the desire for planning.

New town developments have served many needs throughout history, including the following, according to William Alonso (1973): a) the acculturation and absorption of migrants, as in Israel and Australia; b) the development of frontier regions, ranging from tiny ones (Holland, Israel) to vast ones (the nineteenth-century American West, Siberia, and the center of South America); c) the exploration of concentrated resources (Ciudad Guayana, Venezuela and Kitimat, BC) and of extensive ones (central place systems such as the nineteenth-century American Midwest); and d) symbolism and politics (Washington, Brasilia).

In the United States, the Cities Beautiful movement, which architect Daniel Burnham was credited with founding, and which the Chicago Exposition of 1893 was credited with starting, influenced civic-minded citizens and planners in large cities and small towns across the nation. While the City Beautiful movement was based on the principles of Beaux Arts design, it really wasn’t about beauty for its own sake, but for creating social order by instilling civic and moral virtue among the population. In 1906, Burnham and his assistant Edward Bennett designed a plan for the Chicago, which was the first comprehensive plan for the controlled growth of an American city. Happening at roughly the same time, and meshing with the same kind of intentions that the Cities Beautiful movement had was Ebenezer Howard’s Garden City movement in England, founded in 1898, which was a reaction to the dirty, unhealthy conditions of cities caused by the Industrial Revolution. In the United States, bedroom suburbs such as Radburn, NJ, designed by Clarence Stein and the “greenbelt” towns continued the European Garden City tradition during pre-World War II years. In 1962, the modern new town community of Reston, VA, (Columbia, MD, came later) provided social and economic components of community as well as the simple physical aspects of the earlier new towns.

### Table 1: Sustainable Urban Form Matrix

<table>
<thead>
<tr>
<th>Design Concepts</th>
<th>Neo-traditional Development</th>
<th>Compact City</th>
<th>Urban Containment</th>
<th>Eco-city</th>
<th>MXC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>Moderate - 2</td>
<td>High – 3</td>
<td>Moderate – 2</td>
<td>Moderate – 2</td>
<td>Moderate - 2</td>
</tr>
<tr>
<td>Diversity</td>
<td>High – 3</td>
<td>High – 3</td>
<td>Moderate – 2</td>
<td>Moderate – 2</td>
<td>High – 3</td>
</tr>
<tr>
<td>Mixed land use</td>
<td>High – 3</td>
<td>High – 3</td>
<td>Moderate – 2</td>
<td>Moderate – 2</td>
<td>High – 3</td>
</tr>
<tr>
<td>Compactness</td>
<td>Moderate – 2</td>
<td>High – 3</td>
<td>Low – 1</td>
<td>Low – 1</td>
<td></td>
</tr>
<tr>
<td>Sustainable transportation</td>
<td>Moderate – 2</td>
<td>High – 3</td>
<td>Moderate – 2</td>
<td>High – 3</td>
<td></td>
</tr>
<tr>
<td>Passive solar energy</td>
<td>Low – 1</td>
<td>Low – 1</td>
<td>Low – 1</td>
<td>High – 3</td>
<td></td>
</tr>
<tr>
<td>Greening – ecological</td>
<td>Moderate – 2</td>
<td>Low – 1</td>
<td>Low – 1</td>
<td>High – 3</td>
<td></td>
</tr>
<tr>
<td>design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Score</td>
<td>15 points</td>
<td>17 points</td>
<td>12 points</td>
<td>16 points</td>
<td>18 points</td>
</tr>
</tbody>
</table>

In the late 20th century the term sustainable development came to represent an ideal outcome in the sum of all planning goals. As advocated by the United Nations-sponsored World Commission on Environment and Development in Our Common Future (1987), sustainability refers to “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” The latter point has been labelled as ‘inter-generational equity’. More recently, sustainable development is defined as “a dynamic process which enables all people to realize their potential and to improve their quality of life in ways which simultaneously protect and enhance the earth’s life support systems,” (Forum for the Future). While there is widespread consensus on this general goal, most major planning decisions involve trade-offs between subsidiary objectives and thus frequently involve conflict. Jabareen (2006) delineates seven design principles for attaining the goals of sustainable urban development and identifies four urban forms that contribute to the overall sustainability of cities. Neo-traditional Development, Urban Containment, Compact City and Eco-City are the four identified sustainable urban forms comprised of combination of seven design principles or concepts viz a)
Compactness b) Sustainable Transport c) Density d) Mixed Land Uses e) Diversity f) Passive Solar Design g) Greening. The MXC epitomizes the design principles of sustainable urban development and is a forerunner to the present day eco-cities, as can be seen in how the MXC scores using Jabareen’s (2006) Sustainable Urban Form Matrix, measuring the seven principles above, and comparing the MXC to the four sustainable urban forms listed, shown in Table 1.

**OVERLEAP**

By 1967, multi-disciplinary studies for planning the MXC were initiated at the University of Minnesota, under the direction of Walter Vivrett, professor of architecture and planning. Otto Silha was by now the chair of a Steering Committee of 23 well-known individuals from a broad variety of disciplines from around the nation. The word “overleap” was used to describe what the MXC hoped to achieve: “at once an advance into future possibilities and a break with past constraints” (Vivrett, 1972). It was determined that the best avenue for arriving at a concept for the MXC would be to initiate “workshops” which would focus on specific areas:

- Education - Health, medical and environmental health
- City-building technology
- Communications
- Waste management and pollution control
- Transportation (people, goods, and mail)
- Energy and energy transmission

The workshop participants, numbering almost 200 people, met for roughly three days each from late 1967 through early 1968. They were asked to identify, in their areas, what was “state of the art, and then identify major gaps and issues and areas for potential innovation – critical for a city that was truly “experimental.”

One might discount all of this as the efforts of a few scholars and interested business people. By February of 1967, however, grants from three government agencies (Housing and Urban Development, Health Education and Welfare, and Commerce) and 10 corporations – totaling around $300,000, or more than $2 million in today’s dollars – were in place to fund the planning stage of the project. Vice-president Hubert Humphrey had signed on as a supporter, as had the Minnesota State Legislature.

**WHY A NEW CITY?**

The concepts of dispersal and building-from-scratch were critical for the success of a new experimental city. Attempts to repair the existing fabric would present problems having to do with “local traditions, outmoded building codes, restrictive legislation, and the consequences of unplanned, unhealthy growth” (Spilhaus, 1968) in addition to the vested interests of local business and industry. A “dispersed” city, located no less than 100 miles from an existing urban city, would be able to offer the advantages of an existing city but – with a defined perimeter and surrounding reserved land – it could not suffer from unplanned growth. The “built-from-scratch” aspect would allow new innovations in services, waste-management, pollution control, and communication to be fully implemented from the start, and serve as a test environment for other new cities.

A third aspect of the initial concept was that of “urgent need” – the urgent need to build and populate an “instant” city fully and quickly so that it might soon function as the kind of sociological and technological laboratory – the core of the “experimental city” concept - that might lead the way for other new cities and the repair of the environment into the 21st century. It was estimated that the MXC would cost about $4 billion to build ($26 billion in today’s dollars).

While it is interesting to focus on the technological and planning aspects of MXC, it is important to state that from an early point in the conceptual phase it was the community and human values that were stated as the main goals of the project – the phrase “people-oriented, technologically advanced” was often used as a descriptor. Spilhaus said, “We must not force people into what is technologically easy, but find a technological solution which is practical and closely meets their desires” (Spilhaus, 1968).
The overarching goals were these (Vivrett, 1972): “a. man can creatively mold his environment; b. he can, in a positive and constructive manner, unite the resources of private technology with public authority; and c. he can re-orient social, economic, and physical forces to serve people.” The futurist Buckminster Fuller, a member of the Steering Committee, discussed the role of a city of the future as being “metaphysical,” offering a forum for the exchange of ideas, learning and culture, and not just goods.

**MXC PLANNING PRINCIPLES**

It’s important to make clear that site selection was an important aspect of the planning process. A number of sites around the state of Minnesota were considered, with two sites selected as finalists, both of them about two hours north of Minneapolis-St. Paul in rural areas, and both of them in areas of the state that were struggling economically. The basic planning principle that the MXC was based upon was Walter Christaller’s “Central Place Theory” which was developed during the 1930’s in Germany. The theory consisted of two basic concepts – that of “threshold,” which is the minimum population that is required to bring about the provision of certain good or services, and that of “range,” which is the average maximum distance people will travel to purchase goods and services.

![Figure 1](image1.png)

**Figure 1** MXC development plan, combining hierarchical systems of centers with existing development patterns (Minnesota Experimental City Authority – Preliminary Report on Urban Design, 1973).

![Figure 2](image2.png)

**Figure 2** MXC development plans, combining hierarchical systems of centers with existing development patterns (Minnesota Experimental City Authority – Preliminary Report on Urban Design, 1973).
If you begin to “densify” areas of range you get a hierarchical system of centers, with the hexagonal shape ultimately giving better coverage than a circle. This system of hexagonal transportation networks was then laid out over existing potential communities in the initial master planning, as shown in Figure 1.

At the level of the community and neighborhood, as in Figure 2, built forms and development were laid out to maximize solar gain (images to the left), and to accommodate shared community space and close connections to nature (images to the right).

INFRASTRUCTURE AND SUPERSTRUCTURE

Technologically, the most important component of the MXC was its coordinated infrastructure and superstructure – its tunnel system, as in Figure 3. All transportation of goods and services, waste and utilities, and construction materials (small-sized components which could be assembled and disassembled for different configurations) would be handled through the tunnel system. Part of the tunnel system would be a network of environmentally-friendly features – solid waste would all be handled through an underground system that would allow for recycling of materials, the air would be scrubbed of pollutants, waste water would be reused for cooling and then recreation, and the infrastructure would do double-duty as superstructure.

People would arrive by vehicle at the edge of the city and would then be transported through a “pod” system of people movers, with semi-private “cabs” and the ability to select one’s own destination in a way that was more flexible than bus transportation. These cabs would provide door-to-door transportation to both low-density and high-density living and community structures, as in Figure 4.

It was very important to the planners that the communication network for the MXC also be part of the tunnel system. The substructure would be wired with coaxial cable to reach anywhere a telephone might conventionally be located. A wiring system to service radio frequency transmission would also be included. It was anticipated that the communication system would be used for high-speed connections to computers and video monitors which would be used for – among many anticipated uses - shopping, banking, crime prevention and the de-centralizing of learning and health care. It was planned that medical care would be made available through a series of care centers which would provide appropriate care at various levels, with computer connections back to central medical facilities for advice from specialists. Health care would be delivered as a “utility,” with easy access for all.
LIFE-LONG LEARNING

Perhaps one of the most interesting innovations in the MXC plan was in the area of education. The city would be constructed with no schools, but would instead serve as a life-long learning laboratory. Everyone would be a learner and everyone would be a teacher. Learning would occur everywhere within the city. There would be no schools, but instead learning centers located throughout the city in homes, businesses, and public spaces. These would include Beginning Life Centers for very young children, Stimulus Centers for films, tapes, sounds and spells, Gaming Centers for the study of complex realities in a simple fashion, Project Centers where people could work on experimental outcomes, Learner Banks where tools, equipment, print and non-print materials could be checked out, and Family Life Centers where families could learn together (Minnesota Experimental City Authority – Education, 1973).

FINANCING AND MANAGEMENT

With a price tag of over $4 billion, who was to pay for and manage the MXC? The planners of the project suggested several options for management. One would be to have a quasi-public, quasi-private corporation run the city as a public utility (similar to the model that was ultimately used at the London Docklands); another would be to view the city as similar to a large Disney-style hotel complex with lodging, shops, restaurants, and transportation systems, with public services possibly contracted out to private entities. In terms of who would pay the initial price tag for infrastructure, it was hoped that business and industry – recognizing the opportunity that the city would provide as a laboratory for new technologies of pollution control, transportation, communication, and construction - would be willing to invest in the up-front construction costs. Additional costs could be financed through bundled FHA mortgages.

FATE OF THE MXC

The initial project reports were completed in 1969, and the workshops continued their studies. The project lost a strong supporter at a high level when Hubert Humphrey lost his bid for the U.S. presidency in 1968, and MXC gradually lost local support as the state legislature tipped from more liberal to more conservative from 1968-1972. The University of Minnesota at the time was also substantially funded by the legislature, and as the legislative makeup changed, state government was less supportive of the University’s MXC efforts. By late 1972, the final site had been chosen for the project. In January 1973, the final planning reports were issued. But by February of that year it was also the case that local politics had begun to signal the end of the project.

Locally, the MXC project - grounded in environmental innovation - became a victim of the concerns of those who treasured the local environment of Aitkin County, MN, the wooded, rural county which was ultimately selected as the site for the MXC. While many residents of the county welcomed the opportunities which the project would bring, many feared the loss of property and peacefulness. In 1973, TIME Magazine published an article called “The Newest New Town” which spoke positively about the prospects for the MXC. It was the last hoorah, followed by these grim headlines in the Minneapolis Star Tribune from February through May of 1973:

- 2/8 “MXC Prospects Not Bright in Legislature”
- 2/14 “Opponents Term MXC a Trojan Horse”
- 2/16 “MXC Threatens Good Hunting Area”
- 2/20 “Petitions Opposing MXC Presented to Governor”
- 3/13 “PCA Recommends Dropping MXC Plan”
- 3/28 “Senate Sub-Committee Votes to Cut Off MXC”
- 4/4 “House Sub-Committee Votes Against MXC”
- 4/5 “MXC Bill Dead”
- 5/24 “MXC May Be Moved to VA, FL, or OH”

Things were also happening in the larger arena that helped to seal the fate of the MXC. The country was involved in an unpopular war which escalated after the election of Richard Nixon in 1968.
and didn’t end until 1975. From 1973 through 1975 the country experienced what some considered the most severe recession since WWII, with oil shortages, rising interest rates, and the reduction of real income and consumer spending. The notion that we could tackle any challenge if the ideas and the effort were there seemed like an idea whose time had passed. Locally, the MXC project - grounded in environmental innovation, with a tightly interwoven connection between human development and the landscape - became a victim of the concerns of those who treasured the local environment of Aitkin County, MN, the wooded, rural county which was ultimately selected as the site for the MXC. While many residents of the county welcomed the opportunities which the project would bring, many feared the loss of property and peacefulness.

CONCLUSION

Those who contributed to the imagineering of the MXC should recognize aspects of the design in today’s world. Forty years later, we live in a world where the environmental issues of air quality, resource management, and land use are more important than they have been at any time since the 70’s. On-line learning and high-speed internet communication were just speculation in the 60’s – now they’re part of how we learn and communicate. The type of large scale building and planning of “instant” cities that characterized the MXC is now happening in the construction of new cities in India and China. The “cradle to cradle” use of resources we saw proposed for the MXC is now an aim for consumers, industries and nations.

Criticism has sometimes been leveled at the MXC for its top-down planning approach, conceived by an “elite” group of academics and businessmen. Its approaches, however, to sustainable land use, net-zero energy use and waste management, communication, education and health delivery systems still constitute the “overlap” of innovation that was the MXC’s goal. Forty years later, perhaps, the open-source, bottom-up nature of current innovation might take some inspiration, especially in developing societies, from the ideas of an experimental city that was many years ahead of its time. While the “compact city” model is viewed by many as the best answer to a more sustainable urban future, perhaps the idea of smaller - yet dense – communities which are closely tied to nature is more compatible with the patterns that have satisfied our needs for communal habitation throughout history.

REFERENCES

Towards the Improvement of Cooling Energy and seismic performance in Timber buildings using GIS and interactive Database

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ABSTRACT

By increasing the thermal mass of building components, in order to improve its thermal inertia, the whole structure mass rises and therefore reduces structural performance of timber buildings in seismic areas. Italian codes establish restrictive limits for the design of building, particularly in southern regions because of a high seismic activity. In order to answer the question »How can the summer behaviour of timber buildings be improved without worsening their seismic performance?«, Fraunhofer Italia, Free University of Bozen-Bolzano and Trees and Timber Institute CNR – IVALSA developed the research project TIMBEEST, which combines quantities belonging to different engineering branches (energy and seismic) towards their best compromise.

Within this research project, Fraunhofer Italia developed an interactive tool composed of database and Geographical Information System (GIS). This tool stores and analyses data, as well as it allows researchers and professionals to manage and evaluate the interaction of energy and structural characteristics of timber building components during the design phase across the Italian territory.

Starting from energy and structural indicators (the Cooling Degrees Days for the Typical Reference Year and the Seismic Response Spectra, respectively) by a spatial discretization based on Italian Provinces, maps with a classification of the Italian territory were created. Such classification combines energy and seismic indicators to evaluate their impact on buildings. In order to improve the passive cooling performance of timber buildings on the basis of the classification of environmental and structural indicators, enhanced building components has been developed and presented by the interactive tool.

INTRODUCTION

Italy is a country characterized by an intense and widely spread seismic activity (Civil Protection Department) and high temperature during summer (Pinna, 1978), especially in southern areas. For this reason the TIMBEEST research project studies strategies to improve of the summer behaviour of timber buildings across the Italian territory by using thermal mass without worsening their seismic performance.

Since 1970s, researchers have studied the effect of thermal mass on energy demand and cooling/heating peak loads (Robertson (1986), Brown (1990)). Furthermore, the improvement of thermal
building performance through the optimization of thermal mass layer distribution and its effective thickness has been investigated (Baverstock (1986), Shaviv (1988), Kosny and Kossecka (1998), Al-Sanea and Zedan (2001), Paradisi et al. (2012)).

Timber technology presents an excellent structural performance in seismic areas, but its low thermal inertia (compared to clay block or concrete buildings) reduces the energy performance in cooling period. Because of the timber technology is rare or even absent in Central and Southern Italy, it is an opportunity to investigate the technological feasibility and effectiveness of timber buildings, considering both thermal performance and structural implications. Beside its specific goals, TIMBEEST research requires a huge effort in data management because of data intersection and influences from energy and structural branches. This project requires to be managed in flexible way considering continuous alignments and integrations and even changes. In order to satisfy those requirements, an interactive tool based on databases seems to be the best solution.

TOOL STRUCTURE

At building and city level many studies discuss methodologies to store, manage data and catalogue solution in order to create cognitive tools, which enables professionals to visualize data, provide a global interpretation of information and support the decision-making process. Within the available methodologies, the Geographic Information System (GIS), based on the geo-referencing process, and database can be used as a digital tool to provide a support for analysing and managing large sets of data.

The collection and spatial data analysis provided by GIS is necessary for advanced urban planning which focuses on specific topics, i.e. energy management (Fistola, 2010). Coors and Xu (2012) proposed an integrated approach for sustainable assessments of urban area in Stuttgart through GIS cartographies. Fabbri et al. (2012) used GIS tool to collect data regarding energy class of existing buildings in order to suggest a zone energy indicator for evaluating the city. Ascione et al. (2013) developed an analytical methodology combined with GIS, which aims at characterizing energy performances of new and existing buildings in order to allow sustainable planning for energy-oriented cities. The application of database in research projects has been used by Thomson and Hardin (2000), who showed that the efficiently handled data can substantially improve the quality of planning and decision-making process. Sala, Romano and Boganini (2011) developed an interactive database collecting different technologies and construction systems of Mediterranean areas in order to support professionals in the development of a complete project analysis in several specific areas. Moreover, Attia and Wanas (2012) created for the city of Cairo an online source database of building materials, building envelopes and their characteristics, which influence energy consumption in order to support professionals during the design phase. All these researches list up specific characteristics which belong to different branches avoiding their correlations and do not focus on timber buildings.

Based on previous experience of the interactive tool “Timber Construction” (iPad application, Benedetti, 2010), and considering the complex structure of TIMBEEST research project, interactive tools are identified as the best solution for dissemination purposes. Considering the potential of interactive databases and GIS to intersect data at different levels and manage information effectively, the TIMBEEST interactive tool has been developed in order to manage contents throughout all research phases. It is composed of the following parts: a) databases created by FileMaker Pro 11 software, which are structured in three main databases and several sub-databases linked together; b) external GIS database made using Quantum GIS software, which correlates analysed data to Italian territory in order to support databases in point a). A common User Interface (UI) provides a rapid access to the content of three research phases of TIMBEEST project and allows navigating through them easily. These research phases are: 1) state of the art (geographical context, environmental restraints and analysis of standard building components); 2) analysis and simulation of improved building components; 3) results and comparison of previous phases. Each of these phases is structured by the three sections throughout they are developed, which are: a) definition of the specific objectives; b) methodology; and c) collection and
comments of the results (Figure 1 a). The UI switches between research contents and sets of documents by navigational tabs, as shown in Figure 1 b.

Figure 1 (a) Scheme of TIMBEEST interactive tool; (b) User interface for each phase of research project: 1) objectives; 2) methodology; 3) results.

OBJECTIVE AND METHODOLOGY SECTIONS

Objective section

The first phase of research project is focused on geographical context and environmental restraints, which affect thermal and seismic performance of buildings. Furthermore, the standard building components are identified and analysed. The objectives of the first phase are: a) to manage GIS data of physical features regarding environmental restraints such as equivalent Cooling Degree Days (CDD), horizontal elastic response spectrum (S_E), snow load (q_s), wind load (p) and of a synthetic indicator, by mapping Italian territory at Province level; b) to manage energy and structural data of standard building components by the design of a database considering the most common timber technologies – Platform Frame (PF) and Cross-Laminated-Timber Panels (CLT) (Benedetti et al., 2010).

The second phase of research project develops and analyses improved building components by thermal mass in order to find the best compromise between summer thermal performance and seismic performance. Its objectives are: a) to outline suitable solutions for lightweight building components throughout a literature review regarding summer building performance and possible improvements in cooling period; b) to manage throughout a database energy and structural data of improved building components (with additional thermal mass); c) to summarize 256 dynamic simulations made by TRNSYS software for 110 capital cities of the Italian Provinces referred to standard and improved building components, respectively; d) to collect and visualize data of monitoring campaign of two Test Cells in order to validate thermal simulations; e) to manage 60 modal dynamic linear analysis of improved building components in order to evaluate the limit of thermal mass application in timber structures, which accomplish summer thermal improvement without worsening seismic performance of structure. The objectives c), d) and e) are going to be developed during the next months. Thence, the available results are not validated yet.

Furthermore, the third phase of research project will start at the end of year 2014 and it will include results of energy and seismic simulation and comparison of standard and improved building components in order to provide a quick overview of adopted solution.

Methodology section

The methodology section explains the procedures used to develop the scientific contents. This section corresponds to each objectives and it is integrated into the UI tabs (Figure 1b, point 2). Since the specific procedures exceed the goal of this paper, their details are not presented. It is possible to find
such information in the research paper of Ratajczak et al. (2014). submitted to 30th International PLEA Conference 2014 and under the acceptance procedure.

RESULT SECTION

The result section visualizes specific phase outcomes in order to facilitate data analysis, to provide inputs for further steps of the TIMBEEST and to enhance the future implementation of the tool. These outcomes are gathered in result databases, and are correlated to different sub-databases and GIS database, as illustrated in the flow chart (Figure 2).

In detail each phase of TIMBEEST is made of different result databases, as many as the specific objectives. The following result databases are developed or will be implemented:

1. Result database of the first phase:
   a) database of standard building components;
   b) databases of geographical context and environmental restraints (GC&ER) at Province level.

2. Result database of the second phase:
   a) database of improved building components;
   b) database on thermodynamic simulation – has not been yet analysed;
   c) database of seismic dynamic simulation – has not been yet analysed.

3. Database of the third phase: has not been yet developed.

![Figure 2](image)

Flow chart of relations between sub-databases and result databases belonging to the first and second phase of TIMBEEST research project.

Because of the huge amount of data assigned to territory, the use of a GIS database is required to manage, analyse and visualize data as well as a GIS software (Figure 3) is needed to generate maps. The GIS database refers to the previously mentioned result databases.
Considering the huge amount of data and interactions between them, the result databases is linked to different sub-databases in order to visualize data in one UI. The following sub-databases within the TIMBEEST interactive tool are presented: a) sub-database of capital cities; b) sub-database of standard building components; c) sub-database of improved building components.

The sub-database of capital cities (a) consists of geographical context data as: altitude, name of Regions, Provinces and capital cities, population number and population density of Provinces and capital cities; and environmental restraints data as: climatic zone based on Heating Degree Days, class and value of equivalent Cooling Degree Days, value of Test Reference Year, class and value of synthetic indicator, $S_r$, $q_{st}$, and $p$. These environmental restraints data affect the thermal and structural performance of buildings.

Other two sub-databases (b and c) of standard and improved building components include information regarding type of building components and their structural and thermal features.

**Result databases of the first phase**

**Figure 4** shows UI layout of the result database (1a), which is divided into topic area: 1) geographical context and environmental restraints; 2) building information; 3) structural features; 4) thermal features; 5) index of building components related to 110 capital cities of Italian Provinces. These information are visualized when a building component is selected from the index list.

**Figure 4** The UI layout of result database (1c) in the first phase of research project.
The first area regarding geographical context and environmental restraints (Figure 4, point 1) contains information and parameters related to capital cities such as: a) altitude; b) climatic zones and value based on HDD according to D.P.R. n. 412 26/08/93; c) class and value of snow load according to NTC 2008; d) class and value of wind load according to NTC 2008; e) class and value of horizontal elastic response spectrum according to NTC 2008; f) class and value of CDD referred to three different horizontal surfaces with absorption coefficient value ($\alpha$, [-]) respectively 0.3, 0.6 and 0.9; g) class of synthesis referred to three absorption coefficient value. Furthermore, clicking on each parameter users can analyse GIS maps of Italian territory regarding qsk, p, Se, CDD and synthesis, which are structured as shown in Figure 5a: 1) GIS map with a legend and 2) description of parameter. The GIS maps are important to characterized territory and identify critical areas, for instance: the synthesis map allows highlighting the critical areas, affected by risks of overheating and earthquake.

Beside the seismic parameter Se a link to the GC&ER result database (1b) is integrated. Figure 5b shows this result database, which provides information on: 1) map of seismic danger of the Italian territory evaluated under specific hypothesis by Istituto Nazionale di Geotecnica e Vulcanologia; 2) GIS map of related Region and the provincial classification of $S_e$; 3) graph of elastic spectrum, referred to capital city of the selected Province; 4) graph of elastic spectrum with all capital cites presented in selected Region; and 5) environmental restraints – $S_e$ class and value. The graph of elastic spectrum is elaborated using Simqke software developed by the University of Brescia.

Figure 5 (a) The UI layout of the database of geographical context and environmental restraints at Province level; (b) Synthesis map.

The second area is dedicated to building information (Figure 4, point 2) and shows details regarding building components such as type of component (wall/roof/floor) in different technology PF and CLT, total thickness of component and list of layer composition. To enhance a comprehension of building component composition, the 2D drawings are visualized by clicking on text.

The third area is focused on structural features (Figure 4, point 3) and it is arranged in three parts: a) type of timber technology of selected building component; b) information regarding structural dimension of elements; and c) structural connections. Selecting building component from index list, the following information are provide for structural dimensioning: a) height and thickness of horizontal components; b) height, width, thickness and distance between elements (in case of PF) of vertical components; c) height, width and thickness for wall sheathing; d) length, diameter, and centreline spacing of screw connection; e) dimension of beams and studs. Furthermore, details regarding angle brackets, hold-down and screw connection for the following connection are specified: wall-to-concrete slab, wall-to-floor, wall-to-wall and beam-to-wall.

The fourth area presents thermal features (Figure 4, point 4) and provides the following data: a) thermal conductivity ($\lambda$, [W m$^{-1}$ K$^{-1}$]) and thickness of different insulation materials (natural, mineral and synthetic) used in building component; b) thermal parameters, which are verified according to D.P.R. 59/2009 and UNI EN ISO 6946:2008 such as thermal transmittance (U-factor, [W m$^{-2}$ K$^{-1}$]), thermal resistance (R, [m$^2$ K W$^{-1}$]) and mass of component (Ms, [kg m$^{-2}$]); c) thermal parameters used
for dynamic evaluation and verified according to UNI EN ISO 13786:2008 such as decrement factor (f, [-]), periodic thermal transmittance (Y_{ie}, [W m^{-2} K^{-1}]), time shift (\phi, [h]), periodic thermal transmittance on interior side (Y_{ii}, [W m^{-2} K^{-1}]), periodic thermal transmittance on external side (Y_{ee}, [W m^{-2} K^{-1}]), interior areal heat capacity (k_1, [kJ m^{-2} K^{-1}]) and external areal heat capacity (k_2, [kJ m^{-2} K^{-1}]).

The fifth part (Figure 4, point 5) shows the index list of all building components, which are organized by capital city of the Province and type of timber technology.

In the result database (1a) of the first phase, next to U-factor, Y_{ie} and \phi parameters, GIS maps are linked in order to visualize the minimum value required by Italian codes (Figure 6 a, point 1). Figure 6 a, point 2, 3 shows two maps, which express the percent deviation for each parameter between minimum value and value of best and worst solution of standard building components in order to provide a range of variation. Furthermore, evaluations of all thermal parameters according to UNI EN ISO 6946:2008 and UNI EN ISO 13786:2008 using spreadsheet are integrated in database.

**Figure 6** (a) GIS maps referred to thermal parameters; (b) GIS map referred to improved building components, and multi-criteria analyses.

**Result database of the second phase**

In the second part of research project improved solutions for building walls are studied. Four solutions for CLT technology and three solutions for PF technology are identified. The structure of the result database is the same of the (1a) one but the inserted data refer to other components. In order to find out the best solution for 110 capital cities among proposed ones, multi-criteria analysis is developed (Figure 6 b, point 1, 2). In order to combine the percentage improvement/worsening between best solution of standard and improved walls, the GIS database is used. This information are included into the result database (2a) of the second phase just next to thickness of insulation material, total thickness of the building component, the U-factor, the Y_{ie} and the \phi (Figure 6 b, point 3). The layout of Figure 6 b allows having an overview of the best solution identified and its improvement or worsening through Italian territory. Furthermore, evaluations of all thermal parameters according to UNI EN ISO 6946:2008 and UNI EN ISO 13786:2008 using spreadsheet and comparison evaluation between improved solutions are integrated in this result database.

**CONCLUSION**

This research paper describes the structure of the TIMBEEST interactive tool. Since the research project is an on-going research till the first half of the year 2015, the database presented is not completed and is going to be continuously updated. Thereafter, the results of dynamic and structural dynamic simulation will be integrated in the database of the second phase in order to evaluate the percentage of gained improvement in structural and energy fields. Further steps will determine the environmental footprint of the improved building components to highlight the most sustainable solution towards the improvement of timber building performance during the cooling season. Beyond this information, the database of third phase should be developed entirely and it will aim at summing-up the research results.
The TIMBEEST interactive tool proved to be a useful support during different steps of research project. Data collected in various databases, but managed by one UI will allow researchers and professionals to manage and evaluate correctly and quickly the timber building components both from energy and from seismic point of view across the Italian territory during the design phase. Furthermore, considering future development of the project, researchers, who will be in charge of the development of new contents, can easily consult output data and even implement them. Such tool is used also as a controlling tool in order to check possible errors because of huge amount of data and intersection between them. Since the GIS software allows visualising data in the form of maps, errors are immediately highlighted in order to improve research methodology.

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Session 5C : User behavior, thermal comfort & energy performance

PLEA2014: Day 2, Wednesday, December 17
11:30 - 13:10, Grace - Knowledge Consortium of Gujarat
The use of Environmental Controls:
Bioclimatic Performance of “Baixa Pombalina’s” Heritage Buildings.

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ABSTRACT
“Baixa Pombalina”, the downtown and historic district of Lisbon is one of the most important pieces of urbanism and architecture ever built in Portugal, and is at present time a UNESCO World Heritage nominate. Those Buildings were built after the great earthquake of 1755, for housing, commercial, and services’ functions. And they constitute a rational and functional approach for health and comfort to their residents, translating the state-of-the-art of architecture at the time, through the use of lighting and natural ventilation. In this research study, buildings of “Baixa” are observed as a scenario where residents of 21st Century live in spatial and built structures of 18th Century. This paper is about environmental controls within current thermal and lighting performance of “Baixa Pombalina” Buildings. It analyses the efficacy of those buildings from the passive design point of view, as well as the habits of its occupants in controlling and regulating the devices available in “Baixa” buildings at present time. A questionnaire model was developed to study bioclimatic performance of offices, and residences selected in “Baixa”. And field work involved a survey where workers of fifteen offices and residents of five houses have participated. Results demonstrate that in buildings of Baixa, controls are used less interactively during winter season and more interactively during summer season. Results indicate that in the Lisbon climate, it is mainly during the summer season that controls have a major role in thermal performance of these inheritage buildings.
Keywords: Baixa Pombalina, Building Performance, Environmental Controls, Comfort and Occupancy.

INTRODUCTION
This Paper analyzes actions of control by current users in buildings of “Baixa Pombalina”, which are inheritage buildings built in the 18th Century. The goal of this study is to understand these buildings and their diversified systems in the context of current habits of usage and control.

According to a current notion of Sustainability, construction shall ensure bioclimatic and global human comfort, in buildings and urban spaces; sustainable use of construction materials and environmental technologies in buildings (Pinheiro, 2006). The project and work of “Baixa Pombalina” fall in many contemporary concepts of sustainability. When Baixa buildings were designed, in the 18th Century, lighting, heating and cooling were essentially provided by natural light and ventilation. These buildings were built in a time before the use of mechanical lighting and HVAC systems, and are therefore Architecture with capability to ensure energy efficiency. However, during 20th Century, occupancy density was increased and HVAC mechanical devices were introduced, changing the thermal performance of buildings, and the actions and habits of its users before the available controls.

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This Paper provides an overview of actions taken by users: with regard to the use of controls introduced in these buildings, e.g. mechanical devices, as well as actions to use the original controls of these buildings, e.g. windows to regulate natural ventilation.

URBAN AND ARCHITECTURAL CONTEXT

“Baixa Pombalina” is located in the historic city center of Lisbon, near “Tejo” River and between hills. After the Great Earthquake of 1755, the area was rebuilt according to the 1758 Plan. And their buildings are called “Pombalino Yield Buildings” (“Prédio de Rendimento Pombalino”), and have similar architectural features and are grouped into blocks.

The block improves buildings’ salubrity with wider spaces between buildings in order to ventilate and to illuminate. The use of the shape of rectangular block allowed two fronts separated by an inner yard, and also, a large perimeter of the façade. Blocks are of two types: The first are arranged longitudinally with the axis in the direction North-South, and occupy most part of the urban grid. The latter blocks are arranged transversely, with the axis in the direction East-West, in the Southern part of the Plan, interrupting the progression of secondary streets to Trade Square (“Praça do Comércio”). Directions have a torsion of 16.5° to the North axis, making the southeast oriented façades differ in only 1° of the optimal benchmark torsion of 17.5° to the North axis, recommended by Olgyay (1963) for temperate climates.

An inner yard (“saguão”) in the core of the block separates two rows of the lot. For reasons of salubrity, an inner yard was introduced in the block, three metres wide, allowing aeration by ventilation and natural lighting to the interior of buildings. The inclusion of the inner yard (“saguão”) in the block allows a larger passive area, i.e., area that allows to be lit and naturally ventilated, according to the LT Method (Baker & Steemers, 2000).
In buildings of Baixa, the main construction elements responsible for thermal inertia are the exterior walls, due to its thickness, the weight, and due to the inherent coefficient of thermal storage. Consisting of stone masonry wall with lime mortar coating, with approx. 0.60m total thickness (Mascarenhas, 2004), illustrated in Figure 2a.

According to an analysis carried out from the available drawings (CML, 2005) the original windows were double-hung sash windows, which allowed a position of fixed aperture, and casement windows which had top-hung casement windows. Window types allowed to diversify the type of ventilation. These types of window are exemplified in Figure 2b.

In some residences and offices of Baixa, air conditioning devices were introduced. Air conditioning systems were usually introduced in spaces of small or medium sizes, where each space division has its own device, exemplified in Figure 2c.

Baixa’s interior units consist of a row of rooms with windows to the side of the street, and a row of rooms with windows to the side of the rear, to the inner yard (“saguão”). Thus, Baixa’s buildings provide the possibility of having naturally ventilated rooms, in a varied way. Having windows on one side and the other allows various combinations: To open windows on the street side (only), on the rear side (only), or both. And it opens up possibilities of practicing various types of ventilation – single-side, cross, stack effect, as well as night-time ventilation, as shown in Figure 3. The ventilation strategy is a major bioclimatic strategy currently recommended for the Lisbon climate (Gonçalves & Graça, 2004).
THERMAL ENVIRONMENT

Lisbon has a unique variant of the typical Mediterranean climate due to its proximity to the Atlantic Ocean (Ribeiro, 1987). In the center of Lisbon, according to the climatic normal, the monthly average temperature in January is 11.0 °C and in August is 22.3 °C. The minimum temperature is -2.8 °C in February and the maximum temperature is 39.5 °C in July. In what regards to relative humidity (RH), the minimum value is 60% in August, and the maximum value is 87% in December (IM 1981).

The following chart of Figure 4 shows monitoring values registered with datalogger devices during a year, of a selected building, used as office, and representative of the thermal environment of “Pombalino Yield buildings”. Results are presented according to the months of the year. The following chart is organized by data logger device that have registered indoor temperatures in a room with mechanical system off, simultaneously with outside temperatures.

![Temperature Monitoring Chart](image)

**Figure 4** Chart measuring averages, minimum and maximum temperatures registered in a room with mechanical system off, and outdoor spaces of the case study building.

The previous graph in Figure 4 shows that when outside temperatures vary between 5 ºC and 34.5 ºC, indoor temperatures vary between 14 ºC and 28 ºC with the system off. It can be observed that during certain months of the year – from May to October - the average temperatures are within the range of 20 ºC to 26 ºC. - This means that during these months, average temperatures are within the limits of conventional comfort.

METHODOLOGY

A survey was conducted among subjects who live or work in Baixa, in Lisbon. The study was conducted in 20 fractions in 19 diverse buildings of Baixa, in housing and office spaces. Offices range from small private offices to large offices of Governmental Ministries and Institutes. 130 subjects were surveyed during the winter season, and 119 subjects were surveyed during the summer season, in a total of 249 subjects. 18 fractions were observed during each season of winter and summer of 2009. The variety of office and housing situations - in function, type of building, type of floor fraction, size, and location - is representative of the variety that exists in Baixa.

The evaluation was based on a survey, whose model was specifically developed for users of Baixa buildings, in Lisbon. The survey consists of a questionnaire to be answered based on their experience while users who live or work in those selected buildings.
In order to obtain an overview of actions of control applied by users, an analysis of frequency of actions applied by subjects surveyed was conducted, in what regards to:

1. Use of existing mechanical devices.
2. Opening windows, in duration, and spatial distribution.

And a comparison between the actions committed by users during the seasons of winter and summer was conducted.

In this sample, there is a higher percentage of respondents in the office function (95%) than in the residential function (5%). – Because there has been a greater availability from offices than by residences to participate in this study.

The study is focused on the use of windows and mechanical devices because those are the most used environmental controls that were observed in this study. Furthermore, currently most of Baixa’s interior units have air conditioning. Although the use of shading devices was also observed during this research, this paper is focused on analyzing the use of windows and mechanical devices, being the main environmental controls used in buildings of Baixa at present time.

It was chosen to divide the study in winter and summer seasons, being the most representative of the opposite extreme situations that influence spaces during the year: Cold and dark compared to warm and bright climates.

**DISCUSSION OF RESULTS**

**Heating and Cooling Mechanical Devices**

The following Tables 1 and 2 show the frequency of periods of use of heating and cooling devices, in winter and summer seasons, respectively. Periods described correspond to a progression in time duration of use of mechanical devices.

<table>
<thead>
<tr>
<th>Table 1. Frequency of Periods of Use of Heating Devices - Winter.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Periods</strong></td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Never / NA</td>
</tr>
<tr>
<td>Punctually</td>
</tr>
<tr>
<td>Only on the coldest days</td>
</tr>
<tr>
<td>A few times per Winter</td>
</tr>
<tr>
<td>A few times per week</td>
</tr>
<tr>
<td>A few times per day</td>
</tr>
<tr>
<td>Almost always “on” during most of the Winter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2. Frequency of Periods of Use of Cooling Devices - Summer.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Periods</strong></td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Never / NA</td>
</tr>
<tr>
<td>Punctually</td>
</tr>
<tr>
<td>Only on the hottest days</td>
</tr>
<tr>
<td>A few times per Summer</td>
</tr>
<tr>
<td>A few times per week</td>
</tr>
<tr>
<td>A few times per day</td>
</tr>
<tr>
<td>Almost always “on” during most of the Summer</td>
</tr>
</tbody>
</table>

It can be observed in Tables 1 and 2 that most of respondents turn on heating devices in Winter in the period “during most of the Winter”, followed by “only on the coldest days”. In summer, most of respondents turn on cooling devices in the period “during most of the summer”, followed by “a few times per day”.

Comparing both seasons, it can be observed that while in Winter the majority of respondents use the mechanical devices in the periods “almost always on” and exceptionally on (“only on the coldest days”), in Summer most of respondents use devices in periods “almost always on” and “a few times per day”.

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16-18 December 2014, CEPT University, Ahmedabad
day”, revealing the habit of having the cooling devices “on” during most of the Summer. Hence, one can conclude that the use of heating devices in winter presents different periods of use, depending on the type of building’s units. In a different way, in summer, the use of cooling devices is intensive, including AC devices (Air Conditioning devices, the most used), which are almost “on” during most of the season.

Natural Ventilation through opening of Windows

The following Tables 3 and 4 show the frequency of periods of opening windows, in winter and summer seasons, respectively. Periods described correspond to a progression in time duration of open windows.

<table>
<thead>
<tr>
<th>Table 3. Frequency of Opening Windows in the Winter Season.</th>
</tr>
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<tbody>
<tr>
<td>Period</td>
</tr>
<tr>
<td>Never</td>
</tr>
<tr>
<td>Punctually</td>
</tr>
<tr>
<td>Morning / or Afternoon</td>
</tr>
<tr>
<td>Morning + Afternoon / or during the Night</td>
</tr>
<tr>
<td>Always</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4. Frequency of Opening Windows in the Summer Season.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
</tr>
<tr>
<td>Never</td>
</tr>
<tr>
<td>Punctually</td>
</tr>
<tr>
<td>Morning / or Afternoon / or Evening</td>
</tr>
<tr>
<td>Morning + Afternoon / or during the Night</td>
</tr>
<tr>
<td>Always</td>
</tr>
</tbody>
</table>

In Table 3, it can be observed that in the winter, the majority of subjects open windows “punctually” (43,7%) followed by “never” (34,9%). In Table 4, it can be observed that in the summer, the majority of subjects open windows “punctually” (35,3%) followed by isolated periods during the morning, or the afternoon, or in the evening (21,6%) or during all day or all night (21,6%). There are 16,4% of subjects that never open windows and 5,2% that has windows always opened.

The following tables 5 and 6 show the percentages of distribution of open windows, in winter and summer seasons, respectively.

<table>
<thead>
<tr>
<th>Table 5. Distribution of Open Windows in Winter Season.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution of Opening</td>
</tr>
<tr>
<td>Street and Rear</td>
</tr>
<tr>
<td>Only Street</td>
</tr>
<tr>
<td>Only Rear</td>
</tr>
<tr>
<td>No Opening</td>
</tr>
<tr>
<td>NA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 6. Distribution of Open Windows in Summer Season.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution of Opening</td>
</tr>
<tr>
<td>Street and Rear simultaneously</td>
</tr>
<tr>
<td>Street and Rear alternate</td>
</tr>
<tr>
<td>Only Street</td>
</tr>
<tr>
<td>Only Rear</td>
</tr>
<tr>
<td>No Opening</td>
</tr>
<tr>
<td>NA</td>
</tr>
</tbody>
</table>

Table 5 shows that in the winter season, there is a large proportion of all subjects who does not open any window (40,2%). From those who open windows, most of subjects do it in the street side of their space (44,1%), followed by “only” in the rear side (12,6%). And it can be observed that subjects rarely open windows in the street and rear sides simultaneously (3,1%). A possible explanation is to
prevent the drafts of cooling air and unwanted air in winter time. It is observed in Table 6 that in the summer, total of subjects open windows on street side primarily (40%), followed by "no opening" (26,1%) and "street and rear simultaneously" (13,9%). One possible explanation for the windows opening is to give rise to types of single-side ventilation or cross ventilation within the space allowing cooling and air renewal.

It is observed that generally, subjects do not open windows during the night in summer, which could be a strategy to cool the building fabric. This occurrence can be explained by the sample, which is mainly focused in the office function, where it has been observed that subjects do not leave windows open during the evening, i.e., outside working time. It has been described by subjects in residences that in summer, most of subjects have windows always open, during daytime and nighttime, as opposed to subjects in offices, that generally have windows open during daytime only.

These observed frequencies are partially explained by the widespread recurrence of mechanical devices, particularly during the summer season. This higher recurrence affects how windows are used. And to analyze these buildings’ natural performance, it makes difficult to understand how the performance of these buildings would be without the use of mechanical appliances. One question that arises is whether if there were no air conditioning devices, how would be these buildings’ use. And once not being able to use such devices, if there would be a more intensive use of other means that are available to regulate temperature, such as windows, shades or doors.

The observed use frequencies of mechanical appliances and windows can be explained by the sample, which is mainly focused in the office function and less in the residential function. The office function has a considerable density of occupancy and equipment producing internal heat gains, to which users respond turning on the mechanical appliances. This higher recurrence affects how the windows are used.

One can argue about the changing behavior of users of these buildings in the present context, where mechanical devices are available, as compared to the time when these buildings were constructed. Leads to formulate, as hypothesis, that users are not prepared to work with higher temperatures. Maybe because they are not used (anymore) to use all available controls: Users do not have a regular habit of opening windows. And in a simplified way, they are mainly restricted to the use of mechanical devices, neglecting the remaining environmental controls, such as windows or shading.

This complementarity of resources (natural + mechanical) is an important issue in the relationship between the regulation of mechanical equipment and windows. One may question whether this complementarity comes from compensation - triggered by the unnaturalness of mechanical controls, and one tries to compensate the thermal environment and air quality by opening windows, bringing natural air. Or one may ask if this complementarity is a correction - triggered by any fluctuation in temperature during the day, and while using mechanical controls, one tries to fix temperature by opening windows.

**CONCLUSION**

Regarding the thermal performance, it can be observed from analysis of the survey responses that generally:

1. Users turn on mechanical appliances in a greater frequency in summer than in winter;

2. Users open windows more often in summer than in winter.

3. Users open windows with greater distribution variety in the summer season than in the winter season.
After the analysis of results, it can be concluded about how buildings are used by users in each season:

4. In winter, subjects use less frequently heating devices, as well as the remaining elements to regulate temperature – They have a less interactive attitude - They use environmental controls to regulate temperature less frequently.

5. In summer, subjects use more frequently cooling devices, as well as the remaining elements to regulate temperature – They have a more interactive attitude – They use environmental controls to regulate temperature more frequently.

In winter, buildings of “Baixa”, in what regards to their controls are used less interactively. In this season, users use less frequently buildings’ original controls. And in the event of using controls, they use more frequently heating appliances. It must be noted that once, these buildings had fireplaces, that were meanwhile removed, and are now practically nonexistent. Over the years, the fireplace was replaced by heating devices.

In summer, architectural elements are used more interactively. In this season, most users use buildings’ original controls, such as windows. And users use more frequently cooling devices. It is observed that in summer, there is a greater effort than in winter, in using all means of temperature regulation available, such as windows. And in the event that users recur to air conditioning devices, they also use other controls to regulate temperature, such as opening windows (although it is not recommended to be used simultaneously because of conflict with AC). Architectural elements as a mean of temperature regulation are mainly used in the summer season. And it is an indication that under the climate of Lisbon, it is mostly in the summertime that controls have a greater role to play in these buildings in Baixa.

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Development of a Window Opening Algorithm to Predict Occupant Behavior in Japanese Houses

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ABSTRACT

We investigated window opening behaviour and the thermal environment over a period of more than 3 years in the living rooms and bedrooms of dwellings in the Kanto region of Japan. We collected over 32,000 data-samples from 243 residents of 121 homes. The proportion of ‘open window’ in the free running mode is significantly higher than that in the cooling and heating modes. The window opening is related to the indoor or outdoor air temperature. Window opening behaviour as predicted by logistic regression analysis is in agreement with the measured data. These findings can be applied to develop an adaptive algorithm for window opening behaviour in Japanese residences.

INTRODUCTION

Natural ventilation from opening windows has been decreasing in houses in recent years because of the increasing prevalence of mechanical ventilation and air-conditioning. However, temperature control by opening and closing windows can reduce environmental impact by minimizing the period of the year when air-conditioning is needed.

There has been more research into window-opening behaviour in offices (Rijal et al. 2007~2012, Yun & Steemers 2007, Robinson & Haldi 2008, Kim et al. 2009, Haldi & Robinson 2010) and university buildings (Suzuki et al. 2002, Umemiya & Yoshida 2004) than in dwellings (Dick & Thomas 1951, Asawa et al. 2005, Kubota 2007, Rijal et al. 2013). The findings from research in offices and universities cannot be assumed to apply to dwellings, where people’s behaviour is less constrained. There is evidence that people respond differently in their own homes for a number of reasons, social, economic and cultural (Oseland, 1995). Thus it was necessary to conduct research also on residential window opening behaviour.

To explore window opening behavior and develop a window opening algorithm for Japanese residences, thermal measurements were made and an occupant behavior surveys conducted over a period of more than 3 years in the living rooms and bedrooms of dwellings in the Kanto region of Japan.

METHODOLOGY

Thermal comfort surveys and thermal measurements were conducted in 121 houses in Kanto region (Kanagawa, Tokyo, Saitama and Chiba) of Japan from 2010 to 2013 (Table 1). The detail of surveys 1, 2
and 4 can be found in Rijal & Yoshimura (2011), Katsuno et al. (2012) and Rijal et al. (2014) respectively.

Indoor air temperature and relative humidity were measured in the living rooms and bedrooms, away from direct sunlight, at ten minute intervals using a data logger (Fig. 1). The globe temperature was also measured in the living room in surveys 3, 4 & 5. Outdoor air temperature and relative humidity were obtained from the nearest meteorological station.

The number of subjects was 119 males and 124 females. Respondents completed the questionnaire several times a day in the living rooms and twice in the bedrooms (“before go to bed” and “after wake-up from the bed”) (Table 2). The thermal comfort survey was conducted several times a day using seven-point thermal sensation scales (Table 2). The window opening behaviour was recorded in binary form (0 = window closed, 1 = window open). We have collected over 32,000 samples.

### Table 1. Description of survey

<table>
<thead>
<tr>
<th>Survey</th>
<th>Survey period</th>
<th>Surveyed room</th>
<th>Measured variables*</th>
<th>Number of houses</th>
<th>Number of subjects</th>
<th>Number of votes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start date</td>
<td>End date</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>06-7-2010</td>
<td>18-7-2011</td>
<td>Living, Bed</td>
<td>$T_i, RH_i$</td>
<td>11</td>
<td>3299</td>
</tr>
<tr>
<td>2</td>
<td>05-8-2011</td>
<td>06-9-2011</td>
<td>Living</td>
<td>$T_i, RH_i$</td>
<td>55</td>
<td>2558</td>
</tr>
<tr>
<td>3</td>
<td>21-7-2011</td>
<td>08-5-2012</td>
<td>Living, Bed</td>
<td>$T_i, RH_i, T_g$</td>
<td>14</td>
<td>2819</td>
</tr>
<tr>
<td>4</td>
<td>25-7-2012</td>
<td>24-6-2013</td>
<td>Living, Bed</td>
<td>$T_i, RH_i, T_g$</td>
<td>30</td>
<td>463</td>
</tr>
<tr>
<td>5</td>
<td>10-8-2013</td>
<td>03-10-2013</td>
<td>Living, Bed</td>
<td>$T_i, RH_i, T_g$</td>
<td>11</td>
<td>13083</td>
</tr>
</tbody>
</table>

* $T_i$: Indoor air temperature (°C), $RH_i$: Indoor relative humidity (%), $T_g$: Indoor globe temperature (°C), $T_g$ is measured only in the living room.

### Table 2. Thermal sensation scale

<table>
<thead>
<tr>
<th>No.</th>
<th>Now, how do you feel the air temperature?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very cold</td>
</tr>
<tr>
<td>2</td>
<td>Cold</td>
</tr>
<tr>
<td>3</td>
<td>Slightly cold</td>
</tr>
<tr>
<td>4</td>
<td>Neutral (neither cold nor hot)</td>
</tr>
<tr>
<td>5</td>
<td>Slightly hot</td>
</tr>
<tr>
<td>6</td>
<td>Hot</td>
</tr>
<tr>
<td>7</td>
<td>Very hot</td>
</tr>
</tbody>
</table>

### RESULTS AND DISCUSSION

#### 3.1 Distribution of indoor and outdoor temperatures during voting

Table 3 shows the mean and standard deviation of the indoor and outdoor air temperature in each mode. Fig. 2 shows the monthly mean outdoor and indoor air temperature in FR mode in living room and bedroom. The mean outdoor air temperatures during the voting were 19.5 °C, 27.6 °C and 7.2 °C for FR, CL and HT modes respectively (Fig. 2). The mean indoor air temperatures at the time of voting were 24.2 °C, 27.3 °C and 19.2 °C for FR, CL and HT modes respectively. The Japanese government recommends the indoor temperature settings of 20 °C in winter
and 28 °C in summer respectively. The results showed that the mean indoor temperatures during heating and cooling were close to the recommendation. The mean indoor and outdoor temperature difference was 4.7 K, -0.3 K and 12.0 K for FR, CL and HT modes respectively. The results show that the seasonal difference of the indoor air temperature is quite large, and that the data represent a wide range of outdoor temperature.

### Table 3 Indoor air temperature and proportion of open windows in various modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Room</th>
<th>Outdoor air temp. (°C)</th>
<th>Indoor air temp. (°C)</th>
<th>Window opening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>FR</td>
<td>Living</td>
<td>13,454</td>
<td>20.4</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>Bed</td>
<td>9,054</td>
<td>18.2</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>22,508</td>
<td>19.5</td>
<td>7.9</td>
</tr>
<tr>
<td>CL</td>
<td>All</td>
<td>6,677</td>
<td>27.6</td>
<td>2.7</td>
</tr>
<tr>
<td>HT</td>
<td>All</td>
<td>2,982</td>
<td>7.2</td>
<td>4.2</td>
</tr>
</tbody>
</table>

N: Number of observation, SD: Standard deviation

3.2 Evaluation of window opening behaviour

3.2.1 Status of window opening (WO)

To understand the window opening behaviour, the mean proportions of ‘window opening (WO)’ are compared. Table 3 shows the mean and standard deviation of the windows open in each mode. The mean WO is 0.39, 0.03 and 0.00 for FR, CL and HT modes respectively. The mean window opening in living room is higher than in the bedroom (Table 3). Interestingly, the mean WO in UK office buildings was 0.70 in NV mode and 0.04 in AC mode (Rijal et al. 2007). The mean window opening in Pakistan office and commercial buildings was 0.33 in NV mode. The results showed that the mean windows open is close to the Pakistan value and lower than the UK value. We shall limit the analysis to the FR mode.

### Season, month and time of the day

Seasonal and monthly difference in proportion of windows open in FR mode is shown in Fig. 3. The proportion of open windows (WO) is highest in summer and lowest in winter. The WO in autumn is significantly higher than that in spring. This is possibly due to the fact that people are more adapted in spring to the winter low temperature, and in autumn to the summer temperature. In reality, the indoor and outdoor air temperatures in autumn are higher than in the spring (Fig. 3(b)).

Evidently, the proportion of open windows gradually increases towards the summer months (Fig. 3(c)). Conversely, it gently decreases towards the winter months as indoor or outdoor air temperature varies (Figs. 2).

The data were divided into four groups, in ascending order of time. Interestingly, the proportion of open windows gradually increases during the morning, and then decreases towards the evening (Fig. 4(a)). Most of occupants open the windows in the morning and shut them at night. These trends are similar for all seasons (Fig. 4(b)).

![Figure 3](image)

**Figure 3** The proportion of open windows, indoor and outdoor air temperature (at 95% confidence level)
3.2.3 Relationship between the open windows and air temperature

In FR mode the open window correlated better with the outdoor temperature than with the indoor temperature (Table 4). The correlation coefficient for the living room is higher than for the bedroom. From these observations, it can be inferred that the window opening is related to both indoor and outdoor air temperatures.

Fig. 5 shows the proportion of open windows and the corresponding temperatures. The data were divided into ten groups, in an ascending order of temperature. The proportion of the window opening rises as the indoor globe or outdoor air temperature rises. The proportion of window opening in the livingrooms is higher than in the bedrooms. When mean indoor air temperature is 27.1 °C, the proportion of open windows is 0.63 in living room and 0.51 in bedroom (Fig. 5(a)).

When the mean outdoor air temperature is 24.3 °C, the proportion of windows open is 0.71 in livingrooms and 0.58 in the bedrooms (Fig. 5(c)). These proportions are similar to the Pakistan study (Rijal et al. 2008), and significantly lower than that of the UK study (Rijal et al. 2007). This is perhaps because the indoor and outdoor air temperature in Japan and Pakistan are considerably higher than that in the UK.

Table 4. Correlation coefficients in FR mode

<table>
<thead>
<tr>
<th>Room</th>
<th>Items</th>
<th>Window: $T_i$</th>
<th>Window: $T_o$</th>
<th>$T_i$: $T_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Livingroom</td>
<td>Correlation coefficient (r)</td>
<td>0.58</td>
<td>0.62</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>Number of samples (N)</td>
<td>13,289</td>
<td>13,382</td>
<td>13,352</td>
</tr>
<tr>
<td>Bedroom</td>
<td>Correlation coefficient (r)</td>
<td>0.46</td>
<td>0.50</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>Number of samples (N)</td>
<td>8,946</td>
<td>9,000</td>
<td>8,997</td>
</tr>
<tr>
<td>All</td>
<td>Correlation coefficient (r)</td>
<td>0.53</td>
<td>0.58</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>Number of samples (N)</td>
<td>22,235</td>
<td>22,382</td>
<td>22,349</td>
</tr>
</tbody>
</table>

$T_i$: Indoor air temperature (°C), $T_o$: Outdoor air temperature (°C) All correlations are significant (p<0.001)
3.3 Potential of the open window

3.3.1 Indoor air temperature

Fig. 6 and Table 5 show the seasonal variation in indoor air temperature for cases when windows are open and closed. The mean indoor air temperature for the window open condition is 27.7 °C in the living room which is significantly higher by 5.3 K, than for the window closed condition. In UK office buildings, the mean globe temperature for the window open condition is 23.4 °C which is 1.2 K higher than when the window is closed (Rijal et al. 2008a). Thus, the temperature difference between the cases of open and closed window in residential buildings is higher than that of the office buildings. The temperature difference is highest in autumn. In winter, the mean indoor air temperature for the ‘open window’ case is significantly lower than that of the ‘closed window’ case. The results showed that window opening is an effective way to control the indoor thermal environment.

Table 5. Indoor air temperature for windows open and closed

<table>
<thead>
<tr>
<th>Season</th>
<th>Window</th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
<th>t*</th>
<th>Open-Closed</th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
<th>t*</th>
<th>Open-Closed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td>Closed</td>
<td>1,247</td>
<td>18.0</td>
<td>3.2</td>
<td>10.8</td>
<td>4.9</td>
<td>1,261</td>
<td>15.2</td>
<td>4.3</td>
<td>4.4</td>
<td>-2.6</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>55</td>
<td>13.1</td>
<td>4.5</td>
<td></td>
<td></td>
<td>54</td>
<td>12.5</td>
<td>4.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring</td>
<td>Closed</td>
<td>2,025</td>
<td>21.8</td>
<td>2.6</td>
<td>-</td>
<td>2.5</td>
<td>1,631</td>
<td>20.5</td>
<td>3.6</td>
<td>-8.9</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>493</td>
<td>24.2</td>
<td>2.2</td>
<td>19.2</td>
<td></td>
<td>165</td>
<td>23.0</td>
<td>2.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>Closed</td>
<td>1,038</td>
<td>27.5</td>
<td>2.4</td>
<td>-</td>
<td>1.5</td>
<td>1,182</td>
<td>27.7</td>
<td>2.3</td>
<td>-10.0</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>3,685</td>
<td>29.0</td>
<td>2.2</td>
<td>19.0</td>
<td></td>
<td>1,675</td>
<td>28.5</td>
<td>2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autumn</td>
<td>Closed</td>
<td>2,926</td>
<td>22.9</td>
<td>3.3</td>
<td>37.1</td>
<td>3.5</td>
<td>2,198</td>
<td>22.9</td>
<td>3.8</td>
<td>-22.3</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>1,820</td>
<td>26.5</td>
<td>3.0</td>
<td></td>
<td></td>
<td>780</td>
<td>26.3</td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>Closed</td>
<td>7,236</td>
<td>22.4</td>
<td>4.0</td>
<td>-</td>
<td>5.3</td>
<td>6,272</td>
<td>21.6</td>
<td>5.4</td>
<td>-48.8</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>6,053</td>
<td>27.7</td>
<td>3.3</td>
<td>82.1</td>
<td></td>
<td>2,674</td>
<td>27.2</td>
<td>3.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*All open/closed temperature differences are statistically significant (p<0.001)

3.3.2 Comfort temperature

The potential of the open window is further analyzed in the context of comfort temperature. The comfort temperatures were obtained by the Griffiths’ method (Griffiths 1990, Nicol et al. 1994, Rijal et al. 2008, Humphreys et al. 2013, Rijal et al. 2014).

\[ T_c = T_i + (4 - C) / a^* \]  

(1)

where \( T_i \) is the comfort temperature by Griffiths’ method (°C), \( T_i \) is the indoor air temperature (°C) and \( a^* \) is the regression coefficient (≈0.50).

Fig. 7 and Table 6 show the seasonal variation in comfort temperature with windows open and closed. The mean comfort temperature for window open is 26.5 °C in living room which is 3.7 K higher than that of the case of window closed. Brager et al. (2004) found 1.5 K higher comfort temperature for the people with an access to window operation than the group...
without in office buildings. The temperature difference is highest in autumn. In winter the mean comfort temperature for the open window condition is significantly lower than for the window closed condition. The results showed that window opening is effective to create the comfortable thermal environment.

**Table 6. Comfort temperature for windows open and closed**

<table>
<thead>
<tr>
<th>Season</th>
<th>Window</th>
<th>Comfort temperature Tc (°C)</th>
<th>Living room</th>
<th>Bedroom</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Winter</td>
<td>Closed</td>
<td>1,247</td>
<td>19.5</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>57</td>
<td>14.1</td>
<td>4.6</td>
</tr>
<tr>
<td>Spring</td>
<td>Closed</td>
<td>2,025</td>
<td>22.1</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>492</td>
<td>23.8</td>
<td>2.2</td>
</tr>
<tr>
<td>Summer</td>
<td>Closed</td>
<td>1,038</td>
<td>26.5</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>3,683</td>
<td>27.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Autumn</td>
<td>Closed</td>
<td>2,926</td>
<td>23.5</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>1,819</td>
<td>26.0</td>
<td>2.6</td>
</tr>
<tr>
<td>All</td>
<td>Closed</td>
<td>7,236</td>
<td>22.9</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>6,049</td>
<td>26.5</td>
<td>2.8</td>
</tr>
</tbody>
</table>

*All open/closed temperature differences are statistically significant (p<0.001)

3.4 Development of an algorithm to predict window opening behaviour

3.4.1 Logistic regression curves

In the previous section, we analyzed the window opening behaviour based on field data and confirmed some general behavioural trends, but no attempt was made to predict the occupant behaviour in housing (Rijal et al. 2013). Such predictions are needed for the thermal simulation of buildings.

Nicol and Humphreys (2004) made use of Probit analysis to predict occupant control behaviour in NV buildings. For mathematical convenience they used a Logistic distribution in place of the Normal distribution. The relationship between the probability of windows open \( p \) and the indoor or outdoor temperature \( T \) is of the form:

\[
\text{logit}(p) = \log \left\{ \frac{p}{1-p} \right\} = bT + c
\]

\[
p = \frac{\exp(bT+c)}{1+\exp(bT+c)}
\]

and where \( \exp \) (exponential function) is the base of natural logarithm, \( b \) is the regression coefficient for \( T \), and \( c \) the constant in the regression equation.

We have adopted the same method here, using SPSS version 19 for the calculations. The Logistic regression equations, based on the indoor or outdoor temperature, are shown in Fig. 8. The following regression equations were obtained in between the windows open and the indoor or outdoor air temperature:

**Living room**

\[
\text{logit}(p) = 0.394T_i - 10.144 \quad (n=13,289, R^2=0.34, \text{S.E.}=0.007, p<0.001)
\]

\[
\text{logit}(p) = 0.372T_g - 9.659 \quad (n=9,833, R^2=0.29, \text{S.E.}=0.008, p<0.001)
\]

\[
\text{logit}(p) = 0.258T_o - 5.675 \quad (n=13,382, R^2=0.38, \text{S.E.}=0.004, p<0.001)
\]

**Bedroom**

\[
\text{logit}(p) = 0.291T_i - 8.100 \quad (n=8,946, R^2=0.24, \text{S.E.}=0.008, p<0.001)
\]

\[
\text{logit}(p) = 0.206T_o - 5.113 \quad (n=9,000, R^2=0.26, \text{S.E.}=0.005, p<0.001)
\]

**All data**

\[
\text{logit}(p) = 0.349T_i - 9.235 \quad (n=22,235, R^2=0.30, \text{S.E.}=0.005, p<0.001)
\]

\[
\text{logit}(p) = 0.238T_o - 5.466 \quad (n=22,382, R^2=0.34, \text{S.E.}=0.003, p<0.001)
\]

\( T_i \): Indoor air temperature (°C), \( T_g \): Globe temperature (°C), \( T_o \): Outdoor air temperature (°C), n:
sample size, S.E.: Standard error, \( p \): Significance level of the regression coefficient, \( R^2 \): Cox and Snell \( R^2 \).

A regression coefficient of 0.349 is obtained when the indoor air temperature is the predictor. This is higher than that obtained when the outdoor air temperature is used. In the Gifu region of Japan (Rijal et al. 2013), regression coefficients of 0.248 and 0.210 respectively were obtained with indoor or outdoor temperature. In Pakistan (Rijal et al. 2008) and in UK (Rijal et al. 2007) studies, regression coefficients of 0.176 and 0.354 respectively were obtained with indoor globe temperature is the predictor. In Kyoto (Majima et al. 2007) and UK (Rijal et al. 2007) data returned the regression coefficients of 0.119 and 0.181 respectively with outdoor air temperature is the predictor. The regression coefficient in the living room is slightly higer than the bedroom. The predicted window opening is well matched with measured values (Fig. 8).

![Figure 8](image-url) Comparison of measured (open circular dots) and predicted value (curved line) in NV mode. Measured values were grouped for every 1 °C for indoor air temperature and for every 2 °C for outdoor air temperature. The grouped data for samples less than 100 are not shown.

**CONCLUSIONS**

We have investigated the window opening behaviour and corresponding thermal environment over a period of more than 3 years in the living rooms and bedrooms of dwellings in the Kanto region of Japan and the following results were found:

1. The proportion of the window opening in the free running mode is significantly higher than that of the cooling or heating modes.
2. The window opening is related to the indoor and outdoor air temperature in the free running mode.
3. The window opening behaviour is predicted based on indoor and outdoor air temperature using logistic regression analysis. The predicted window opening matched well with that of the measured value.

**ACKNOWLEDGEMENTS**

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**REFERENCES**


Determining the Trade-offs between Thermal Comfort and Cooling Consumption in Indian Office Buildings

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Yash Shukla
[CARBSE, CEPT University]

ABSTRACT
The present work is to understand the impact of setpoint temperature and coefficient of performance (COP) of a cooling system on cooling energy consumption, and its effect on thermal comfort of occupants in office spaces for the different climate zones of India. The occupants’ thermal comfort sensation is addressed here by the PMV (Predicted Mean Vote) index. The investigation of the mutual relationship between thermal comfort and energy demand is of the foremost importance to define the benchmarks for calibrating the energy use in office buildings. The first approach of this study is associated with the thermal comfort optimization and the second strategy includes energy consumption minimization while maintaining adequate thermal comfort. Results from the parametric energy simulation of a typical open plan office building are presented for different cases in order to evaluate the results with variations in cooling setpoint temperature and COP (an indicator of chiller performance). The results indicate there is a scope to reduce cooling energy consumption without compromising thermal comfort. India has a wide range of climatic conditions, hence this research comes up with a comparative analysis of cooling energy savings per unit increase in the cooling setpoint temperature for different climatic zones based on the system efficiency. Looking at the total energy use, this study suggests, the appropriate modulations in the setpoint temperature with respect to its climate zone.

INTRODUCTION
Any building requires energy for many functions like construction, operation and demolition. The main sector for energy consumption is building operation, of which HVAC systems form the most important end-use (Mathews, Botha, Arndt, & Malan, 2001). Buildings consume 33% of total energy in India and this is growing at the rate of 8% per annum (Rawal et al., 2012). Estimates reveal that, total built-up area will increase rapidly, as nearly 66% of the commercial sector is yet to be built by 2030 (Ramesh & Khan, 2013). Energy efficiency in buildings is a critical issue due to the increase in energy costs, energy consumption and the related environmental impacts, especially those related to global warming.

It is therefore, important to realize the energy consumption while regulating the indoor temperature. In the past, the thermal comfort standards was not analysed to optimize energy efficiency (Indraganti & Rao, 2010). Thermal comfort has a significant impact on the productivity of building occupants and it is also important to consider energy consumption with it. Recently, the idea of comfort and good living has
been re-defined completely and the building industry responded to this new comfort expectation with
glory. In the last two decades, there has been exceptional increase in demand for air conditioned
buildings as perception of comfort is changing rapidly. A building may be designed or retrofitted with
energy efficiency measures resulting in substantial energy bill savings. These savings show great loss
with respect to workplace inefficiencies, if the occupants are not comfortable (Mathews et al., 2001).

Most published research work deals with common “quantifiable” factors such as temperature,
humidity and air velocity etc. However, the state of comfort depends on a wide range of factors, which
are “not quantifiable” such as mental status, habits, education of the people etc. Among these factors, the
one that is most studied is “acclimatization” to a particular climate. Various studies confirm that
preferences/ acclimatization of people in different locations vary. This may result in people of warmer
climate having a tolerance to higher temperatures as compared with people in colder region (Corgnati,
Fabrizio, & Filippi, 2008; Indraganti & Rao, 2010; Mallick, 1996). There is a need to define comfort
range of setpoint temperature according to the context of region and ambient temperature (Indraganti &
Rao, 2010). This study attempts to understand the impact of variation in cooling setpoint temperature and
chiller coefficient of performance (COP) on energy consumption as well as thermal comfort of
occupants in office spaces.

India is a vast country with a variety of geographical features resulting in a multitude of climatic
conditions. These have been simplified and categorized into five climate zones – hot and dry, warm and
humid, composite, moderate and cold. Detailed characteristics of these zones are provided in the
National Building Code of India (Bureau of Indian Standards, 2005). For this study, one representative
city from each of these climate zones was identified: Ahmedabad, Chennai, Delhi, Bangalore and
Guwahati.

**METHODODOLOGY**

For the purpose of this study, a typical office building was modeled in Design Builder 3.0.0.104
using input parameters obtained through literature study. Simulations were run for five climatic zones
mentioned earlier and the roof and floor were treated as adiabatic representing a typical intermediate
floor.

<table>
<thead>
<tr>
<th>ACTIVITY DETAILS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupancy details</td>
<td>0.01 people/m² or 6.25 m²/person</td>
</tr>
<tr>
<td>Metabolic rate</td>
<td>0.9 (typing)</td>
</tr>
<tr>
<td>Other gains: computer</td>
<td>11 W/m²</td>
</tr>
<tr>
<td>Clothing for winter</td>
<td>1.0 Clo</td>
</tr>
<tr>
<td>Clothing for Summer</td>
<td>0.5 Clo</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LIGHTING</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Target illuminance</td>
<td>500 lux</td>
</tr>
<tr>
<td>Default display lighting</td>
<td>11 W/m²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CONSTRUCTION DETAILS</th>
<th></th>
</tr>
</thead>
</table>
| Walls                             | 230mm thick brick wall with 60 mm XPS
polystyrene in outer surface       |
| U-Value                           | 0.440 W/m².K (as per ECBC)           |
| Roof                              | Flat roof of 150mm in cast concrete
with XPS polystyrene and Asphalt
insulation on top surface          |
| U-Value                           | 0.409 W/m².K (as per ECBC)           |

<table>
<thead>
<tr>
<th>OPENINGS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>WWR</td>
<td>30%</td>
</tr>
</tbody>
</table>
| Window details                    | 1500mm window height, 800mm sill
height                                |
Considerations

Thermal comfort depends on four environmental factors – air temperature, mean radiant temperature, air velocity and relative humidity. For the purpose of this study, only air temperature is being varied for the purpose of simulation study and the other parameters are allowed to float as per the variation in temperature. Although the operative temperature thermostat AC system gives more significant results for PMV values, air temperature thermostat is used for this study so as to match it with the conventional practice carried out in India. PTAC system is considered for air conditioning. As this system specification does not allow the humidity to vary considerably at a given temperature. Also variation is too less to impact the PMV values.

Runchart: To understand the influences of setpoint temperature and COP values on thermal comfort and energy consumption, a pathway or a methodology was planned to gain the required results:

<table>
<thead>
<tr>
<th>Glass</th>
<th>6mm Low E clear glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-Value and SHGC</td>
<td>1.65 W/m².K and 0.293 respectively</td>
</tr>
<tr>
<td>Frames</td>
<td>UPVC frames</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HVAC Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVAC Type</td>
</tr>
<tr>
<td>Cooling Setpoint temperature</td>
</tr>
<tr>
<td>Cooling system COP Values</td>
</tr>
</tbody>
</table>

**Figure 1 Run chart for simulations**

It can be noticed that there are three major and intentional variables (outdoor temperature, COP values and setpoint temperature). For this study, two major outputs: cooling energy consumption and PMV index are analyzed that are obtained from design builder output data sheet.
RESULTS

To resolve the obtained results for comparison of each case, the cooling energy consumption is converted into EPI (energy performance Index i.e. the ratio of total electricity used in a building to its total built up area. It is expressed as KWh/m^2/annum).

![Energy Performance Index for Ahmedabad at particular COP value at Corresponding temperature](image)

Figure 2 Shows all cases are split into four distinct lines representing cooling energy on 2, 3, 4 and 5 COP value. The case with COP value 2 has the highest cooling energy consumption and those with COP values 3 and 4 have the lower intermediate values and COP 5 being the lowest. Cooling consumption reduces as the COP value increases, however, this decrement varies drastically. Cooling energy consumption decreases significantly from COP 2 to 3 at particular temperature. The difference of almost 30 units (KWh/m^2/annum) is constant for each setpoint temperature for COP 2 and COP 3. The gradient slope for a single COP value having different setpoint temperature is steep till COP 3, and becomes gentler between COP 4 and the gradient line becomes almost straight for COP 5. This means that cooling consumption becomes nearly constant for higher COP value and there is not much net savings with increase in setpoint temperature. To quantify the same, there is a difference of 21 units of cooling consumption between setpoint 22°C to 28°C when COP is 2, however the difference get as low as only 8.0 units for setpoint temperature variations of COP value 5. So it is critical to decide the correct COP value as well for the desired setpoint temperature.

<table>
<thead>
<tr>
<th>SETPOINT/COP</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>22°C</td>
<td>103</td>
<td>68</td>
<td>51</td>
<td>41</td>
</tr>
<tr>
<td>23°C</td>
<td>98</td>
<td>65</td>
<td>49</td>
<td>39</td>
</tr>
<tr>
<td>24°C</td>
<td>94</td>
<td>62</td>
<td>47</td>
<td>37</td>
</tr>
<tr>
<td>25°C</td>
<td>91</td>
<td>61</td>
<td>45</td>
<td>36</td>
</tr>
<tr>
<td>26°C</td>
<td>88</td>
<td>59</td>
<td>44</td>
<td>35</td>
</tr>
<tr>
<td>27°C</td>
<td>85</td>
<td>57</td>
<td>43</td>
<td>34</td>
</tr>
<tr>
<td>28°C</td>
<td>82</td>
<td>55</td>
<td>41</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 1: EPI at particular Setpoint temperature and COP value for Ahmedabad

The values in Table 1 show EPI (KWh/m^2/annum) at respective setpoint temperature and cooling system COP values. It can be seen that the EPI value decreases with increment in the cooling setpoint temperature as well as COP value. Maximum amount of cooling energy consumption per annum takes place at COP 2 and cooling setpoint of 22°C. And the minimum cooling energy consumed annually for this case is 33 units, for COP 5 and setpoint 28°C. There is also a reduction in cooling consumption of about 5.0 % annually with 1°C increment in cooling setpoint. With an increase in COP value at the same setpoint, cooling consumption can be decreased substantially. It decreases by almost 30.0% when COP
is changed from 2 to 3. However, changing COP value from 4 to 5 leads to only 10.0% decrease.

### Table 2 Percentage of hours falling under a given range of PMV value

<table>
<thead>
<tr>
<th>SETPOINT/COP</th>
<th>-2.5</th>
<th>-1.5</th>
<th>-0.5</th>
<th>0.5</th>
<th>1.5</th>
<th>2.5</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>22°C</td>
<td>2%</td>
<td>31%</td>
<td>62%</td>
<td>7%</td>
<td>0%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>23°C</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>70%</td>
<td>30%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>24°C</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>45%</td>
<td>55%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>25°C</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>44%</td>
<td>56%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>26°C</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>1%</td>
<td>99%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>27°C</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>28°C</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>72%</td>
<td>28%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 2 gives the percentage of hours out of occupied hours falling under particular bin of PMV value at a given setpoint temperature. It shows that at 22°C and 23°C setpoint temperature gives more than 60% hours having PMV value in a range of 0.5 to -0.5. i.e., more than 60% of the occupied hours are comfortable for the occupants. The percentage gets reduced to 45% at 24°C. It can be noticed that no matter 26°C or 27°C is maintained as indoor temperature 100% of the occupied hours fall under PMV value 0.5 to 1.5 i.e. uncomfortable thermal conditions. Table 3 shows a comparative analysis of different climatic zones of India on how much one can save on each degree rise of setpoint temperature. The table can be used by the occupant to interpret at what temperature it will make sense to reduce or modulate the indoor temperature and how much one can save against it with respect to the climatic zone.

### Table 3 Shows percentage of reduction in cooling energy consumption at corresponding temperature in particular cities

<table>
<thead>
<tr>
<th>Ahmedabad</th>
<th>Bangalore</th>
<th>Chennai</th>
<th>Delhi</th>
<th>Guwahati</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>7%</td>
<td>7%</td>
<td>6%</td>
<td>7%</td>
<td>6%</td>
</tr>
<tr>
<td>7%</td>
<td>8%</td>
<td>6%</td>
<td>7%</td>
<td>6%</td>
</tr>
<tr>
<td>6%</td>
<td>7%</td>
<td>7%</td>
<td>7%</td>
<td>6%</td>
</tr>
<tr>
<td>8%</td>
<td>8%</td>
<td>8%</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>9%</td>
<td>9%</td>
<td>9%</td>
<td>8%</td>
<td>9%</td>
</tr>
<tr>
<td>10%</td>
<td>9%</td>
<td>10%</td>
<td>9%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Figure3 gives an idea of percentage of people dissatisfied with their thermal environment at each setpoint temperature considered in each particular city, representing respective climatic zone.
**Figure 4**  
Comfort conditions for Chennai at given setpoint temperatures

<table>
<thead>
<tr>
<th>SETPOINT/COP</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>22°C</td>
<td>97</td>
<td>65</td>
<td>49</td>
<td>39</td>
</tr>
<tr>
<td>23°C</td>
<td>91</td>
<td>61</td>
<td>46</td>
<td>36</td>
</tr>
<tr>
<td>24°C</td>
<td>85</td>
<td>57</td>
<td>43</td>
<td>34</td>
</tr>
<tr>
<td>25°C</td>
<td>80</td>
<td>53</td>
<td>40</td>
<td>32</td>
</tr>
<tr>
<td>26°C</td>
<td>74</td>
<td>49</td>
<td>37</td>
<td>29</td>
</tr>
<tr>
<td>27°C</td>
<td>67</td>
<td>44</td>
<td>33</td>
<td>27</td>
</tr>
<tr>
<td>28°C</td>
<td>60</td>
<td>40</td>
<td>30</td>
<td>24</td>
</tr>
</tbody>
</table>

**Figure 5**  
Comfort conditions for Bangalore at given setpoint temperatures

<table>
<thead>
<tr>
<th>SETPOINT/COP</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>22°C</td>
<td>84</td>
<td>56</td>
<td>42</td>
<td>34</td>
</tr>
<tr>
<td>23°C</td>
<td>78</td>
<td>52</td>
<td>39</td>
<td>31</td>
</tr>
<tr>
<td>24°C</td>
<td>72</td>
<td>48</td>
<td>36</td>
<td>29</td>
</tr>
<tr>
<td>25°C</td>
<td>67</td>
<td>44</td>
<td>33</td>
<td>27</td>
</tr>
<tr>
<td>26°C</td>
<td>61</td>
<td>41</td>
<td>31</td>
<td>24</td>
</tr>
<tr>
<td>27°C</td>
<td>56</td>
<td>37</td>
<td>28</td>
<td>22</td>
</tr>
<tr>
<td>28°C</td>
<td>50</td>
<td>34</td>
<td>25</td>
<td>20</td>
</tr>
</tbody>
</table>
Table 6. EPI at particular Setpoint temperature and COP value for Guwahati

<table>
<thead>
<tr>
<th>SETPOINT/COP</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>22°C</td>
<td>86</td>
<td>57</td>
<td>37</td>
<td>30</td>
</tr>
<tr>
<td>23°C</td>
<td>81</td>
<td>54</td>
<td>35</td>
<td>28</td>
</tr>
<tr>
<td>24°C</td>
<td>76</td>
<td>51</td>
<td>33</td>
<td>27</td>
</tr>
<tr>
<td>25°C</td>
<td>72</td>
<td>48</td>
<td>32</td>
<td>25</td>
</tr>
<tr>
<td>26°C</td>
<td>66</td>
<td>44</td>
<td>29</td>
<td>24</td>
</tr>
<tr>
<td>27°C</td>
<td>60</td>
<td>40</td>
<td>27</td>
<td>22</td>
</tr>
<tr>
<td>28°C</td>
<td>54</td>
<td>36</td>
<td>25</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 7. EPI at particular Setpoint temperature and COP value for Delhi

<table>
<thead>
<tr>
<th>SETPOINT/COP</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>22°C</td>
<td>90</td>
<td>60</td>
<td>45</td>
<td>36</td>
</tr>
<tr>
<td>23°C</td>
<td>84</td>
<td>56</td>
<td>42</td>
<td>34</td>
</tr>
<tr>
<td>24°C</td>
<td>78</td>
<td>52</td>
<td>39</td>
<td>31</td>
</tr>
<tr>
<td>25°C</td>
<td>73</td>
<td>48</td>
<td>36</td>
<td>29</td>
</tr>
<tr>
<td>26°C</td>
<td>67</td>
<td>45</td>
<td>34</td>
<td>27</td>
</tr>
<tr>
<td>27°C</td>
<td>61</td>
<td>41</td>
<td>31</td>
<td>25</td>
</tr>
<tr>
<td>28°C</td>
<td>56</td>
<td>37</td>
<td>28</td>
<td>22</td>
</tr>
</tbody>
</table>

Comparison:
At the very first observation, comparing the case of Bangalore (Table 5) to Ahmedabad (Table 1), the highest annual cooling energy consumption at setpoint 22°C for COP 2 is 103 units for Ahmedabad whereas as it is as low as 84 units for the case of Bangalore. By changing the COP value from 2 to 3, the reduction in cooling energy consumption is 29 units for Bangalore whereas the reduction is more
significant (35 units) in case of Ahmedabad. For COP 3, there is a reduction of on an average 4 units per degree setpoint temperature in Bangalore. In case of Ahmedabad the difference is of 2 units. Bangalore and Guwahati (Table 6) shows a very similar consumption pattern for all temperatures and COP values with a difference of 3 to 4 units, Bangalore being the lowest. Likewise, Chennai and Ahmedabad shows similar trend of consumption, Ahmedabad being the highest of all the cities (Table 4).

CONCLUSION

The most important observation of this study is that, low cooling setpoint temperature does not contribute significantly in lowering the cooling energy consumption at higher COP value of the PTAC cooling system. This is, however, true only for systems with average or low efficiency. The study proves through quantification the importance of using appropriate COP for achieving cooling energy savings while maintaining thermal comfort.

The outdoor environment also plays an important role in determining the trade-offs between comfort and cooling energy consumption. For instance, it was observed that Ahmedabad and Chennai had the highest cooling energy consumption of 103 and 97 units at COP of 2 and setpoint 22°C, whereas Bangalore, Guwahati and Delhi show almost 8 to 10 units less cooling energy consumption for the same cooling setpoint and COP values.

Another important observation for each city is that the comfort levels at 24°C and 25°C are more or less the same (more than 50% of the occupants feel neutral on PMV scale). 24°C setpoint consumes almost 6% higher cooling energy annually than 25°C (Table 3) so one can make a decision of maintaining one degree higher and contribute in saving cooling energy consumption.

ACKNOWLEDGMENTS

The authors are thankful to Saket Sarraf for his help with the statistical analysis of the simulation results.

REFERENCES


THERMAL COMFORT IN HOUSING OF THE METROPOLITAN AREA OF THE VALLEY OF MEXICO

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[Universidad Autonoma Metropolitana] [Universidad Autonoma Metropolitana] [Universidad Autonoma de Baja California]

ABSTRACT

This research is based on the principles of adaptive focus. In this document, the results of the field research on thermal comfort regarding housing produced in series are presented. The survey was conducted in the municipalities of the Metropolitan Area of the Valley of Mexico that have presented the most urban growth in the last 10 years. Measurement times were determined according to bioclimatic analysis: cold, warm and transition. The environmental variables, such as dry bulb temperature, wet bulb temperature, black globe temperature, relative humidity and wind speed in the living room of the houses, were measured while, simultaneously, 426 surveys about thermal sensation were conducted to the inhabitants. The questionnaire was performed according to ISO 10551 and ASHRAE 55 Regulations. The annual neutral temperature in naturally ventilated houses in the Metropolitan Area of the Valley of Mexico is 21.3°C and extensive thermal comfort limits are 16.0°C and 26.7°C. The Mexico’s Energy Efficiency Standard in residential buildings, NOM 020 ENER-2011, suggests that the ideal temperature for interiors is 23°C, which is inconsistent with the neutral temperature resulting from the investigation; therefore, considering it favors the use of artificial devices for air conditioning and the energetic cost of housing.

INTRODUCTION

The purpose of the neutral temperature and ranges of thermal comfort in the housing of the Metropolitan Area of the Valley of Mexico, allows the development of tools and information that is useful for the planning and designing of houses which promote the thermal comfort wellbeing of residents. The perception of thermal comfort is important for carrying out activities without compromising the physical and mental performance of the subjects, however, if the thermal environment does not provide the right conditions, the subjects can take action to adapt or reduce the length of their stay in that space (Bojorquez Morales, 2010).

The ASHRAE 55-2004 Regulation incorporates the method for determining acceptable thermal conditions in naturally ventilated environments. This method was based on work done by de Dear and Brager (1998), in which several climatic zones were analyzed, each in different countries and buildings. However, data from countries in Latin America and Mexico are not included. In order to establish standards for thermal comfort, in the last years there have been investigations on thermal comfort in countries that were not included in this rule; Japan (Bahadur, 2013), China (Wang, et al., 2010), and several cities with warm weather in Mexico (Gomez Azpeitia, et al., 2009).
This investigation is based on the focus of adaptation, since it allows to evaluate, both, the subjects’ perceived thermal sensation in a natural environment and the psychophysiological reactions generated to feel comfort.

The climate analysis determined the study periods: cold (December-January); warm (May); and transition (October-November, March). The field work consisted in conducting surveys, regarding thermal perception, to residents of municipalities with the highest urban expansion in 10 years. During the three periods, 377 observations were obtained.

**METHOD**

The investigation was divided in three stages: 1) Site Analysis, in which the urban growth in the Metropolitan Area of the Valley of Mexico (MAVM) was diagnosed to determine areas of study, and a description of the climate to show environmental conditions was made; 2) Correlational Study, in which the measurement periods, variables and instruments were defined; and the questionnaire and the sample was designed; 3) Data Analysis, which was by an unconventional method of regressional statistics by layers.

1. Site Analysis

The selected municipalities are the top ten municipalities with the highest population growth in the last ten years. As shown in Table 1, the number of houses built is greater than 5,000. The condition in order to be among the selected was that the average annual temperature could not present variations greater than 1°C. The field study was conducted in houses produced in series of the municipalities of: Tecamac, Nicolás Romero, Cuautitlán Izcalli, Tultitlan and Huehuetoca.

Table 1. Location Description

<table>
<thead>
<tr>
<th>#</th>
<th>LOCALITIES</th>
<th>HOUSING (N)</th>
<th>LATITUDE (N)</th>
<th>LONGITUDE (W)</th>
<th>ALTITUDE (m.a.s.l.)</th>
<th>LOW TEMP.</th>
<th>AVERAGE TEMP.</th>
<th>HIGH TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tecamac</td>
<td>132,275</td>
<td>19°39'24&quot;</td>
<td>99°01'02&quot;</td>
<td>2,340</td>
<td>6.9</td>
<td>15.6</td>
<td>24.4</td>
</tr>
<tr>
<td>2</td>
<td>Nicolás Romero</td>
<td>15,012</td>
<td>19°34'52&quot;</td>
<td>99°16'42&quot;</td>
<td>2,360</td>
<td>6.9</td>
<td>15</td>
<td>23.1</td>
</tr>
<tr>
<td>3</td>
<td>Cuautitlán Izcalli</td>
<td>11,964</td>
<td>19°42'16&quot;</td>
<td>99°13'09&quot;</td>
<td>2,365</td>
<td>7</td>
<td>15.6</td>
<td>24.1</td>
</tr>
<tr>
<td>4</td>
<td>Huehuetoca</td>
<td>7,653</td>
<td>19°41'03&quot;</td>
<td>99°07'36&quot;</td>
<td>2,245</td>
<td>6.1</td>
<td>14.9</td>
<td>23.5</td>
</tr>
<tr>
<td>5</td>
<td>Tultitlan</td>
<td>7,305</td>
<td>19°50'55&quot;</td>
<td>99°12'45&quot;</td>
<td>2,258</td>
<td>6.1</td>
<td>14.8</td>
<td>23.5</td>
</tr>
</tbody>
</table>

Table 1 shows the location of the municipalities, minimum temperatures, average and annual maximums, as well as the number of built houses which were produced in series.

2. Correlational Study

The questionnaire on thermal sensation was designed according to the ISO 10551 Regulation, using the 7-point scale (Table 2); and proposed in the study "Thermal comfort and Energy Savings in Affordable Housing in Mexico" (Azpeitia Gómez, et al., 2009), based on the previous rules.

Table 2. Thermal sensation scale by ISO 10551

<table>
<thead>
<tr>
<th>#</th>
<th>VALUE</th>
<th>COMFORT VOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>3</td>
<td>Hot</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>Warm</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>Slightly warm</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
<td>Slightly cool</td>
</tr>
<tr>
<td>2</td>
<td>-2</td>
<td>Cool</td>
</tr>
<tr>
<td>1</td>
<td>-3</td>
<td>Cold</td>
</tr>
</tbody>
</table>
The survey was conducted on healthy subjects from 15 to 60 years of age, with average levels of clothing from 0.30clo to 1.5clo. The subjects were grouped into three levels of physical activity: passive or resting, from 0 to 75W/m², moderate with 76W/m² to 180W/m² and severe, greater than 185W/m²; simultaneously the surveys were measured by the following variables: dry bulb temperature (TBS), wet bulb temperature (TBH), black global temperature (TGN), relative humidity (RH) and wind speed (VV); the measurements were performed with a heat stress monitor, which according to the ISO 7726 (1998) Regulation the information obtained is classified in Group I.

To determine the study periods, de Dear’s and Brager’s (1998) neutral temperature equation ± 2.5K was applied to normal weather of the before mentioned municipalities. The periods are shown in Table 3. The study sample was determined by the amount of affordable housing built and the total population of people of the ages between 12 and 60 years of the MAVM. It was decided, based on statistical data, that the sample should include at least 120 people per measurement period. The selection of subjects who were surveyed was random within housing developments, and deterministic, since the subjects were the ones who chose to part take or not part take in research.

<table>
<thead>
<tr>
<th>ZONE</th>
<th>PERIODS</th>
<th>MONTHS</th>
<th># OF SAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAVM*</td>
<td>Transition</td>
<td>October</td>
<td>152</td>
</tr>
<tr>
<td>MAVM*</td>
<td></td>
<td>November</td>
<td></td>
</tr>
<tr>
<td>MAVM*</td>
<td></td>
<td>March</td>
<td></td>
</tr>
<tr>
<td>MAVM*</td>
<td>Cold</td>
<td>December</td>
<td>135</td>
</tr>
<tr>
<td>MAVM*</td>
<td></td>
<td>January</td>
<td></td>
</tr>
<tr>
<td>MAVM*</td>
<td>Warm</td>
<td>May</td>
<td>139</td>
</tr>
<tr>
<td>MAVM*</td>
<td></td>
<td>June</td>
<td></td>
</tr>
</tbody>
</table>

*Selected locations of the Metropolitan Area of the Valley of Mexico

For the conducting of the surveys, students of the Universidad Autónoma Metropolitana were trained and trial surveys were conducted to improve the application method and become familiar with the measuring equipment. Fieldwork was conducted from 09:00 hrs. to 19:00 hrs. and the data collected on site were captured using an Excel database to facilitate statistical analysis.

3. Data Analysis

The statistical method of analysis, was a nonconventional method of linear regression by layers, developed by Gómez-Azpeitia et al. (2007), was based on Nicol’s (1993) proposal. The main difference with the conventional method is that prior to obtaining the regression, the sample is grouped by levels of perceived thermal sensation. After obtaining the average values of temperature (TMean) and standard deviation of the responses for each level of perceived thermal sensation, distribution ranges are establishes for each response category from the value of the corresponding TMean and adding or subtracting 1σ, representing 68% of the population whom expressed the same thermal sensation; the adding procedure is repeated, this time by adding or subtracting 2σ, representing 95% of the population.

Finally, the linear regression is done with the series of values of TMean, ±1σ and ±2σ of each thermal sensation. The intersection of each of the regression lines with the ordinate four (corresponding to the thermal comfort sensation) determines the value of the neutral temperature, as well as the limits of the comfort zone. In this method, what determines the validity of the regression, is the determining coefficient resulting of the straight line (R²); this value ranges from 0 to 1, while it is closer to one, the value obtained has more representation on the sample, in other words, greater validity.
Figure 1 shows the graphs obtained from the data analysis collected from the field work done under the above mentioned method; TMean regression lines are observed, ±1σ and ±2σ, like the intersection of these, with the value of 4 for the ordinate y, which gives origin to the neutral values of temperature and thermal comfort range.

Figure 1. Determination of Tn and the comfort ranges by non-conventional method of statistical regression by layers in Metropolitan Area of Mexico. (a) Cold period (b) Transition period (c) Warm period (d) Annual

Figure 1a shows that the regression lines of -2σ y -1σ visually are parallel to the average line of regression, however, they are slightly convergent as the sensations increased from 2 to 4, which represents that the thermal perception of temperatures less than 22.2°C is similar in all the sensations. Lines +2σ and +1σ have the same behavior but with steeper slopes, indicating that when the temperature is above 22.2°C the capability of adaptation is reduced during cold sensations. Figure 1b shows some observations outside the limits of comfort sensations 6 and 7 to the limit +2σ, which indicates that most subjects have a preference for temperatures below 27.2°C. The regression lines ±1σ and ±2σ are divergent in regards to the mean regression line as the cold sensation increases, which indicates that subjects are better able to adapt to these conditions in the warm period.

In Figure 1c, the regression lines -2σ y -1σ are visually parallel to the average regression line, however, are slightly convergent as the sensation increases from 6 to 7, the opposite occurs with the regression lines +2σ and +1σ which are slightly convergent to the sensations of cold; indicating that when temperatures
are below 22.9°C the subjects show less adaptability to the sensations of heat, and the opposite occurs when they are higher. Figure 1d shows that the regression lines of ±2σ and ±1σ are divergent to the regression line Tn average as the thermal sensation of cold increases, which indicates that each year there is more capability of adaptation to these conditions; however sensations 3 and 2 show greater scatter in the data, which is possibly due to clothing levels and metabolic activity of the subjects; the levels of activity in these sensations were: 40% while resting, 55% in moderate work and 5% during intensive work; while 80% of the subjects were dressed between normal and snug (from 0.60 to 1.0clo).

RESULTS

The resulting values of the above analysis are presented in Table 4; the neutral temperature, reduced and extensive limits of the thermal comfort zone and degrees of openness each study period has are shown. It is observed that the lowest value of Tn is the transition period, this is because in these months the weather has greater fluctuation, making it difficult for subjects to adapt to the thermal conditions; the highest value is observed in the cold period, which means that subjects have greater adaptation to thermal conditions that occurred in this period, which is consistent with the mild climate of the MAVM. The neutral temperatures resulting from the analysis in each period have a difference = or <5%; however, as shown in Table 4, the lowest value of Tn is given in the annual evaluation, since this one takes into account all the observations.

Table 4. Comfort temperatures and ranges determined in the field study

<table>
<thead>
<tr>
<th>ZONE</th>
<th>PERIOD</th>
<th>Tn</th>
<th>COMFORT CLOSE RANGE</th>
<th>COMFORT WIDE RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower Limit</td>
<td>Upper Limit</td>
</tr>
<tr>
<td>MAVM*</td>
<td>Transition</td>
<td>22.9</td>
<td>21.1</td>
<td>24.5</td>
</tr>
<tr>
<td></td>
<td>Cold</td>
<td>22.2</td>
<td>19.6</td>
<td>24.9</td>
</tr>
<tr>
<td></td>
<td>Warm</td>
<td>23.4</td>
<td>20.7</td>
<td>25.6</td>
</tr>
<tr>
<td></td>
<td>ANNUAL</td>
<td>21.3</td>
<td>18.7</td>
<td>24.0</td>
</tr>
</tbody>
</table>

* Selected locations of the Metropolitan Area of the Valley of Mexico

Table 5 shows the comparative analysis of neutral temperatures obtained with the equations proposed by different authors; it is apparent that in all the periods the neutral temperature resulting from this research is more the others, therefore, suggests an adjustment to the models of assessment of thermal comfort for the mild climate of the MAVM. However, the Tn results of de Dear’s and Brager’s (1998) equation, has a smaller difference of 1°C with the results obtained, which is an indicator for validating data through the application of ASHRAE Standard 55-2004.

Table 5. Comparative chart of comfort temperatures calculated by different authors

<table>
<thead>
<tr>
<th>ZONE</th>
<th>PERIODS</th>
<th>To*</th>
<th>Neutral Temperature (Tn)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Humpeys</td>
</tr>
<tr>
<td>MAVM</td>
<td>Transition</td>
<td>14.3</td>
<td>19.7</td>
</tr>
<tr>
<td></td>
<td>Cold</td>
<td>11.6</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td>Warm</td>
<td>17.5</td>
<td>21.4</td>
</tr>
<tr>
<td></td>
<td>ANNUAL</td>
<td>15.1</td>
<td>20.1</td>
</tr>
</tbody>
</table>

*To: monthly average outdoor temperature

Finally the method was applied to determine the acceptable thermal conditions in naturally ventilated spaces (ASHRAE Standard 55-2004). Figure 2 shows the analysis through period of acceptable operating temperatures. It is observed that the thermal conditions of the houses fall in the range of 90% acceptability of this standard.
Figure 2. Acceptable operative temperature ranges by study period in naturally ventilated housing in MAVM (ASHRAE Standard55, 2004).

CONCLUSIONS

The ability to adapt to the thermal environment of houses built in mass production in the Metropolitan Area of the Valley of Mexico, is now higher; considering that 94% of the subjects said that the environment of their home was acceptable; nevertheless, only 48% said they felt comfort, possibly due to physical factors that were not evaluated in this investigation.

The annual neutral temperature in housing produced in series with natural ventilation in the Metropolitan Area of the Valley of Mexico is 21.3°C, with a narrow range of ± 2.7°C thermal comfort, for that reason it is suggested to make the appropriate amendments to Mexico’s Energy Efficiency Standard, NOM 020-ENER-2011, which suggests an internal temperature of 23°C, hence, favors the use of active devices to acclimatize spaces.

Finally, the study validates the use of the adaptive method of ASRAE 55-2004 Standard to determine the thermal comfort conditions of the houses in the Metropolitan Area of the Valley of Mexico.

ACKNOWLEDGMENTS

This research was supported by the PROMEP project, “Lineamientos para el confort y desempeño energético de la vivienda urbana” ("Guidelines for the comfort and energy performance of urban housing"). I would like to extend my gratitude to the Universidad Autonoma Metropolitana, to all those who participated in the study and made possible its progress, to the people who conducted the surveys and partook in the fieldwork and to my partner, April Rueda, for her important collaboration and support in this investigation.

REFERENCES


Session 5D : Tools and methods/ framework

PLEA2014: Day 2, Wednesday, December 17
11:30 - 13:10, Trust - Knowledge Consortium of Gujarat
Empirical and software verification of a simplified predictive model of luminous efficiency of light-pipes

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ABSTRACT
This article presents the verification of a mathematical model for predicting the luminous efficiency of light-pipes, based on the principle of unit hemisphere and solid angles. For this, light-pipes were simulated in the software photopia and essayed under real sky conditions. The adopted method in this research is theoretical deductive, developing a luminous efficiency predictive model of light-pipes and its complementation by the lumens methods. In order to verify the results, an empirical inductive method was applied, considering physical models under real sky conditions. In addition to the empirical results, simulations were carried out in raytracing software Photopia. The first method calculates the value of the relationship (LPE) between the availability of light in the central point in the output section of the light-pipe and that in the horizontal plane of its entrance. The high correlation found between results from the measured data and results from the proposed luminous efficiency predictive model of light-pipes (LEPMLP) with the results obtained from the software Photopia, in terms of estimated values of light-pipes efficiency (LPE), showed that it is a reliable tool and is easily applicable for dimensioning this kind of system for taking advantage of daylighting in everyday architectural and building design practice, allowing to deliver daylight to rooms without direct contact with the external environment.

INTRODUCTION
The global scenario has been changing with the exigencies of the environment resources, which were used by past generations inconsequently. Currently, the concern for the planet and future generations puts emphasis on the use and development of efficient products that consume or use clean or renewable energy. In this context, light-pipe systems are developed to conduct the daylight to internal environments far from the envelope, as, for example, rooms without direct contact with the external environment or in undergrounds.

Considering the advances in researches, new technological innovations have been developed to bring daylight to indoor environments. A variety of devices aimed at lighting were designed and researched to improve the quality of daylighting to increase user acceptance and provide tools for designers to specify and size these systems.

Kocifaj et al. (2008) observe that beginning research on products of light had interest in the innovative system, seeking to eliminate the deficits and gaps offered by conventional systems openings. In the beginning, installed systems have been researched and prototypes as a "black box" comparing the performance of the system as a whole with other systems. Within this group are works such as: Al-Marwae & Carter (2006), Oakley et al. (2000). In a second step the interest of the academic community becomes more specifically to the driver turning his scientific interests to the efficiency of those seeking to unravel the behavior of light to be conducted this phenomenon and propose predictive
models resulting in the prediction of the efficiency of light transmission along the conductor and several theoretical predictive mathematical models and semi-empirical. Esse in the case of papers presented by Swift & Smith (1995), Swift et al. (2008) and Luz et al. (2010). Finally, recently, in the third stage of the research for the products of light, the interest is focused on the transport of light from the diffuser (commonly placed at the exit of the pipe-line) to the work plan or a point in this internal environment.

These searches are resulting predictive mathematical and computational models of the luminous efficiency by providing data on the luminous flux emitted by the environment in pipelines, and distributed illuminance on the working plane in lux. This allows the comparison of these systems with artificial lights and allows you to choose when you design with precise image scaling of the lighting system, allowing the association between daylighting and artificial lighting. The predictive models of light pipe efficiency have been developed by several researchers. S-DPF e E-DPF (Zhang, Muneer & Kubier, 2002), Universidade de Liverpool (Carter, 2002), Luxplots (Jenkins & Muneer, 2003), CIE Method (CIE 173, 2006). Dutton and Shao (2007) validate the software Photopia as a tool to predict the performance of pipelines, comparing this with six existing predictive methods (Wittwer, 1986; Swift & Smith, 1995; Edmonds, 1995 and Zhang et al., 2002, Jenkins & Muneer 2003, and Carters, 2002). This work presents the verification of a mathematical model for predicting the luminous efficiency of light-pipes (LEPMLP), in comparison with the results of raytracing simulation on Photopia software.

The LEPMLP was based in the principle of projected solid angle or unit hemisphere. This principle is used by many graphic methods in order to obtain information on the sky component. Allowing the determination of its value even in situations in which the area of the luminous source is constituted by irregular forms (Hopkinson et al., 1975).

The objective of this paper is the use raytracing simulation (Photopia) to verify a mathematical simplified model that friendly estimates the light-pipe efficiency (LPE). For this, light-pipes were simulated in the software Photopia and tested under real sky conditions.

PREDICTIVE MODEL OF LUMINOUS EFFICIENCY OF LIGHT-PIPES (LEPMLP)

It was adopted the condition of uniform sky as source of daylight. The input section of the light-pipe is considered an emitter plane, which luminance is gathered in a horizontal unobstructed plan (considering a real situation).

The developed model predicts the value of the light-pipe efficiency (LPE), which is the ratio, in percentage, of illuminance in the output section and the available illuminance in the input section. The ratio is obtained through the sum of the illuminances in the output section of the light-pipe, arising from the luminance of the input section, as well as from the luminance of the reflected images in the mirrors, considering the successive losses due to absorption in the multiple reflections through the light-pipe.

The adopted procedure to consider the contribution of each image of the primary source (input section) is the projection of the images in the unit hemisphere considering the solid angle constituted by the input section and the centre point of the output section of the light-pipe. It’s to say that luminance of the input section and its reflections in the mirrors are delivered to the unit hemisphere.

The projected luminances in the unit hemisphere are in solid angles, constituting with the light-pipe vertical central axis angles (θi), which are the vertices of rectangles triangles, which base is the segment [(b+i)+b/2], where b is the input section length, and the height (h) is the length of the light-pipe. The value of the angle θi is determined by Equation 1.

$$\theta_i = \arctan\left(\frac{i + \sqrt{2}}{2} \cdot \frac{b}{h}\right)$$  \hspace{1cm} (1)

where: i is the number of reflections in the length of the pipe-light, or in other words, the number or images projected in the unit hemisphere; b is the input section length; h is the length of the light-pipe.

The projected luminances in the unit hemisphere produce circular sectors in the base of such hemisphere, which areas (Ai) (annulus) are defined by Equations 2 and 3.

$$a_i = \sin \theta_i \cdot r$$  \hspace{1cm} (2)

$$A_i = (a_i^2 - a_{i-1}^2) \cdot \pi$$  \hspace{1cm} (3)

where: Ai is the apparent area of the annulus; ai and ai-1 are the radius of the concentric circles determined by the projected luminances; r is the radius of the hemisphere (in this specific case, r=1).
Figure 1. Projected luminances in the unit hemisphere

Figure 2. Annulus
The illuminance $E_i$ is the contribution of each annulus. The sum of $E_i$ for all annuli is the illuminance gathered in the central point of the output section, or it is to say, in the central point of the unit hemisphere. $E_i$ is determined through Equation 4.

$$E_i = A_i \cdot L_0 \cdot \rho^i$$  \hspace{1cm} (4)

where: $E_i$ is the illuminance of the annulus; $A_i$ is the area of the annulus; $L_0$ is the luminance in the light-pipe input section; $\rho$ is the light-pipe internal reflectance. Considering the previous four equations, one may obtain the equation 5.

$$LPE = \frac{E_p}{E_{ext}} = \frac{\sum_{i=0}^{n} E_i}{\pi \cdot L_0}$$  \hspace{1cm} (5)

where: LPE is the light-pipe efficiency; $E_p$ is the light-pipe output section illuminance; $E_{ext}$ is the available illuminance in the unobstructed horizontal plane; $E_i$ is the annulus illuminance; $L_0$ is the light-pipe input section illuminance; $n$ is the number of the emitter plane reflections.

Mathematically, substituting equation 1 into 2, one obtains Equation 6.

$$a_i = \sin \cdot \tan \left[ \left( i + \frac{1}{2} \right) \cdot \frac{b_i}{h} \right]$$  \hspace{1cm} (6)

Substituting equation 6 into 3, one obtains Equation 7 and Equation 8.

When $i = 0$;

$$A_0 = \sin^2 \cdot \tan \left( \frac{1}{2} \cdot \frac{b}{h} \right) \cdot \pi$$  \hspace{1cm} (7)

When $i > 0$;

$$A_i = \left\{ \sin^2 \cdot \tan \left[ \left( i + \frac{1}{2} \right) \cdot \frac{b_i}{h} \right] - \sin^2 \cdot \tan \left[ \left( i - \frac{1}{2} \right) \cdot \frac{b_i}{h} \right] \right\} \cdot \pi$$  \hspace{1cm} (8)

Substituting equations 7 and 8 into 4, one obtains Equation 9 and Equation 10.

When $i = 0$;

$$E_0 = \sin^2 \cdot \tan \left( \frac{1}{2} \cdot \frac{b}{h} \right) \cdot \pi \cdot L_0 \cdot \rho^0$$  \hspace{1cm} (9)

When $i > 0$;

$$E_i = \left\{ \sin^2 \cdot \tan \left[ \left( i + \frac{1}{2} \right) \cdot \frac{b_i}{h} \right] - \sin^2 \cdot \tan \left[ \left( i - \frac{1}{2} \right) \cdot \frac{b_i}{h} \right] \right\} \cdot \pi \cdot L_0 \cdot \rho^i$$  \hspace{1cm} (10)

Substituting equations 9 and 10 into 5, one obtains Equation 11, in order to predict the light-pipe efficiency (LPE).

$$LPE = \sin^2 \cdot \tan \left( \frac{1}{2} \cdot \frac{b}{h} \right) + \sum_{i=1}^{n} \left\{ \sin^2 \cdot \tan \left[ \left( i + \frac{1}{2} \right) \cdot \frac{b_i}{h} \right] - \sin^2 \cdot \tan \left[ \left( i - \frac{1}{2} \right) \cdot \frac{b_i}{h} \right] \right\} \cdot \rho^i$$  \hspace{1cm} (11)

The absolute values of LPE, obtained by equation 11, can be also considered in percentage values, as it is commonly used with the daylight factor (DF).
SOFTWARE SIMULATION

Photopia is a general 3D luminaire design and analysis program specifically designed for non-imaging and illumination optical systems. Photopia’s calculation basis is probabilistic raytracing, using real lamp geometries and measured intensity distributions, as well as measured directional reflectance and transmittance data for luminaire materials. User specified analysis settings allow for quick or detailed analyses of the luminaire design. In addition, all calculated output is available for viewing as calculations are in progress via a display update facility. In this way, a user can observe evolving output as a function of a specified percentage of the total analysis process.

Photopia includes “lamp” models for use in modeling daylight input into devices such as skylights, light pipes, solar collectors and room windows using daylight control systems. These source (lamp) models are based on the IESNA RP-21 daylight equations that model the absolute illuminance from the sun (solar disk) at various altitude angles and the sky for various sky conditions and solar altitude angles. The sky domes include variable luminance values across the hemisphere as described in RP-21. The sun models include a 0.53 deg. spread in their beam to model the actual angular size of the solar disk, averaged over its elliptical orbit. The combination of both the sun and sky dome models produces a total illuminance onto the daylighting device area that is intended to match real outdoor conditions. Keep in mind that real conditions can vary widely and the RP-21 equations represent average conditions. Such variability is what makes consistent physical measurement of daylight devices such a challenge and is one reason why daylight simulation is desirable.

Using the daylight source models is different than using the electric lamp models in Photopia’s library since the daylight models illuminate the outside of a device to get light into it instead of illuminating a luminaire from within.

The default sky dome models are configured so that they uniformly illuminate about a 4’ diameter area. Because of the way the light is emitted from the sky dome patches, light does spread beyond this 4’ circle but it fades to a much lower level. In order to fully illuminate your device and also maximize the portion of sky dome rays that enter your device this model should also be scaled up or down depending on your device size relative to this 4’ circular reference.

Since the sun and sky dome models will produce some rays that don’t enter the daylight collection device, the complete model generally needs to include a shield so that the output of the device is isolated from the source models’ stray light. The sky domes are relatively large in diameter since they need to generate a relatively even illuminance over an area large enough to accommodate the daylighting device. They concentrate most of their light toward the center of the hemisphere, but some light also strays away from the center. Only that light falling near the center of the hemisphere accurately models the way light is received from the sky dome.

The sky domes are relatively large in diameter since they need to generate a relatively even illuminance over an area large enough to accommodate the daylighting device. They concentrate most of their light toward the center of the hemisphere, but some light also strays away from the center. Only that light falling near the center of the hemisphere accurately models the way light is received from the sky dome.

The efficiency (LOR) shown in the Photopia report will be the ratio of the lumens exiting the skylight divided by the total lumens produced by the sun and sky dome models. The total lumens produced by the sun and sky dome models is very large compared to the total number of lumens that are actually incident onto the daylight device. A more appropriate measure of the device efficiency is the ratio of the lumens exiting the device divided by the number of lumens incident onto it.

The studies presented by DUTTON & SHAO (2007) showed good results in using this software for predicting the performance of pipelines bright light compared to existing mathematical models. The simulations presented here, aimed to predict the transmittance of light through light pipes. For both pipelines were simulated with 36 input section ranging from 10cm, 20cm, 25cm, 30cm, 40cm and 50cm and lengths ranging from 1m, 1.5m, 2m, 3m, 4m and 5m.

DATA TREATMENT

Photopia provides a photometric report in which the luminous flux emitted by the luminaire is given. This report also shows the efficiency of the light, but in the case of the pipeline. This efficiency is false because the Photopia calculates it based on total luminous flux produced by the light source, in which case the pipe-line is the celestial vault. Thus, the value of the efficiency of a lamp is always the ratio between the total fixture lumens coming out of the total lumens generated by the sources (lamps). In the case of designs that use daylight, this result does not match the efficiency of the lamp itself, in order that the source light does not emanate from within the machine but from outside. Thus, as only a small fraction of this light is captured through the pipe-line, the calculated result is usually negligible.
Therefore, it is necessary to know the value of the luminous flux that actually enters the pipe-line so that one can calculate the correct efficiency. To calculate the luminous flux entering the pipe-line light is necessary to calculate the horizontal illuminance at the opening of the pipe-line (lm/m²) and multiply it by the area of the opening.

Photopia provides an Excel spreadsheet for this calculation. This is the "Daylighting Calculator" option that is on the menu "Help". This tool provides two options for sky condition, with sun or no sun and two choices of units of measure to be chosen, the international system and the Imperial system for the simulations was chosen the international metric system, the units are in meters, lumens and lux. For these simulations we used the "Enter Altitude Solar" option because this option, simply enter the angular position of the sun and the area of the inlet opening of the collector, the spreadsheet calculates the luminous flux entering the pipe-line.

The Daylighting Calculator spreadsheet only requests diameter header pipe because it is assumed that the shape of the device is round. As the simulated pipe-lines were square in section, the area of the section was calculated and then multiplied by the value of the horizontal illuminance average daylight in the pipe-line. The average horizontal illuminance is calculated by the referred spreadsheet.

\[ \phi_{in} = E_{média} \cdot A \]  

(12)

Where: \( \phi_{in} \) is the total luminous flux entering the pipeline; \( E_{média} \) is the mean horizontal illuminance; \( A \) is the entrance area of the pipeline.

Having obtained the luminous flux input, calculated by "Daylighting Calculator" (\( \phi_{in} \)), the value of the total flux emitted by the product of light at the end of the simulation (\( \phi_{out} \)) Photometric report and calculate the efficiency of the light pipe (in terms of percentage) by the following equation.

\[ E = \frac{\phi_{out}}{\phi_{in}} \cdot 100 \]  

(13)

where: \( E \) is the light-pipe efficiency (LPE); \( \phi_{out} \) is the luminous flux from the light pipe.

MEASUREMENTS

For the empirical research nine light-pipes, made of wood coated by mirror (optimirror plus, reflectance \( \rho=0.86 \)), with square sections of 10cm, 25cm and 40cm and lengths of 100cm, 150cm and 200cm were considered.

The mathematical model considers a theoretical uniform sky, thus in order to approximate the conditions of a real sky to the considered model, it was considered a real unobstructed overcast sky through the use of acrylic diffusers in the input section of the light-pipes.

The empirical field researches were done during 22/04/2009 and 06/05/2009.

Figure 3. Light-pipes of the empiric field research.

In order to log the data, digital luximeters HOMIS model 824 were used. They were set in the central spot of the input and output section of the light-pipes (respectively P1 and P2 in Figure 4). The data were collected in each point and each light-pipe one at a time, considering, as a reference, an external luximeter, measuring simultaneously the unobstructed horizontal plane.
COMPARATIVE RESULTS

The results obtained in the simulations with 36 pipelines were compared with a real scale model under real sky condition (LUZ, 2009) and with results calculated using the luminous efficiency of light pipes predictive model (MPELD. These comparisons are presented in the following figures.

Figure 5. Correlation between predicted and measured LPE (light-pipe efficiency).

![Figure 5. Correlation between predicted and measured LPE (light-pipe efficiency).](image)

Figure 6. Correlation between predicted and simulated LPE (light-pipe efficiency).

![Figure 6. Correlation between predicted and simulated LPE (light-pipe efficiency).](image)
Figure 7. Correlation between predicted and simulated LPE (light-pipe efficiency).

CONCLUSION

The high correlation found between results from the measured data and results from the proposed luminous efficiency predictive model of light-pipes (LEPMLP) with the results obtained from the software Photopia, in terms of estimated values of light-pipes efficiency (LPE), showed that the model is a reliable tool and is easily applicable for dimensioning light-pipes, taking advantage of daylighting in everyday architectural and building design practice, allowing to deliver daylight to rooms without direct contact with the external environment.

ACKNOWLEDGMENTS

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Development of a High-resolution Meteorological Model for Urban Heat Island Effect Assessment

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ABSTRACT

Facing rapid urbanization, sustainable urban developments become important in urban planning. To tackle urban climate issues in a planning context, a meteorological model with high resolution is useful for evaluating different planning scenarios. This study used the Weather Research and Forecast (WRF) with a single-layer urban canopy model to simulate summer meteorological conditions in Hong Kong, downscaling the spatial resolutions from 4.5 km to 500 m. Hong Kong (HK) was taken as an example due to its high building density in a sub-tropical climate region. The model results were compared against measurements at 25 weather stations. We quantified the urban heat island effect (UHI) in the summer in 2009, and estimated the resultant health impacts based on a temperature-response function. The model results and measurements show a good agreement with an index of agreement of 0.71 and a percentage difference of mean temperature of 1.33%. Our analysis estimated that the hourly temperature in urban areas (29.6°C) is higher comparing to that in rural areas (28.1°C). The Urban Heat Island Intensity (UHII) was estimated to be 1.6°C on average. The UHI results in different Primary Planning Units show a north-south gradient pattern over Hong Kong: the highest UHII (1.7°C) in northern part of HK, whereas the lowest UHII (0.8°C) in southern part of HK. We found UHII correlates well with urban area size instead of population, highlighting that policy makers of high-density cities should pay attention to urban area size when tackling UHI. In addition, UHI was estimated to cause 75 [95%C.I. 22-158] mortalities in summer. Of which, ~55% of the UHI-related health impact occurs in New Territories, while 39% and 6% of the impact happen in Kowloon and Hong Kong Island, respectively. The results provide critical implications for urban planners to mitigate UHI in cities, especially in less developed countries.

NOMENCLATURE

PPU  Primary Planning Units
TPU  Tertiary Planning Units
UHI  Urban heat island effect
UHII  Urban Heat Island Intensity

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INTRODUCTION

Urban heat island effect (UHI) is one of the major environmental problems in urban areas. Increases in temperature were found to have impacts on energy consumptions, public health and even air quality (Sarrat et al., 2006). According to the United Nations (2012), total urban population is projected to increase to ~67%. Thus, it is of importance to understand the urban heat island effect and the resultant impacts, especially in high-density cities such as Hong Kong (HK) given that the urban infrastructure and building morphology play an important role in the UHI (Rizwan et al., 2008).

Previous studies have shown that UHI was observed in Hong Kong. Memon et al. (2009) examined the reliability of urban heat island intensity (UHII), which was defined as the temperature difference between urban and rural areas. Based on the measurements collected at six weather stations, the study estimated that the mean hourly UHII ranged between 0.8°C and 2.0°C. Giridharan et al. (2004 and 2005) investigated the UHI in urban high-density residential developments in both daytime and nighttime. Based on the measurements on several selected days in the summer in 2002, Giridharan et al. estimated that the magnitudes of UHI within an estate were 1.5°C and 1.3°C in daytime and nighttime, respectively. Although the UHI was estimated in the previous studies, the majority of the studies were based on measurements at sparsely-distributed locations. Thus, the spatial distribution of UHI and the resultant impacts have not yet been fully understood.

Changes in ambient temperature due to UHI may cause heat-related mortality, especially in summer. The health impacts of extreme hot weather events such as heat wave were previously studied (Bai et al., 2014; Zeng et al., 2014; Amengual et al., 2014). For Hong Kong, Chan et al. (2010) employed a statistical approach to investigate the relationship between the heat-related mortality due to changes in ambient temperature. However, the mortality due to UHI was not calculated in the study.

Therefore, this study is aimed at estimating the magnitude of summer UHI in Hong Kong and the resultant heat-related mortality. The results are anticipated to provide critical implications for urban planners and authorities to mitigate UHI in cities, especially for the ones which are being developed in less developed countries such as mainland China.

METHODS

Meteorological Model

![Figure 1](image-url) (a) The three WRF simulation domains. (b) The locations of the 25 HKO monitoring stations. The station names are provided in Table 1.

In this study, two months (Jul and Aug, 2009) were selected to investigate the summer UHI in HK. The Weather Research and Forecast model (WRF) (Skamarock et al., 2008) was used to reproduce the spatial...
distribution of temperature over Hong Kong in the study period. The WRF model has been widely used in urban heat island studies (Chen et al., 2014; Giannaros et al., 2013; Salamanca et al., 2012; Yang et al., 2012). The WRF model was configured to have three one-way domains, using which the meteorology was downscaled from a regional scale to a local scale. Figure 1(a) depicts the WRF domains. The outermost domain (D1) covers most of Guangdong province. D1 has 264×240 grid points with a spatial resolution of 4.5 km. The results of the D1 were then downscaled to the second domain (D2), which encompasses the Pearl River Delta. D2 has 136×124 grid points with a spatial resolution of 1.5 km. The innermost domain (D3) covers Hong Kong. D3 has 130×112 grid points with a spatial resolution of 500 m. A single-layer urban canopy model was adapted to improve the lower boundary conditions and the WRF performance within the urban regions (Masson, 2000). The WRF was configured to have 34 vertical sigma levels from the ground to the model top (50 hPa), with the first 11 layers being concentrated in the first 1 km above the ground level to resolve the structure of meteorology in the planetary boundary layer.

Table 1. The Names and Labels of the 25 Hong Kong Observatory Stations. The Locations of the Stations Are Shown in Figure 1(b).

<table>
<thead>
<tr>
<th>Station name</th>
<th>Label</th>
<th>Station name</th>
<th>Label</th>
<th>Station name</th>
<th>Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheung Chau</td>
<td>CCH</td>
<td>Tai Mei Tuk</td>
<td>PLC</td>
<td>Tuen Mun</td>
<td>TUN</td>
</tr>
<tr>
<td>Ching Pak House</td>
<td>CPH</td>
<td>Shek Kong</td>
<td>SEK</td>
<td>Tsak Yue Wu</td>
<td>YW</td>
</tr>
<tr>
<td>Ping Chau</td>
<td>EPC</td>
<td>Sha Tin</td>
<td>SHA</td>
<td>The Peak</td>
<td>VP1</td>
</tr>
<tr>
<td>Wong Chuk Hang</td>
<td>HKS</td>
<td>Sai Kung</td>
<td>SKG</td>
<td>Waglan Island</td>
<td>GL</td>
</tr>
<tr>
<td>Tseung Kwan O</td>
<td>JKB</td>
<td>Sha Lo Wan</td>
<td>SLW</td>
<td>HKO</td>
<td>HKO</td>
</tr>
<tr>
<td>Kat O</td>
<td>KAT</td>
<td>Tap Mun</td>
<td>TAP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>King's Park</td>
<td>KP</td>
<td>Tate's Cairn</td>
<td>TC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lau Fau Shan</td>
<td>LFS</td>
<td>Ta Kwu Ling</td>
<td>TKL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ngong Ping</td>
<td>NGP</td>
<td>Tai Mo Shan</td>
<td>TMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nei Lak Shan</td>
<td>NLS</td>
<td>Tai Po</td>
<td>TP</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple WRF simulations were conducted with a length of each simulation not exceeding a seven-day period. The results of first 24 hours were discarded as a spin-up period. The land use data was provided by the Lands Department of Hong Kong. The initial and boundary conditions were provided by the 1º×1º NCEP FNL (Final) Operational Global Analysis data (NCEP, 2000) at six-hour intervals.

Measurement data to evaluate the WRF model were provided by the Hong Kong Observatory (HKO). The HKO stations are listed in Table 1 and plotted in Figure 1(b). To quantify the model performance, a set of statistical measures was computed similar to Yim et al. (2007; 2012; 2013).

The UHI was quantified by the Urban Heat Island Intensity (UHII), which represents the temperature difference between urban and rural areas. In this study, non-urban areas (except water bodies) were defined as rural areas. Both hourly and two-monthly mean UHII were estimated based on the WRF outputs. Figure 2 depicts urban areas (brown), non-urban areas (green) and water bodies (blue) in Hong Kong.
Figure 2  A land use map for urban areas (brown), non-urban areas (green) and water bodies (blue) in Hong Kong.

Health Impact

Figure 3  The nine Primary Planning Units (PPU) in Hong Kong. The PPU numbers are marked in the figure. New Territories includes PPUs 3, 4, 5, 6, 7, 8 and 9. Kowloon includes PPU 2, while Hong Kong Island includes PPU 1. The urban heat island intensity (UHII) (°C) values are provided in the brackets.

The health impact due to UHI was estimated based on the Chan et al. (2010). Their study estimated that 1.83% (95% C.I.: 0.73%-3.00%) increase in mortality in Hong Kong is associated with an average of 1°C temperature increase in daily mean temperature above 28.2°C. In their study, the increase of relative risks of heat-related mortality in different areas of residence including Hong Kong Island, Kowloon, New Territories and others were estimated to be 1.43% (95% C.I.: -1.20%-4.30%), 1.36% (95% C.I.: -0.63%-3.47%), 1.40% (95% C.I.: -0.53%-3.43%) and 9.27% (95% C.I.: 1.93%-18.17%), respectively. The areas of residence are depicted in Figure 3.

To estimate the population-exposure to UHI, the daily mean temperature of each day in the study period was overlaid onto the population data in a Tertiary Planning Units (TPU) level provided by the Hong Kong Planning Department. The average daily mortality per 1,000 persons was derived by
dividing the annual mortality rate (6.1 deaths per 1,000 persons) provided by the Centre for Health Protection (2012) by 365 days. Thereafter, based on the aforementioned temperature-response function (Chan et al. 2010), the resultant mortality was estimated. We note that the temperature in indoor environments and the influence of population daily mobility were not taken into account in this study due to lack of data that may result in a higher bias in our results.

Uncertainty

For all the input data in the heat-related mortality calculation, an uncertainty distribution was estimated based on a Monte Carlo simulation, in which a triangular distribution of estimates was constructed on the basis of 10,000 samples. Uncertainty bounds were for a 95% confidence interval.

RESULTS

Model Evaluation

Figure 4 depicts time series plots of temperature at 2 m above ground at two HKO stations: HKO (urban) and TKL (rural). The results show that the modelled temperature agrees well with the measurements. As shown in Table 2, the index of agreement of temperature is 0.71 on average. The percentage difference of mean temperature is 1.33%, indicating that the simulation results are promising for our analyses in this study.

![Figure 4](image)

**Table 2. The Statistical Measures of Model Evaluation.** Obs: Observation; IOA: Index of Agreement; Corr: Correlation coefficient; RMSE: Root Mean Square Bias; MB: Mean Bias; MNB: Mean Normalized Bias; NMB: Normalized Mean Bias; MFB: Mean Fractional Bias; ME: Mean Error; NME: Normalized Mean Error; MNE: Mean Normalized Error; MFE: Mean Fractional Error; MPD: Mean Percentage Difference; DA: Data Availability.

| Station name | Model | Obs | Mean (ºC) | SD (ºC) | Mean (ºC) | SD (ºC) | IOA | Corr | RMSE (ºC) | MB (%) | MNB (%) | NMB (%) | MFB (%) | ME (ºC) | NME (ºC) | MNE (ºC) | MFE (ºC) | NME (ºC) | MFB (%) | ME (ºC) | NME (ºC) | MNE (ºC) | DA (ºC) |
|--------------|-------|-----|-----------|--------|-----------|--------|-----|------|----------|-------|--------|--------|-------|--------|---------|---------|---------|--------|---------|--------|---------|---------|--------|------|
| CCH          |       |     | 28.7      | 1.1    | 28.2      | 2.0    | 0.6 | 0.5  | 1.8      | 0.5   | 2.3     | 2.0    | 2.1   | 1.4     | 5.0      | 5.0     | 5.1     | 2.0     | 5.1      | 2.0     | 99.9   |
| CPH          |       |     | 28.9      | 1.6    | 29.2      | 1.8    | 0.8 | 0.6  | 1.5      | -0.3  | -0.8    | -0.9   | -0.9  | 1.2     | 4.0      | 4.0     | 4.0     | -0.9    | 4.0      | -0.9    | 99.9   |
Temperature Differences between Urban and Rural Areas

Figure 5 depicts the hourly temperature distributions in urban (red) and rural (blue) areas. The results show that the hourly temperature in urban areas (29.6°C) is higher comparing to that in rural areas (28.1°C).

Chan et al. (2010) has found that a unit change in temperature in daily temperature above 28.2°C is critical temperature in this study. Figure 6(a) depicts the daily temperatures in urban and rural areas. We estimated that the daily temperature in urban areas is always (>98%) higher than the critical temperature. However, only ~35% of the time the daily temperature in rural areas exceeds the critical temperature. As shown in Figure 6(b), the mean UHII was estimated to be 1.6°C on average.

Figure 3 depicts the UHII in different Primary Planning Units (PPU). In the figure, a north-south UHI gradient pattern is shown. We estimated that the magnitude of UHI (1.7°C) in northern part (PPU 5 and PPU 6) of HK is the highest among the PPUs. The urban population of the both PPUs, when combined, accounts for 12.6% of the total urban population in HK. The lowest UHI (0.8°C) was estimated to occur in PPU 1, which is located at the southern part of HK. The PPU 2, where its population accounts for 29.6% of total urban population in HK, was estimated to have 1.4°C UHI.

Our estimate shows that the intensity of UHI correlates well with the size of urban areas instead of population. Hong Kong is a high building-density and high-population density city (Ng et al., 2012) due to limited lands for development, and thus its population is not proportional to the size of urban areas. Despite a lower population such as PPU 5 which accounts for only 8.2% of the total HK population, a larger urban area receives more solar radiation and may therefore result in a higher UHII. On the other hand, it should be highlighted that the urban area size pattern is consistent with the UHII pattern as observed in Figure 3. Figure 7 depicts that PPU 5 and 6 have a larger urban area, while PPU 1, 8 and 9 have a smaller urban area. This result indicates that the north-south UHI gradient pattern is associated

<table>
<thead>
<tr>
<th>Location</th>
<th>Mean UHII</th>
</tr>
</thead>
<tbody>
<tr>
<td>HKI</td>
<td>1.6°C</td>
</tr>
<tr>
<td>HKJ</td>
<td>1.5°C</td>
</tr>
<tr>
<td>HKK</td>
<td>1.4°C</td>
</tr>
<tr>
<td>KHL</td>
<td>1.3°C</td>
</tr>
<tr>
<td>KHM</td>
<td>1.2°C</td>
</tr>
<tr>
<td>KHN</td>
<td>1.1°C</td>
</tr>
<tr>
<td>KHO</td>
<td>1.0°C</td>
</tr>
<tr>
<td>KHP</td>
<td>0.9°C</td>
</tr>
</tbody>
</table>

Our estimate shows that the intensity of UHI correlates well with the size of urban areas instead of population. Hong Kong is a high building-density and high-population density city (Ng et al., 2012) due to limited lands for development, and thus its population is not proportional to the size of urban areas. Despite a lower population such as PPU 5 which accounts for only 8.2% of the total HK population, a larger urban area receives more solar radiation and may therefore result in a higher UHII. On the other hand, it should be highlighted that the urban area size pattern is consistent with the UHII pattern as observed in Figure 3. Figure 7 depicts that PPU 5 and 6 have a larger urban area, while PPU 1, 8 and 9 have a smaller urban area. This result indicates that the north-south UHI gradient pattern is associated.
with the pattern of urban area size.

![Figure 5](image1.png)

**Figure 5**  The frequency distribution of hourly temperature in rural (blue) and urban (red) areas in the study period. The x-axis represents temperature (°C), while y-axis represents normalized frequency.

![Figure 6](image2.png)

**Figure 6**  (a) The time series of daily mean temperature (°C) at 2 m above ground in urban (+ in red) and rural (o in blue) areas. (b) The time series of daily urban heat island intensity (UHII) in the study period.
Figure 7  the relationship between area of urban areas (km$^2$) and urban heat island intensity (UHII) ($^\circ$C). The numbers near the data points represent the corresponding Primary Planning Unit number.

Health Impacts

We estimated that UHI causes 75 [95%C.I.: 22-158] mortalities in HK in summer, indicating that ~38 [95%C.I.: 11-79] mortalities are more likely associated with UHI each month in summer. The results show that ~55% of the UHI-related health impact occurs in New Territories, while 39% and 6% of the impact happen in Kowloon and Hong Kong Island, respectively.

DISCUSSIONS

Our results show that HK is affected by UHI in summer, where the mean hourly UHII is 1.6$^\circ$C. This estimate is consistent with Memon et al. (2009), in which mean hourly UHII was estimated to range between 0.8$^\circ$C and 2.0$^\circ$C. According to Leung et al. (2004), the temperature increase rates at an urban station (HKO) and a rural station (TKL) from 1989 to 2002 were estimated to be 0.61$^\circ$C and 0.15$^\circ$C per decade. The different increase rate between urban and rural areas indicates that the magnitude of UHI and the resultant health impact may increase in the next decade. Thus, mitigation measures should be implemented to address the UHI. Previous research has studied different mitigation measures such as green roof (Coutts et al., 2013; Zhao et al., 2014), vertical greening (Perini et al., 2011; Tan et al., 2014), and root coating (Bretz et al., 1997). On the other hand, Cheung et al. (2012) showed the importance of air ventilation for enhancing thermal comfort in a city.

Chen et al. (2010) reported that some sensitive groups such as the elderly may be more vulnerable to heat-related mortality. However, age distributions were not taken into account in our estimation due to lack of data. Therefore, more investigations should be done to further estimate the UHI-related mortality among different groups within urban community. In addition, we note that anthropogenic heat emissions, which could play an important role in the formation of UHI, were not taken into account in this study due to lack of the corresponding data. The lack of anthropogenic emissions may cause a lower bias of our results. Nevertheless, this work identified the UHI and its health impacts due to land use variations (urban vs rural).

Another important impact of UHI is additional energy consumption. Fung et al. (2005) studied the energy consumption due to increase in urban temperature of Hong Kong. Based on the data from 1990 to 2004, the study estimated that the energy cost in summer due to an increase in 1$^\circ$C ambient temperature would increase by HK$1.6 billion per year. The study showed an important relationship between the...
additional energy consumption due to change in ambient temperature. However, the change in energy consumption due to UHI has not been studied in the literature, and thus needs to be quantified in a global change adaption context in the future work.

CONCLUSION

In this study, we quantified the urban heat island effect (UHI) in the summer in 2009 and estimated the resultant health impacts based on a temperature-response function reported in the literature. Our analysis estimated that the hourly temperature in urban areas (29.6°C) is higher comparing to that in rural areas (28.1°C). The Urban Heat Island Intensity (UHII) on average. The UHI results in different Primary Planning Units show a north-south gradient pattern over Hong Kong: the highest UHII (1.7°C) in northern part of HK, whereas the lowest UHII (0.8°C) in southern part of HK. We found that UHII correlates well with urban area size instead of population, indicating that policy makers of high-density cities should pay attention to urban area size when tackling UHI. In addition, UHI was estimated to cause 75 [95%C.I. 22-158] mortalities in summer. Of which, ~55% of the UHI-related health impact occurs in New Territories, while 39% and 6% of the impact happen in Kowloon and Hong Kong Island, respectively. The results provide critical implications for urban planners to mitigate UHI in cities, especially for the ones which are being developed in less developed countries such as mainland China.

ACKNOWLEDGEMENT

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ABSTRACT

This paper describes the development of a sustainability assessment framework designed to be used in the Gulf Region, which is an area which has experienced large scale building development and also a region in which sustainability assessment is not yet widely used. The complexity and time resources needed to apply existing methods act as a deterrent to active use. Three well-known methods available at the time of the study were investigated in some detail. These were: BREEAM Gulf; Green Building Council LEED; and Estidama Pearl. Cross comparisons of the factors involved in each method were carried out on several levels including: theoretical comparison; practical development and usability; compliance with regulations and standards; and ability to achieve synchronization. A considerable degree of compatibility was found to exist between the methods, particularly if focused on key criteria. As a result a new and specific framework was developed which grouped 24 indicators under five principal headings: site/location, biodiversity and accessibility; energy; water; occupant well-being; and resources and wastes. This new framework was then evaluated by testing with practitioners resulting in confirmation of 20 out of the 24 indicators, and identification of suitable benchmarks.

INTRODUCTION

The Arabian Peninsula is located in a hyper-arid zone, apart from the oil and gas there are minimal natural resources (Galbraith 2008) and the volume of construction work in the region, and Dubai in particular, has been unprecedented. There are impacts on many levels: economic; regional investment; and more specifically on the real estate sector. Dubai in particular has developed some astounding architecture and demonstrates inspiring achievements in form, scale, and budget. However and consequently, the construction industry has laid a heavy burden on natural resources (Al Marashi, 2006).

The Gulf region countries as a group are popularly referred to as the ‘The Gulf Cooperation Council’ (GCC) countries, consisting of: Saudi Arabia, Bahrain, Kuwait, Qatar, the United Arab Emirates, and Oman, with a total population estimated as 46.8 million. At the regional level, the characteristics that are common to the six countries reflect their similar rapid economic expansion, but they also originate from the fact that power generation in the six countries is mainly oil and gas based.

The energy sector, has played a crucial role in the socio-economic development of the GCC countries and also plays a significant role in economic growth and in development of policies towards environmental and sustainability issues in the GCC (Al Zubaidi, 2007).

Meanwhile sustainable buildings construction is still very limited in the region compared to the total building market and as a consequence, their cumulative impact on the reduction of ecological footprint is currently almost negligible. Recognizing the poor ecological situation, a study by Lahn, Stevens and Preston (2012) estimated a 29% potential energy saving in the building sector by 2025 (the...
highest among all sectors potential savings) if effective efficiency measures were followed. There is a however reluctance to take up environmental assessment methods in the region; barriers encountered are varied in their type and magnitude. A general lack of understanding, and the level of complexity found in the methods are attitudes reflecting the main issues of concern. There is a need to develop more sophisticated targeted evaluation techniques and to limit the number of prescribed indicators to those of high sensitivity in a more effective basic environmental assessment for buildings in the Gulf region.

An analysis of a previous questionnaire distributed to 120 practitioners in the Gulf region, concluded that 78% had concerns about the difficulty in quantifying the benefits of green buildings and problems with the evaluation documentation process (Salama and Hana, 2010). It was also concluded that the construction industry in the UAE was witnessing a growing awareness of sustainability but the inconsistency of the responses reflected a blurred awareness of the key concepts of green building.

The Emirates Green Building Council (GBC) encourages the use of any recognized green building rating method as a means to creating a more sustainable built environment. There are several methods in the global market place as well as several methods commonly used in the United Arab Emirates (UAE). In the sections below a description of the commonly used methods is given together with a critique followed by the explanation of how an alternative assessment framework was developed, which was devised to be more straightforward to use and addressed the main needs expressed by professionals.

It is important to pursue development and integration of sustainability assessment at this period in history and some argue for intervention from governments to legislate for sustainable buildings and to create design and construction strategies to minimize the environmental impact of new building construction activity. In Kuwait, a survey indicated that 88% of respondents agreed that rules and legislation from government are required to enforce the concept of green buildings (Al Sanad, Gale, and Edwards, 2011). Another survey, concerned with evaluation of new residential building codes in the UAE, showed that using such codes could reduce the CO2 emissions of buildings by 50% (Radhi, 2010).

EXISTING ASSESSMENT METHODS

Assessment tools for environmental analysis of buildings and their surroundings come in many shapes and forms. Some address single issues such as energy use/carbon dioxide production or indoor air quality, whilst others incorporate a wide range of issues under an umbrella tool. The criticism that can be leveled at the latter when it results in a single figure outcome or single rating is that the overall rating compares dissimilar things. This criticism can be partly dealt with by using weighting systems between sub-categories that are agreed across issue boundaries and which can be periodically adjusted. Nevertheless it is the case that most countries have opted to use an overall assessment system as the notion of a single descriptor/evaluation has more public appeal. Over the years a large number of assessment systems have been developed in different countries. Some are prescriptive requiring answers to a large but defined set of questions; some are more flexible. The categorisation can also arise from whether the method is aimed at design features and operation (LEED, BREEAM) or whether dealing with life cycle assessment in great detail such as the German Deutchse Gesellschaft fur Nachhaltiges Bauen (DNGB), the Dutch EcoQuantum, or North American ATHENA. Methods also exist that are wider in scope and more dynamic, such as SBTool (developed by the IISBE organisation from the earlier GBTool). SBTool uses a toolkit approach from which users select relevant issues to suit their building type and location. The Living Building Challenge (LBC) which comprises seven performance categories: place, water, energy, health & happiness, materials, equity, and beauty, takes the approach to a different level by focusing on ‘imperatives’ which can be applied to a wide range of projects and which are updated in response to the market and current state of knowledge.

In this study a wide range of options were considered from which it was decided to focus on three examples of the design-led assessment, two of which have been widely used around the world and have established a place in the market. To these was added a more recently developed local GCC tool. A wide range of assessment methods and tools were examined for use in the study and three well-known options which could be applied were identified.

The reasons for choosing the three methods with their indicators for evaluation were: they are the most common methods in the Gulf region and are recommended by the UAE GBC; they had the ability to offer comparisons and benchmarking; they evaluated whole buildings and not only building parts; they provided a label and third party certification; there was a credible responsible organization behind
the label; and they could be applied in different countries or were designed for cross-border application.

**BREEAM Gulf 2008**

BREEAM (the Building Research Establishment Environmental Assessment Method) was the first assessment system, launched in 1990, to offer an environmental label for buildings. BREEAM Systems are voluntary, consensus-based, and market-driven. Different schemes of BREEAM exist around the world and have been adapted to suit the regions in which they are to be used and to reflect differences in standard practice or cultures (Saunders, 2008). For international projects seeking evaluation under the BREEAM scheme, they should initially use BREEAM Bespoke International. This also allows an opportunity for the client to appoint a local consultant/expert to research the local codes and standards for the particular country/region. The Building Research Establishment uses this information to devise a set of final criteria to be used by the assessor to carry out the assessment on that particular building.

BREEAM Gulf was developed in collaboration with a variety of large organizations based in Qatar, Abu Dhabi and Dubai, with its objective to assist the construction industry in the region to achieve higher levels of sustainability and to recognize local context and issues (BREEAM, 2008).

**LEED v.3 2009**

LEED (Leadership in Energy and Environmental Design) is owned and administered by the US Green Building Council (USGBC). The method is flexible and can be applied to all building types: commercial, residential and entire neighborhood communities; and works throughout the building lifecycle: design and construction, operations and maintenance. LEED was identified by the Dubai authorities as a ‘tool’ to implement the region’s sustainability ambitions in a systematic manner, with the aim of an end-product that could be officially certified and therefore, internationally recognized. The Green Building Certification Institute (GBCI) was established in 2008 as a separately incorporated entity with the support of the U.S. Green Building Council for project registration and certification. LEED addresses several different project scopes for different building types; the latest version is version 4 which was released in late 2013; the version used in this analysis however was version 3 from 2009.

**Pearl 2010**

The Pearl Rating System was a key initiative of the Abu Dhabi Urban Planning Council (UPC) under the title Estidama (which means ‘sustainability’ in Arabic) and is a comprehensive rating system. Pearl was released early in April 2010 to provide a sustainability assessment program that aimed to be robust and tailored to the United Arab Emirates in terms of culture and climate. The system covers four pillars of sustainability: environmental, economic, cultural and social. The Pearl system aimed to address the sustainability of a given development throughout its lifecycle from design through construction to operation. The system provides design guidance and detailed requirements for rating a project’s potential performance (Estidama, 2010). It is however, like the others, a complex assessment to implement.

**RESEARCH PROCESS**

The aim of this research has been to develop a suitable sustainability assessment framework for office building relevant to the local context and priorities of the Gulf region. The research used ‘Mixed Methods Sequential Exploratory Design’ as a research methodology. The purpose of this exploratory sequential design was to develop and test a simple but reliable assessment framework and to generate design parameters. The first stage of the study was a qualitative exploration of theories regarding local context constraints and assessment method practices in the Gulf region. The second, quantitative stage followed-up on the findings from the qualitative stage for the purpose of examining the findings from multiple perspectives. Alternative sources and methods were used to compare, validate, and triangulate results and to examine processes/experiences along with outcomes. Comparative analysis data, case study and self-administered questionnaire were the main elements of the quantitative research.

The main task in the research was to choose and formulate the most appropriate ‘indicator set’,
which considered the building’s performance in relation to the local environment, culture and economy, as well as business goals. Furthermore, it was the intention to limit the number of indicators in the proposed framework to encourage take-up. Fernández-Sánchez and Rodriguez-López (2010) proposed a methodology used here, based on the identification of sustainability indicators by considering sustainability as opportunities for the project and on the establishment of indicators for measuring and controlling these opportunities. A framework would be essential for linking the vision and goals to the evaluation methodology and the indicators that are to be selected. The initial step was to choose the most appropriate criteria for the indicator set. Alwaer and Clements-Croome (2010) suggested four hierarchical categories of indicators to facilitate the selection process: Pre-requisite (Mandatory) indicators which are compliant with standards, regulations and quantified minimum targets; Desired indicators: ideal targets for building performance beyond the minimum required by regulations and codes of practice, to include the users vision; Inspiring indicators: goals and visions set by client: referring to long term mission and values; Non-active indicators or non-applicable indicators (the scope of this research project does not require these, and are thus ignored in the analysis). They should also be:

- Representative: Assist in informing choice in design decisions.
- Reasonably simple: Be usable by anyone, including professional designers and lay users with a simple and clear interface.
- Sensitive to change: Be flexible, multipurpose and generic in nature, and useable on many different types of buildings. Therefore enduring and persisting.
- Time resilient: Reflect specific aspects that could have impacts on sustainable buildings for current and future developments.
- Quantitative: Be quantifiable and scientifically valid (quantitative aspects or qualitative converted to quantitative).
- Accurate: Accurately/objectively measure progress towards sustainable development goals.
- Cost-Effective: Be cost effective but give value.
- Accessible: Data accessibility should be made easy and not constrain the process.

A methodology of five design sequential stages was employed: Stage 1 - Critical selection of aspects and indicators; Stage 2 - Structuring of the framework and refinement of selected indicators through comparative review of three existing sustainability assessment methods; Stage 3 - Structuring of the framework and refinement of selected indicators through a case study building study and comparative analysis; Stage 4 - Validation of the framework and indicators through questionnaire survey to local sustainable buildings industry professional; Stage 5 - Results analysis.

Arising from the evaluation, it was clear that all three methods required a high level of professionalism in sustainable design knowledge to be effectively used. The time and cost associated with this specialized knowledge is an important consideration. Moreover, the time required for documentation production is long and even though online submission is possible, the response time from the organisations is relatively lengthy. Typically four to six months is required for complete processing the applications; local experts’ opinions suggest that it is usually longer, which also hinders acceptance in the marketplace. Also found as a result of the questionnaire was that the culture of the building industry relied on quick decisions. Credits within the assessment schemes that required substantial effort to be documented and which used external expertise, resulted in extra cost and time for the applicant, and this was one of the major criticisms. The survey also revealed that cost of assessment and documentation was a difficulty as was lack of awareness of the benefits. It was also found that expanding the range of issues in the methods, would also act as a disincentive to use.

The analysis showed that there was a good degree of commonality in approach of the three methods. The compatibility ratio among all the credits of the methods is high when related to the full data set: 65.2% for BREEAM Gulf and 77.27% for LEED. And in spite of the expanded structure of Pearl in covering more phases of the life cycle, cultural themes of sustainability, natural systems and compliance with the Abu Dhabi plan 2030; the method showed 55.86% compatibility. This gives confidence in being able to define a reduced set of key indicators in a new framework.
DETAILED DEVELOPMENT OF FRAMEWORK

Thirty LEED certified projects in UAE, representing 90% of all LEED certified projects in the Gulf region up to August 2012, were analysed and evaluated and compared to BREEAM and Pearl at the same time. The projects were mostly offices, offices combined with industrial premises, and hotels; ratings achieved fell into the following categories: platinum 10%; gold 46.6%; silver 36.7%; and certified 6.7%. This thirty-project analysis provided a basis for understanding which indicators would be of most value from the wide range to be found if every credit from all three systems were combined.

In order to limit the number of indicators in the proposed new framework to the most relevant and significant, a prioritization process was required. Areas of assessment that were common to all evaluation processes were immediately designated for inclusion in the proposed framework. For the remainder, an analysis was made to determine what priorities would be selected if considered relevant to the following: the most severe local problems; local governmental and stakeholder objectives; mandatory rules and regulations of authorities; Gulf region environmental practices; and regional priorities and synergistic strategies. The sections below indicate in more detail the activities carried out.

Theoretical comparison: To characterize the essence of the three methods, the evaluative framework for environmental management approaches developed by Baumann and Cowell (1999) was adopted to structure the frameworks of the three methods. The purpose of using a framework is to give a better understanding of the context structure with recognized terminology and methodology.

Review of criteria addressed by area-context priorities: To allow review information for each of the three applicable assessment methods, by using the local context priorities drivers for sustainable design, seven criteria were identified: applicability, development, usability, system maturity, technical content, measurability & verification and communicability (Fowler and Rauch, 2006).

Comparison of methods standards and regulations: This aspect investigated and compared each of the three methods to show the level of compliance with standards and regulations on international, regional and local levels.

Comparison of methods impact categories/indicators: To examine the degree of synchronization and the potential for harmonization; since the same elements sometimes appear in different categories in the three methods a direct credit points allocation comparison can be difficult if not impossible (Smith et al., 2006). Accordingly, to allow for more objective comparison and to minimize internal systematic biases associated with the benchmarking of a comparative study, a system of harmonization was employed in which some aspects were reclassified. Figure 1 illustrates the outcomes following the harmonization process by comparing the allocation of weighting from the three methods across ten categories into which the indicators were allocated.

Information and findings from the theoretical and synchronized comparison revealed that the three methods were important in stimulating the market for sustainable building in the Gulf region and that the existence of more than one method could create competitive practices that might enhance the industry. None of methods were fully compatible with regional requirements, particularly in addressing criteria of some environmental issues, or in providing practical applicability to deal with regional contextual issues.

The detailed comparisons were then informed by analysis of their application to a case study building: one for which detailed design information was available and which had already achieved a high classification in LEED. The total number of sustainability certified new buildings up to July 2012 was thirty; two of them having LEED platinum certifications; the case study building was chosen to be one of these: the ESAB Middle East FZE office building. Space does not permit a detailed description of the case study analysis; however it enabled the choice of indicators to be substantiated.
Arising from the various analyses, 24 indicators were initially chosen grouped under 5 main categories: Site Location Biodiversity & Accessibility; Energy; Water; Occupant Well-being; and Resources and Waste. The allocation of indicators was as follows:

**Site location, biodiversity and accessibility (7 indicators):** Site ecology; Construction pollution; Public Transport accessibility; Travel planning; Cycle facilities; Electric cars and car-pooling facilities; and Heat island effects on roof and other surfaces

**Energy (5 indicators):** Primary energy consumption for building operation; Commissioning; Energy monitoring; Ozone depletion/enhanced refrigerant management; and On-site power generation

**Water (4 indicators):** Interior water consumption; Exterior water consumption; Waste water technologies; Water consumption monitoring

**Occupant Well-being (4 indicators):** Indoor air quality; Thermal comfort; Smoking; and Emissions from materials.

**Resources and Waste (4 indicators):** Waste storage/recycling; Recycled construction materials; Locally sourced materials; and Construction site waste management.

**SURVEY OF BUILDING PROFESSIONALS AND SELECTION OF INDICATORS**

In order to validate the approach being used a survey of building professionals’ attitudes was carried out using a questionnaire based on the assessment framework. In total 91 responses were received and 87 of those were deemed to be valid and answered all questions. Responses to key questions are shown in Table 1. The survey also asked participants to rank the importance of the proposed indicators on a scale of 1 to 4. It was also found 87% of industry professionals agreed that the proposed framework would be effective in enhancing performance of office buildings in the Gulf region.

One of the most important aspects of the survey was to confirm or exclude indicators and to check for availability of appropriate benchmarks or indicator-specific analytical tools in order that the value of the indicator could be calculated. A cut-off value of 3.0 was chosen as signifying the professionals’ acceptance of the indicator. Table 2 shows the summary results and that four indicators were excluded. The determination of the availability of benchmarking/analysis tools was made easier by the previous comprehensive assessment of available methods for the Gulf Region. In two cases specific additional information to that normally used would be needed to enable the calculation, and in two further cases it was determined that a slightly modified version of the benchmark analysis would be required.
Table 1. Responses from Building Professionals to key questions about sustainability

<table>
<thead>
<tr>
<th>Response to question</th>
<th>Sustainable Development is a very important concept and principle for the Gulf region countries</th>
<th>Sustainability assessment is an important issue for office building development in the Gulf region</th>
<th>Current design approaches adopted within the building industry in Gulf region countries are creating sustainability problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly agree</td>
<td>59 (67.9%)</td>
<td>50 (57.5%)</td>
<td>49 (56.4%)</td>
</tr>
<tr>
<td>Agree</td>
<td>25 (28.7%)</td>
<td>34 (39.1%)</td>
<td>32 (36.8%)</td>
</tr>
<tr>
<td>Disagree</td>
<td>1 (1.1%)</td>
<td>3 (3.4%)</td>
<td>4 (4.6%)</td>
</tr>
<tr>
<td>Strongly disagree</td>
<td>2 (2.3%)</td>
<td>0 (0%)</td>
<td>1 (1.1%)</td>
</tr>
<tr>
<td>No response</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>1 (1.1%)</td>
</tr>
</tbody>
</table>

Table 2. Gulf-region Office-building Sustainability Assessment Framework: confirmation of indicators to be used from survey and benchmarks

(*= further information needed for benchmark use; **=modified benchmark)

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Rank weighting (out of 4)</th>
<th>Confirmed as included</th>
<th>Benchmark availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site ecology</td>
<td>3.91</td>
<td>Confirmed</td>
<td>Confirmed*</td>
</tr>
<tr>
<td>Construction pollution</td>
<td>3.67</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Public transport access</td>
<td>3.55</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Travel planning</td>
<td>3.40</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Cycle facilities</td>
<td>2.93</td>
<td>Not confirmed</td>
<td>Excluded</td>
</tr>
<tr>
<td>Electric cars</td>
<td>2.84</td>
<td>Not confirmed</td>
<td>Excluded</td>
</tr>
<tr>
<td>Heat island effects</td>
<td>2.84</td>
<td>Not confirmed</td>
<td>Excluded</td>
</tr>
<tr>
<td>Minimise primary energy</td>
<td>3.83</td>
<td>Confirmed</td>
<td>Confirmed**</td>
</tr>
<tr>
<td>Commissioning</td>
<td>3.77</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Energy monitoring</td>
<td>3.55</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Ozone depl/refrigerants</td>
<td>3.54</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>On-site power generation</td>
<td>3.37</td>
<td>Confirmed</td>
<td>Confirmed**</td>
</tr>
<tr>
<td>Interior water use</td>
<td>3.94</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Exterior water use</td>
<td>3.74</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Waste water technologies</td>
<td>3.45</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Water use monitoring</td>
<td>3.36</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Indoor air quality</td>
<td>3.78</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Thermal comfort</td>
<td>3.76</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Smoking</td>
<td>3.71</td>
<td>Confirmed</td>
<td>Confirmed*</td>
</tr>
<tr>
<td>Emissions from materials</td>
<td>3.58</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Waste storage/recycling</td>
<td>3.70</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Recycled const. materials</td>
<td>3.43</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Locally sourced materials</td>
<td>3.46</td>
<td>Confirmed</td>
<td>Confirmed</td>
</tr>
<tr>
<td>Const. site management</td>
<td>2.92</td>
<td>Not confirmed</td>
<td>Excluded</td>
</tr>
</tbody>
</table>

A further question concerned the respondents’ perceptions regarding impact categories that affect sustainable design of office buildings. Energy and water at 97.7% and 93.4% respectively were the most frequently cited issues. Other categories scored as follows: occupant well-being 73.6%; site location and biodiversity 70.1%; resources and wastes 56.3%; and operation and maintenance 49.4%.

The impact of the survey results was to confirm the approach and scope of the new assessment method described in this paper and to encourage further research and development.

CONCLUSIONS

This paper has presented the key features of a research project designed to generate a new and more easily applied sustainability assessment framework suited to the circumstances of the Gulf Region. The Framework is well-founded being derived from a detailed analysis of available international methods but

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enhanced by focusing on the key parameters that can be applied efficiently in the Gulf Region. Further analysis and evaluation is required to determine the most effective means to bring the system to the market-place and to assess any potential limitations of the Framework in practice. The data gathered from the professionals and from the study of the previously assessed thirty projects will permit the next stage – that of allocating a more sophisticated and justified weighting to each indicator, to be carried out.

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Session 5E : Material technology

PLEA2014: Day 2, Wednesday, December 17
11:30 - 13:10, Faith - Knowledge Consortium of Gujarat

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ABSTRACT
Photovoltaics (PV) deployed in high solar radiation high ambient temperature climate suffer huge loss in efficiency and degrade faster due to higher panel temperature. In order to overcome the temperature induced loss of power and life, a paraffin wax based solid-liquid phase change material (PCM) integrated at the back of PV is investigated in high temperature climate of UAE. The temperature drop on the PV panels due to inclusion of the PCM is recorded and compared to a reference panels without PCM. The associated voltage gain caused by temperature drop of PV due to PCM also recorded to evaluate the effectiveness of PCM in temperature regulation and electrical performance enhancement of PV. A temperature drop of 12 °C and associated voltage gain of is observed which shows such systems are effective in even mild weather condition of a hot climate

INTRODUCTION
Silicon photovoltaics (PV) show a power drop above 25 °C with a temperature coefficient of up to -0.65 % K⁻¹ depending on type of the PV cell and the manufacturing technology [1]. The operating temperature reached by PV panels and associated power drop largely depends on the climate of the site. In Germany 50 % of the solar radiation incident on a PV panel is above 600 W/m² while in Sudan this value reaches 80 % resulting different operating temperatures and associated power drop [2] urging a strong need for PV temperature regulation to maximize both panel lifetime and power output. Different passive and active heat removal techniques have been used to maintain PV at lower temperatures. Passive heat removal in free standing PV relies on the buoyancy driven air flow in a duct behind the PV [3]. Heat removal depends on ratio of length to internal diameter (L/D) of the duct [4] with the maximum heat removal obtainable at an L/D of 20 [5]. Passive heat removal in building integrated photovoltaics (BIPV) relies on buoyant circulation of air in an opening or air channel, instead of a duct, behind the PV [6]. Active cooling of PV relies mostly on air or water flow on the front or back of the PV surface. Effect of air flow at different inlet velocities and air gaps on front side and back side of PV temperature was modelled and a maximum 34.2 °C temperature decrease was predicted at air inlet velocity of 1 ms⁻¹ and front and back air gap of 20 mm [7]. Water flow on the front surface of a free standing PV has a decreased cell temperature of up to 22 °C along with decreasing reflection losses from PV surface yielding an 8-9 % increase in electrical power output [8]. Water flow on the back of a façade integrated PV has theoretically shown optimum electrical and thermal performance at a water flow rate of 0.05 kgs⁻¹ for a particular system in the weather conditions of Hefei, China at insolations of 405 W/m² and 432 Wm⁻² [9].

Passive cooling of BIPV with solid-liquid PCMs were experimentally and numerically evaluated using a paraffin wax as PCM and an a rectangular aluminum container with internal dimension of (300

¹United Arab Emirates University, United Arab Emirates, ²Lebanese International University, Lebnese Republic, ³Dublin Institute of Technology, Republic of Ireland,
mm x 132 mm x 40 mm) having selectively coated front surface to mimic a PV cell [10]. Temperature distributions on the front surface and inside the PCM were measured experimentally and predicted numerically with 2D and 3D finite volume heat transfer models which showed good agreement between experimental and numerical results [11,12]. Building on this work, Hasan et al., fabricated and characterised 4 different cell size PV-PCM systems to investigate performance of 5 different types of PCM to find out the optimum PCM and the PV-PCM system for this application. Two PCM, a eutectic mixture of capric-acid-palmitic acid, PCM1 and a salt hydrate CaCl2.6H2O, PCM2 were found promising in an aluminum based PV-PCM system [13]. In current work larger PV panels are integrated with in an aluminum based PV-PCM system containing PCM fitted internally with back to back vertical aluminum fins. The devised system is deployed outdoors in UAE climate during a mild season to observe the effectiveness of such PV-PCM systems.

METHODOLOGY

EXPERIMENTAL SETUP

Two 30W polycrystalline EVA encapsulated PV panels with dimensions of 500 mm x 400mm (PTL-Solar) were used in the experiments where one served as a reference and the other contained PCM. The calibrated t-type copper-constantan thermocouples with a measurement error of ±0.2 °C were installed on all and a National Instruments Compact- Rio data acquisition system was used to record the weather data on site for solar radiation intensity, wind speed and ambient temperature shown in figure 1. Rectangular PCM containers of internal dimensions 480 mm x 380 mm x 50 mm were fabricated from a 5 mm thickness aluminum alloy (1050A) and fitted with straight vertical back to back fins of the same alloy with 60 mm horizontal spacing. A 1 mm thin layer of silicon based glue was applied at the interface of the PV panel and the PCM container and kept under pressure for two days until the glue settled and a strong bond was realized between the aluminum container and the PV panel. The reference PV and PV-PCM were installed at the latitude angle in Al Ain, UAE between 23/03/2014 and 02/04/2014. The data acquisition measured temperatures on front and back surface for the reference PV and on front and back surface and in the middle of the PCM slab contained at PV back for the PV-PCM system. The open circuit voltage and short circuit currents were also measured for both the reference PV and PV-PCM system.

![Figure 1- Schematics of the experimental setup](image)
DATA ACQUISITION

Data acquisition system was built to record readings of the panel's voltage, current, temperature, and solar insolation. Besides, the site ambient temperature and wind speed were included in the data-logging architecture. CompactRIO 9073 was used as a real time data-logging device, while the data can be remotely monitored on a LabVIEW interface program. The developed LabVIEW program stores the PV panels’ electrical and environmental variables during the daily sun hours. The data acquisition setup consists of the following components:

-CompactRIO 9073 : a reconfigurable real time controller and data acquisition chassis. The used model comprises 8 slots for I/O modules, 2 M gate embedded FPGA core, and a 266 MHz real time controller.

-NI 9227 : 4 channel differential analog current input module with nominal current rating of 5 A and maximum rating of 14 A. Two NI 9227 modules were used in this project, since 8 current measurements are required to be stored from the 8 PV panels.

-NI 9229: 4 channel differential analog voltage input module with maximum voltage range of -60 to 60 V. Two NI 9229 modules were used in this project to carry out 8 voltage measurements for the 8 PV panels.

-NI 9205: 32 single-ended channels or 16 differential channels analog voltage input module with maximum voltage range of -10 to 10 V. One NI 9205 module was used in this project, where 9 input ports were deployed to store measurements from weather sensors (8 pyranometers & 1 anemometer).

-NI 9213: 16 channel thermocouple input module. Only one module was used in this project, since only 9 channels were required, 8 to measure the 8 PV panels temperature and 1 was dedicated to measure the ambient temperature.

-Ethernet cable: Category 5 cable to establish the network between the host computer and the real time target (CompactRIO).

-NI LabVIEW development software: this includes the standard LabVIEW modules, the LabVIEW FPGA Module, the LabVIEW Real-Time Module, and the NI-RIO driver.

First, the NI CompactRIO system was assembled by installing the NI analog input modules, connecting the system to the host PC via an Ethernet cable, and powering up the device with its corresponding DC power supply. Then the network setting was configured to establish a communication between the CompactRIO and the host computer. Finally, an FPGA program was built on the LabVIEW development software and then stored in the real-time target. A host VI was built along with the FPGA VI to monitor the captured signals and represent them in plots and indicators.

RESULTS AND DISCUSSION

Figure 2, 3 and 4 shows the solar radiation intensity, ambient temperature and wind speed for the duration of experiment. Figure 2 shows that the day time peak ambient temperature varied between 29 °C to 37 °C which is a mild temperature for UAE weather conditions offers a peak day time summer temperature of upto 50 °C. Figure 3 shows that the peak time wind speed varied between 7km/h to 23 km/h. Figure 4 shows that peak time solar radiation intensity varied between 480W/m² on a cloudy day to 1240 W/m² on a very clear day. This weather caused the PV panel to heat resulting peak time reference PV temperature between 45 °C to 58 °C owing to the cloudy and sky respectively shown in Figure 5. The inclusion of PCM into PV resulted in a drop in PV temperature which reduced peak time PV temperature down to between 44 °C and 47°C shown on cloudy and sunny day respectively shown in Figure 5. The cooling effect produced by the PCM contained at the back of PV resulted in a peak time temperature drop of 7 °C to 11 °C on cloudy and clear sky conditions respectively shown in Figure 6. The temperature drop shown in Figure 6 reduced PV temperature resulted a higher open circuit voltage on PV containing PCM compared to PV without PCM shown in Figure 6 and yielded a voltage improvement peaked at 1.3 volts to 1.7 volts. The results shown in figure 6 explain that the PCM demonstrated a temperature regulation effect which was lower early in the morning for every day and
increased as the PV reference temperature increased. Temperature results plotted over several days (Figure 5) also show that the PV with PCM showed a consistently lower temperature than PV without PCM which explains that the PCM regenerated every night to produce cooling for the next day. It is important to note that the PCM showed lower temperature regulation earlier in the morning while the reference PV panel temperature is below 40 °C, above this temperature during noon time, PCM showed higher temperature regulation. Figure 5 shows that the PCM achieved temperature regulation ranging from 8 °C in the modest temperature day compared to 11 °C on the hot day. It also points out that the PCM is expected to achieve higher temperature regulation in the higher temperature peak summer days which will be tested in coming months. From Figure 5 and Figure 6 it can be observed that the decreased temperature on the PV panel yielded an increase in PV voltage to enhance electrical power output from the PV.

Figure 2: Ambient Temperature measured in Al Ain UAE, between 23/03/2014 and 02/04/2014

Figure 3: Wind speed measured in Al Ain UAE, between 23/03/2014 and 02/04/2014

Figure 4: Solar radiation measured in Al Ain UAE, between 23/03/2014 till 02/04/2014.
Figure 5: Reference PV and PV-PCM temperatures measured in Al Ain UAE, between 23/03/2014 till 02/04/2014

Figure 6: Reference PV and PV-PCM open circuit voltage measured in Al Ain UAE, between 23/03/2014 till 02/04/2014.

ECONOMIC EFFECTIVENESS

Authors have evaluated the use of PCM for lowering of PV temperature and extra power produced for Vehari, Pakistan which has very similar climate to the current site on experiments, Al Ain UAE. In the previous research, the PCM have been found cost effective with a return on investment about two years considering
mass produced PV-PCM systems. Similar results are expected for the current research which will be a subject of future publication for a year around testing of such systems [14]. The stored heat can be used for space or water heating. In case of UAE, the space heating demand is rare therefore Authors are currently conducting experiments for the extraction of stored heat for water heating applications in UAE and will soon publish the results. The hot water produced have larger demand in hospital buildings in UAE compared to residential developments.

CONCLUSION
The results obtained for testing PCM in higher temperature climate shows a promise for PV temperature regulation and power enhancement in the mild season of February where it always get back to solid. It needs still to be tested in the peak summer whether the PCM regenerates and gets back to solid at night by natural convection or it needs forced coolant flow to remove the heat contained in PCM.

ACKNOWLEDGMENTS
The authors would like to acknowledge the United Arab Emirates University (UAEU) and National Research Foundation (NRF) for its support through seed and NRF funding. They would also like to acknowledge COST Action TU0802: Next generation cost effective phase change materials for increased energy efficiency in renewable energy systems in buildings for providing an invaluable platform to discuss and develop this work.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AHU</td>
<td>Air handling unit</td>
</tr>
<tr>
<td>EER</td>
<td>Energy efficiency rating</td>
</tr>
<tr>
<td>R-value</td>
<td>Thermal resistance value</td>
</tr>
<tr>
<td>VFD</td>
<td>Variable frequency drive</td>
</tr>
<tr>
<td>WWR</td>
<td>Window to wall ratio</td>
</tr>
</tbody>
</table>

REFERENCES


The Role of Thermal Mass in Humid Subtropical Climate: Thermal Performance and Energy Demand of CSET Building, Ningbo

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ABSTRACT
The role of thermal mass in humid subtropical climate has always been intriguing. Located on the eastern coast of China, in humid subtropical climate zone, the Centre for Sustainable Energy Technology (CSET) building, Ningbo, is the first of its kind in the country. It is developed as an exemplar building which displays various energy efficient techniques to increase user comfort and reduce energy demand. Although, the use of heavyweight construction has always been controversial in such climates due to small diurnal range (10°C) and high humidity (65%-95%), the building possesses high thermal mass in the form of 300mm thick concrete walls and 400mm thick concrete slab. The objective of this study was to analyse the thermal performance of CSET building, Ningbo in terms of thermal comfort and energy demand, with respect to the high thermal mass. Through this study, it was also aimed to establish the role of thermal mass in humid subtropical climate zone. Parametric analysis was performed on the building using computer simulations, carried out on TAS Thermal Analysis Simulation Software, to obtain comparative results with and without night ventilation, for four cases: (i) As-designed case, (ii) Reduced building mass, (iii) Heavyweight building materials substituted with lightweight materials and (iv) Omission of the building’s glass envelope. Results indicated that the as-designed case i.e high thermal mass coupled with night ventilation performs the best in terms of thermal comfort and energy demand and hence plays a vital role in the thermal performance of CSET building. It was further established that in humid subtropical climates, night ventilation, proper shading, controlled daytime ventilation and moderate internal gains could improve the performance of heavyweight buildings, such that they perform better than the traditionally accepted lightweight buildings.

Keywords: humid subtropical climate, thermal mass, night ventilation, thermal comfort, energy demand

INTRODUCTION
Thermal mass is said to function as a climate moderator as massive building envelopes can attenuate the temperature fluctuation and reduce the indoor peak temperature. Thermal mass has been defined by Yannas (1994) as the capacity of a building to store and release heat at different times of the day. Thermal capacity is expressed as “the energy required to raise the temperature of a layer of material”. Usually, “higher the density of a material, higher is the resulting thermal capacity” (ibid).

Nishita Baderia is an architect working as a sustainable building design professional in India
Therefore, buildings with high thermal capacity are termed as heavyweight and include all masonry construction, while buildings with low thermal capacity are thermally lightweight and include timber or steel frame construction (ibid). It is often believed that using thermal mass is a universally ‘good thing’ (Baker & Steemers, 2000). However, the benefits of the effect of thermal mass depend on several parameters such as climate conditions, building thermal properties, ventilation, thermal insulation, occupancy and internal heat gains.

Traditionally, it was believed that the use of thermal mass did not have any benefits in humid subtropical or warm-humid climates. According to Szokolay (2000), up to the mid 1980s it was considered preferable to have elevated, lightweight, cross-ventilated buildings in such climates. However, these traditional design principles were being questioned by researchers like Szokolay (2000) and Soebarto (1999) who have investigated the role played by thermal mass in warm-humid climates. Their studies suggested that the debate between the performance of heavyweight and lightweight buildings in such climates was futile as both constructions performed equally well, with heavyweight performing slightly better than lightweight buildings (see Figure 1).

![Figure 1](image_url)  
**Figure 1** Performance of lightweight and heavyweight buildings in warm-humid climate, Source: Szokolay, 1985 cited by Baker & Steemers, 2000

Although much work has been done till date, more studies need to be conducted to ascertain the effects of the much debated use of thermal mass in humid subtropical climate. For the purpose of this study, an exemplar building (using high thermal mass), located in humid sub-tropical climate was selected.

The Centre for Sustainable Energy Technology (CSET) building is situated in Ningbo (28°51'-30°33'N and 120°55'-122°16'E) which is located on the eastern coast of China, to the South of the Yangtze River Delta (see Figure 2.1) (Lau et. al. 2006). According to the most widely used world climate classification done by Köppen-Geiger (Kottek et. al. 2006), Ningbo lies in the humid subtropical zone. The building is developed as an exemplar building which displays various energy efficient techniques to increase user comfort and reduce energy demand. The building incorporates high thermal mass i.e. it is thermally heavyweight.

The climatic analysis of Ningbo revealed a diurnal range of about 10°C and a relative humidity of 65-95%. Due to the small diurnal swing and high humidity in summer, it was felt that the thermal mass may not perform as expected. Lau et al. (2006) also suggested that night ventilation may not be very effective in providing pre-cooling in summer. Due to these reasons, it was considered essential to analyse the role of thermal mass in CSET building. Through this analysis, it was aimed to re-establish the role of thermal mass in humid subtropical climate zone so that this study can be referred to by designers designing in similar climate all over the world.

**CSET BUILDING, NINGBO**

The CSET building, developed as a climate integrated design, promotes energy efficiency, generates its own energy from renewable sources, uses locally available materials with low embodied
energy and harvests rainwater (Lau et al., 2006). Along with other climate responsive strategies, the building has internally exposed 300mm thick concrete walls and 400mm thick concrete slab. This implies that the building uses internally exposed thermal mass to minimize temperature fluctuations in summer & winter. The architectural drawings of the building are presented in Figure 2 (a), 2 (b) and 3.

The section shown in Figure 3 depicts the building functions. The laboratory, a workshop and an exhibition space are located in the semi-basement floor. While the research and teaching areas for post graduate students are situated on the second and third floor. The offices, a meeting room with staff kitchenette are all distributed on the fourth and fifth floor (see Figure 3).

![Figure 2](image.png)  
**Figure 2**  
(a) Ground floor plan  
(b) Third floor plan, Source: MCA

![Figure 3](image.png)  
**Figure 3**  
Building function, Source: MCA

![Figure 4](image.png)  
**Figure 4**  
The building envelope, Source: (MCA, SBE, 2006)

The opaque parts of the building are made of externally insulated concrete and have openings for natural ventilation. The transparent parts of the building are made of high performance glass which in
combination with the external façade provides thermal insulation while optimising daylight penetration into the internal spaces. The second skin makes an external envelope around the building. This external envelope is made of silk screen laminated glass in order to avoid direct solar penetration into the internal spaces (refer Figure 4). The double skin on the south side is sealed providing a thermal buffer, passive pre-heating in winter and exhausting unwanted warm air in summer. The skin on east and west walls is open and provides solar protection and vents excess solar gains.

METHODOLOGY

This research was based on thermal performance analysis of parametric variations in the building envelope which could be tested by performing computer simulations. The parametric analysis was performed for the following cases:

**Case I: Base Case**
- I - a: Base Case without Night Ventilation
- I - b: Base Case with Night Ventilation

**Case II: Reduction in Mass**
- II - a: Reduced Mass without Night Ventilation
- II - b: Reduced Mass with Night Ventilation

**Case III: Lightweight Construction**
- III - a: Lightweight Walls without Night Ventilation
- III - b: Lightweight Walls with Night Ventilation
- III - c: Lightweight Walls and Suspended Ceiling without Night Ventilation
- III - d: Lightweight Walls and Suspended Ceiling with Night Ventilation

**Case IV: Omitting the Glass Envelope**
- IV - a: Omitting the Glass Envelope without Night Ventilation
- IV - b: Omitting the Glass Envelope with Night Ventilation

The comparative analysis of the above mentioned cases helped in answering the much debated question about the difference in the performance of heavyweight and lightweight buildings in humid subtropical climate. The following considerations / assumptions were made for performing the dynamic thermal simulations on the software.

**Comfort Range / Energy Demand.** As per the climate analysis of Ningbo as well as review of available literature regarding comfort range, 19°C to 27°C was classified as the thermal comfort range for CSET building. Similarly, based on Pasivhaus and Keller Technology’s standards, the benchmarking for heating and cooling demand for Ningbo is taken in the range of 30 KWh/m² to 40 KWh/m².

**Building Analysis Software.** The Building Thermal Analysis Program used for performing the analysis, the New Generation TAS v. 9.1.3a developed by Environmental Design Solutions Ltd. (EDSL). TAS, is a dynamic thermal simulation tool. It allows the user to model, zone and subsequently simulate the building to predict its energy consumption, CO2 emissions, operating costs and occupant comfort.

**Model Geometry.** The geometry of the model was created in accordance with the information provided on the architectural drawings. Due to the limitations of the software, the façades were modelled based on the assumption that they are vertical i.e. they were modelled without the inclination indicated in the drawings (See Figure 5 (a) and (b)).

*Figure 5*  (a) South-west view of model  (b) South-east view of model (the tilt on the south is not considered). Source: Created by author using TAS
**Weather Data.** The weather file used for the analysis was sourced from Energyplus and the nearest available location to Ningbo was Shanghai. After reviewing the two weather files, the difference between their temperature profiles were considered negligible. Therefore, the weather file of Shanghai was used for all simulations (refer Lau et al., 2006).

**Building Elements.** Information regarding construction materials to be applied to the various building elements like external wall, internal walls, floor, roof, glass etc. was obtained from Lau et al. (2006). Some of the specified materials were not available in TAS construction database; hence the closest to the specified were selected. For this reason, a slight variation occurred in the U-values of some of the building elements. The details of the building elements are as given in Table 1.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Building Element</th>
<th>Building Material</th>
<th>U-Value (W/m²°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Externally insulated wall</td>
<td>300mm concrete with 120mm insulation</td>
<td>0.24</td>
</tr>
<tr>
<td>2</td>
<td>Internal wall</td>
<td>200mm concrete</td>
<td>1.9</td>
</tr>
<tr>
<td>3</td>
<td>Floor</td>
<td>400mm concrete</td>
<td>1.4</td>
</tr>
<tr>
<td>4</td>
<td>Basement floor</td>
<td>Concrete Slab with cavity insulation</td>
<td>0.4</td>
</tr>
<tr>
<td>5</td>
<td>Roof</td>
<td>Concrete</td>
<td>0.24</td>
</tr>
<tr>
<td>6</td>
<td>Openings in external wall</td>
<td>High performance clear glass</td>
<td>1.5</td>
</tr>
<tr>
<td>7</td>
<td>External glass envelope</td>
<td>Silk screen laminated glass</td>
<td>5.6</td>
</tr>
</tbody>
</table>

**Internal Conditions.** Based on the use of the space, assumptions were made regarding occupancy, equipments and lighting gains in the building and the same are presented in Table 2. These assumptions were kept constant throughout the study.

<table>
<thead>
<tr>
<th>Floor</th>
<th>Space</th>
<th>Occupancy (@ 80W/ person)</th>
<th>Equipment</th>
<th>Lighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-basement</td>
<td>Reception, exhibition, lab, workshop</td>
<td>15 persons</td>
<td>No equipment</td>
<td>None in summer, 6W/m² in winter</td>
</tr>
<tr>
<td>Ground Floor</td>
<td>Expo area</td>
<td>3 persons</td>
<td>No equipment</td>
<td>None in summer, 6W/m² in winter</td>
</tr>
<tr>
<td>First Floor</td>
<td>Teaching room</td>
<td>30 persons</td>
<td>30 laptops @ 80W per laptop</td>
<td>None in summer, 6W/m² in winter</td>
</tr>
<tr>
<td>Second Floor</td>
<td>Resource room</td>
<td>15 persons</td>
<td>No laptops</td>
<td>None in summer, 6W/m² in winter</td>
</tr>
<tr>
<td>Third Floor</td>
<td>Offices</td>
<td>10 persons</td>
<td>10 PCs @ 100W per PC</td>
<td>None in summer, 6W/m² in winter</td>
</tr>
<tr>
<td>Fourth Floor</td>
<td>Meeting room</td>
<td>10 persons</td>
<td>No equipment</td>
<td>None in summer, 6W/m² in winter</td>
</tr>
</tbody>
</table>

As mentioned earlier, the comfort range was classified as 19°C to 27°C. Simple natural ventilation was simulated for all cases. The aperture settings were such that the apertures began to open if the dry bulb temperature in the adjacent zone exceeded 23°C, and were fully open if the dry bulb temperature reached 26°C. The apertures began to close when the internal temperature exceeded the external temperature. The building is occupied from 8:00am to 6:00pm and for incorporating night ventilation, all windows were opened from 7:00pm to 8:00am, for all seasons except winter. The maximum wind speed was assumed to be 10m/s, beyond which the apertures began to close regardless of the temperature. An infiltration rate of 0.2 ach was considered.

No heating or cooling was modeled, as the intent of the study was to test the performance of the building with or without thermal mass, isolated from all heating and cooling strategies. For the purpose
of calculating heating and cooling demand, another set of simulations were run for which the heating set point was taken at 19°C and the cooling set point was taken at 27°C.

**Data Selection.** For evaluating thermal comfort, firstly the dry bulb temperature was observed over a period of a week in summer (17th – 23rd July, warmest week), mid-season (15th – 21st October) and winter (18th – 24th December, coldest week). Secondly, the total number of occupied hours from the whole year, when the temperature exceeded 27°C was extracted for every zone for each case. As the occupied time for this building is 8:00am to 6:00pm, the total annual occupied hours is 3650. Finally, the energy demand was observed in terms of the total annual heating and cooling demand of the building. The internal gains due to equipments, lighting and occupancy were expressed in KWh/m² and remained constant throughout the study. The solar gains varied according to the building fabric.

**COMPARATIVE ANALYSIS**

The parametric analysis conducted for the specified cases revealed that the performance of the building deteriorates upon reduction in building mass. It was identified that the main benefit of a heavyweight building was that the variation in internal temperature was smaller and closer to the average external temperature than a lightweight building. In the lightweight substitute of the building, the fluctuations in internal temperature were larger and presented higher peaks than the heavyweight building as well as the ambient temperature (refer Figure 6). From the comparison of the building with and without the glass envelope, it was found that the thermal mass became more effective when it received lower solar gain since the low transmittance glass acted as a shading device for the building.

![Figure 6](image)

*Figure 6 Indoor summer temperature profile: Basecase v/s Lightweight Construction, Source: Author*

In general, for all cases, night ventilation (NV) enhanced the performance of the building. In summer, during the warmest week, the condition “with night ventilation” was found to perform better than “without night ventilation” for the Ground Floor, while the upper floor temperatures for the two conditions, were almost coinciding with “with night ventilation” performing better. Even though night ventilation assists in lowering the temperatures, they were still found to be above 27°C during the occupied hours implying that extreme summer conditions would result in overheating unless cooling is provided. During mid-season, all the temperatures lay in the comfort zone i.e. 19°C to 27°C. Although both lower as well as upper floors benefited from the effect of night ventilation, the benefits were more visible in in the lower floors. In extreme winter conditions, the internal temperatures lay out of the comfort range i.e. they were below 19°C.
During the 3650 occupied hours, the building was found to experience comfortable temperatures in mid-seasons. The number of hours when the ambient temperature exceeded 27°C, the upper limit of the specified comfort range, is 760. Even during the warmest summer days the building exhibited stable indoor temperatures, though at temperatures above the thermal comfort range i.e. 27°C. The graph shown in Figure 7 reveals that for all the cases, without night ventilation, the number of hours exceeding 27°C during occupied hours is similar in each zone. Night ventilation enhances the building performance and there is variation in the results for this condition among the various cases. For every zone, the Base-case, a combination of thermal mass and night ventilation works best. Floor wise analysis revealed that the first floor was the worst performing floor, probably due to very high gains from occupancy and equipments. The performance became better with night ventilation. The semi-basement floors performed the best as they had low occupancy and high thermal mass. The ground floor performed better than the upper floors in all cases. The ground floor experienced about 770 hours exceeding 27°C, i.e. similar to ambient, while for the upper floors the number was about 1010 (refer Figure 7).

**Figure 7** Hours exceeding 27°C during occupied hours: Comparison between all cases, Source: Author

**Figure 8** Annual loads: Comparison between all cases, Source: Author
In terms of energy demand, although the annual cooling load reduced with the incorporation of night ventilation, the annual heating load increased (refer Figure 8). Due to the limitation of the software, for some days in spring and autumn when the ambient temperature was very low, although night ventilation was not required, the apertures were still open. This might have resulted in an overestimate of the heating loads. The total annual heating and cooling load for the building was found to be 39 KWh/m² and 42 KWh/m² for Base-case without night ventilation and with night ventilation respectively. These values are higher than the Passivhaus standard of 30 KWh/m²; however the values lie in or slightly above the specified range of 30 KWh/m² to 40 KWh/m² for heating and cooling. This implies that there is scope for improvement in the thermal performance of CSET building.

The lower floors (semi-basement and ground) in the building perform well due to low occupancy and equipment gain, while the upper floors (1st to 4th) suffer due to higher gains and lesser openings. Therefore it is strongly believed that reducing the gains and provision of more openings in the upper floors would improve the performance of the building.

CONCLUSION

From the above analysis, a broader conclusion can be drawn that a heavyweight building i.e. a building with high thermal mass, when coupled with night ventilation, appropriate shading and moderate internal gains from occupancy, lighting and equipments, performs better than a lightweight building in a humid subtropical climate even though this climate has small diurnal range and high humidity. This conclusion is in conjunction with the results of the studies conducted by Szokolay (2000) and (Soebarto, 1999) on the role of thermal mass in warm-humid climate.

Although, this research was contextually bound to one building in Ningbo, China, the inferences made would be helpful in establishing the general performance of thermal mass in humid subtropical climate which would assist building designers designing in this climate anywhere in the world. However, as the design and microclimate of each building plays a very important role in its performance, there are limits to the generalisability of the results. For this reason, it will not be advisable to prepare design guidelines based on the analysis of only one building. Based on a similar methodology as followed in this research, further research may look at thermal performance analysis of more institutional buildings in this climate zone. Due to high relative humidity associated with humid sub-tropical climate, there is risk of condensation occurring due to contact of moist air with cold internal surfaces in buildings. As an extension to this study, further research may test the risk of condensation associated with lightweight and heavyweight construction in humid sub-tropical climate zone.

ACKNOWLEDGMENTS

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REFERENCES

Extensive Green Roofs: Potential for Thermal and Energy benefits in buildings in central India

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ABSTRACT

Any building essentially contains walls and roof which are directly exposed to external environment. Undoubtedly the most critical part of the whole building surface is the roof as it receives the maximum solar radiation particularly in summer months thereby increasing the heat load in buildings. Many studies have been conducted over the years to consider the potential building energy benefits of Extensive Green Roofs. There is a sharp increase in the number of countries that conduct green roof research in the last two decades realizing its importance globally. A green roof offers a building and its surrounding environment many benefits, which include: storm water management, improved water run-off quality, improved urban air quality, extension of roof life and a reduction of the urban heat island effect; other benefits also include enhanced architectural interest and biodiversity.

Green roofs cool through latent heat loss and improved reflectivity of incident solar radiation. This suggests that green roofs are predominately seen as a passive cooling technique. Intensive literature review shows that barely any research is done in Indian context for usage of green roof. Green roofs are hardly visible in Indian context: probable reasons are lack of awareness, socio-cultural backgrounds and cost factors. Also it has not been given importance in local building bylaws. Moreover, an in-depth research is needed on green roof in Indian climatic conditions as we have longer sunny days with higher solar intensity (thereby increasing load on air conditioning). It may prove to be important ‘investment’ in longer terms considering the huge energy requirements in the future.

The paper also highlights study in composite climate of central India with high global horizontal irradiation. It highlights thermal simulation modelling using Autodesk Simulation CFD (Computational Fluid Dynamics) software, used as a tool to validate the summer cooling potential of extensive green roofs.

Key words: Extensive Green Roofs, Passive and Low Energy Architecture, Energy consumption in Buildings, Simulation Modelling

INTRODUCTION

Walls only receive about two-thirds of the maximum solar radiation that falls on the roof, and considerably less than this on the wall which faces away from the equator. The period of reception of direct solar radiation on walls is shorter than on roofs: east and west walls will only receive direct sunlight for half of the day. Undoubtedly the most critical part of the whole building surface is the roof.
In any location near the equator this receives the greatest amount of solar radiation, thus the highest heat load. The horizontal roof receives maximum solar radiation during the summer and generally is the main path of heat flux entering the living space.

City surfaces are prone to absorb and release large quantities of heat thereby creating urban heat-island effect. Urban heat-island (UHI) is a common phenomenon where urban temperatures are significantly higher than those of its surrounding suburban and rural areas in summertime. UHIs can affect communities by increasing summertime surface temperature of building envelopes and infrastructures; intensifying thermal discomfort; elevating cooling energy use and peak energy demand; adding air pollution; and raising risks in heat-related illness or mortality. A higher air temperature tends to increase cooling needs and reduce working efficiency of cooling systems for built environments, resulting in higher power demand and energy use.

The roof of a building can be fully or part covered with a layer of vegetation known as a Green Roof. A green roof is a layered system comprising of a waterproofing membrane, growing medium and the vegetation layer itself. There are two main classifications of green roofs; extensive and intensive. Extensive green roofs have a thin substrate layer with low level planting, typically sedum or lawn, and can be very lightweight in structure. Intensive green roofs have a deeper substrate layer to allow deeper rooting plants such as shrubs and trees to survive. Extensive systems offer the most cost effective solution over intensive types. Extensive roofs are the preferred option for retrofitting onto existing buildings as the structural capacity of the roof will often not have to be increased. Green roofs greatly reduce the proportion of solar radiation that reaches the roof structure beneath as well as offering additional insulation value.

India is experiencing an unprecedented construction boom. The country doubled its floorspace between 2001 and 2005 and is expected to add 35 billion m² of new buildings by 2050. Buildings account for 35% of total final energy consumption in India today, and building energy use is growing at 8% annually. Studies have shown that carbon policies will have little effect on reducing building energy demand. Various researchers have predicted that, if there are no specific sectoral policies to curb building energy use, final energy demand of the Indian building sector will grow over five times by the end of this century, driven by rapid income and population growth. The growing energy demand in buildings is accompanied particularly by an increase in electricity use. This also leads to a rapid increase in carbon emissions and aggravates power shortages in India. Growth in building energy use poses a challenge for the Indian government.

It becomes very important for architects, designers, builders and owners to focus on building designed with Passive measures, design tools and methods thereby reducing/kerbing energy consumption in buildings thereby moving in the direction of sustainability.

This paper addresses the potential building energy reduction benefits arising from the enhanced thermal properties of a Green Roof making it essential part of passive design and low energy architecture.

THE STUDY CASE

Variation of the solar thermal gain in a typical room with green roof using Autodesk Simulation CFD (Computational Fluid Dynamics) software as an analysis tool is investigated in this study as compared to that of a conventional bare roof situated in the state capital of Chhattisgarh state, Raipur having composite climate. Simulation is performed for one typical solar day corresponding to the peak summer season and generally peak temperature of the day in a given time so as to understand the difference between conventional and green roof outcomes. Because this scenario simulates a design day, the simulation of air movement is done with natural convection only.

Geometry

The room admeasuring 6.0 M X 3.5 M consisted of two windows on the southern side and a door on the northern side, east-west being the longer axis of the room, which is naturally ventilated had been taken as a case for the study. The construction of the room is of RCC framed structure having conventional RCC beams, columns, floor and roof along with brick work (0.23 M thick) covered with cement plaster as infill. Total height of the room taken including parapet is 4.05 M and interior room
height is 3.0 M.

The green roof consists of a waterproofing membrane (thickness taken as: 0.01 M), growing media: soil (thickness taken as: 0.15 M) and green cover: grass (thickness taken as: 0.10 M)

**Material Properties**

The simulations are performed for peak summer hours of 2:30 PM on 30th of May (Figure 1 to Figure 5). Considering the fact that because of time lag, temperatures in late hours than afternoon peak temperatures may give varied results; simulations are also done with the same parameters on the same day changing the time only to 6:00 PM in the evening (Figure 6 to Figure 10).

**Simulations**

The simulations are performed for peak summer hours of 2:30 PM on 30th of May (Figure 1 to Figure 5). Considering the fact that because of time lag, temperatures in late hours than afternoon peak temperatures may give varied results; simulations are also done with the same parameters on the same day changing the time only to 6:00 PM in the evening (Figure 6 to Figure 10).

**Table 1. Material Properties for Simulation Modeling**

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/m-K)</th>
<th>Resistivity (K-m/W)</th>
<th>DENSITY (kg/m^3)</th>
<th>SPECIFIC HEAT (J/kg-K)</th>
<th>EMISSIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air (variable) (void)</td>
<td>0.02563</td>
<td>-</td>
<td>Equation of state</td>
<td>1004</td>
<td>1</td>
</tr>
<tr>
<td>Brick with plaster: walls</td>
<td>1.44</td>
<td>0.69</td>
<td>2100</td>
<td>875</td>
<td>0.94</td>
</tr>
<tr>
<td>Glass (window)</td>
<td>0.78</td>
<td>1.28</td>
<td>2700</td>
<td>840</td>
<td>0.92</td>
</tr>
<tr>
<td>Hardwood (door)</td>
<td>0.16</td>
<td>6.25</td>
<td>720</td>
<td>1255</td>
<td>0.8</td>
</tr>
<tr>
<td>Steel concrete cement (floor, roof slab, columns &amp; beams)</td>
<td>1.75</td>
<td>0.57</td>
<td>2400</td>
<td>840</td>
<td>0.92</td>
</tr>
<tr>
<td>Water proofing membrane</td>
<td>1</td>
<td>1</td>
<td>950</td>
<td>837</td>
<td>0.8</td>
</tr>
<tr>
<td>Growing media: Soil</td>
<td>1</td>
<td>1</td>
<td>766</td>
<td>1000</td>
<td>0.92</td>
</tr>
<tr>
<td>Grass</td>
<td>0.115</td>
<td>8.69</td>
<td>500</td>
<td>1380</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Figure 1** (a) Temperature distribution without green roof and (b) Temperature distribution with green roof (both simulations at 2:30 PM, outside temperature: 44°C, humidity-13%, highlighting external surface temperatures around the room and roof)
Figure 2 (a) Temperature distribution without green roof and (b) Temperature distribution with green roof (both simulations at 2:30 PM, outside temperature: 44°C, humidity-13%, highlighting external surface temperatures around the room and roof)

Figure 3 (a) Temperature distribution without green roof and (b) Temperature distribution with green roof (both simulations at 2:30 PM, outside temperature: 44°C, humidity-13%, highlighting external surface temperatures around the roof)

Figure 4 (a) Temperature distribution without green roof and (b) Temperature distribution with green roof (both simulations at 2:30 PM, outside temperature: 44°C, humidity-13%, highlighting internal and external surface temperatures)
Figure 5 (a) Temperature distribution without green roof and (b) Temperature distribution with green roof (both simulations at 2:30 PM, outside temperature: 44°C, humidity-13%, highlighting internal surface temperatures)

Figure 6 (a) Temperature distribution without green roof and (b) Temperature distribution with green roof (both simulations at 6:00 PM, outside temperature: 40°C, humidity-12%, highlighting external surface temperatures around the room and roof)

Figure 7 (a) Temperature distribution without green roof and (b) Temperature distribution with green roof (both simulations at 6:00 PM, outside temperature: 40°C, humidity-12%, highlighting external surface temperatures around the room and roof)
Figure 8 (a) Temperature distribution without green roof and (b) Temperature distribution with green roof (both simulations at 6:00 PM, outside temperature: 40°C, humidity-12%, highlighting external surface temperatures around the roof)

Figure 9 (a) Temperature distribution without green roof and (b) Temperature distribution with green roof (both simulations at 6:00 PM, outside temperature: 40°C, humidity-12%, highlighting internal and external surface temperatures)

Figure 10 (a) Temperature distribution without green roof and (b) Temperature distribution with green roof (both simulations at 6:00 PM, outside temperature: 40°C, humidity-12%, highlighting internal surface temperatures)
RESULTS

As shown in Figure 1 to Figure 5, up to 4°C reduction in temperature difference is visible in simulation modeling above the green roof as well as inside the room in given location and environmental conditions as compared to that of bare conventional roof.

And in the same model changing timings of the simulation to 6:00 PM (shown in Figure 6 to Figure 10), shows difference more than 4°C temperature i.e. interior of the room will be more than 4°C cooler because of the presence of a green roof and similarly temperatures above the green roof also show similar differences.

CONCLUSION

Review of various scientific research works shows the importance and potential of green roof in numerous ways. Energy required for conditioning of spaces is aggravated in urban areas through the exhaustion of natural resources spent for electricity production (electricity production in the state of Chhattisgarh, India is by coal fired thermal power plants). Harnessing conventional fossil fuels and heat emissions by AC systems further add to the temperature increment in the environment. Planting a green roof will reduce a. exterior temperatures: thereby controlling micro climate because of plant’s presence and will reduce the urban heat island effect and b. inside temperatures: thereby reducing cooling loads inside the buildings.

The analysis of the simulations done with the help of computational fluid dynamics (CFD), clearly highlight the importance of a green roof as a passive design measure to be incorporated in buildings which would decrease the cooling requirements or the burden on the Air Conditioning systems for Raipur city in geographical location of the state of Chhattisgarh in central India.

An extensive review of the computational fluid dynamics (CFD) simulation results have exposed the following key factors when assessing their energy saving potential in the context of building use:

1. Observations of simulations providing green roofs in the buildings in the city of Raipur showed that green roofs are effective in reducing heat flow through the roof, thus lowering the energy demand for space conditioning in the building.
2. The green roof was effective in reducing high temperature and temperature fluctuations experienced by the roof membrane in conventional roofing system in the summer.
3. Since the average mean temperature was greater then comfort level temperature therefore, thermal comfort cannot be achieved only by providing green roof but it can reduce the load on air conditioning systems to considerable levels.
4. Results proved highly satisfactory and provided enough confidence for the study to be extended further for a larger solution space in real life measurements.

Figure 11 Benefits of Providing Green Roofs
Enormous use of ground for various purposes has lead to disappearance of green planted surfaces. In order to prevent dangerous and uncomfortable urban heat island effects the indispensable need of planted surfaces is quiet inevitable as is confirmed by many researchers. For example, a study estimated that an increase of 1°C in air temperature would require the addition of about 500 megawatts (MW) for air-conditioning of buildings in the Los Angeles Basin. Similar air temperature increases in urban areas are taxing the ability of developing countries to meet urban electricity demand while raising global greenhouse gas (GHG) emissions associated with energy use and power generation. Space constraints have further reduced the applicability of green surfaces in various areas surrounding the building envelope. Consequently, planting green roofs become very promising and stabilizing choice in the present scenario.

ACKNOWLEDGMENTS

The authors would like to acknowledge various works and researches performed by individuals and groups with the help of which authors achieved insight for writing this paper. This paper also benefits from CFD assistance of Ms. Pratibha Khandey.

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Session 6A : Material technology

PLEA2014: Day 2, Wednesday, December 17
14:10 - 15:50, Faith - Knowledge Consortium of Gujarat
WinOpt – An Early Stage Design Tool for Optimizing Window Parameters

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ABSTRACT

To help architects and designers make early design decisions, an online tool (WinOpt) has been developed. WinOpt optimizes various components associated with the design of windows, such as Building orientation/Azimuth Angle (angle with respect to North), Aspect Ratio, WWR (Window Wall Ratio), SHGC (Solar Heat Gain Coefficient) of glass used for windows, and various local shading strategies such as overhang and side fins. WinOpt performs annual energy simulations for a given location using EnergyPlus. It uses an optimization tool in the back end (GenOpt) to reduce the few million simulations to a few hundred, thus helping in making rapid design decisions. WinOpt optimizes the design to minimize the operational energy for conditioned buildings and could maximize thermal comfort for unconditioned buildings. It also has a parametric option where parametric simulations are performed for selected values for various input parameters. This can help the user understand the spectrum of design solutions. Since EnergyPlus can evaluate both thermal comfort conditions and energy consumption in a building, WinOpt could help in design decisions for low energy/ net zero energy buildings.

INTRODUCTION

Among the various end use energy consuming sectors, buildings form a significant portion. There have been various efforts to reduce building energy consumption during design as well as operational phases. Most of the solutions could be used in a cost effective manner when incorporated during the building design phase. To evaluate the performance of various energy conservation measures, there are various simulation tools available. A list of these tools is provided at the US Energy Efficiency and Renewable Energy website (Building Technologies Program: Building Energy Software Tools Directory, 2013). A comparison of available tools can be found at Crawley B. D. et al. (2008).

There are various tools available that can help in early design. Autodesk Vasari (2013) focuses on conceptual building design using both geometric and parametric modeling. It supports performance-based design via integrated energy modeling and analysis features. EnergyPlus (Building Technologies Program: EnergyPlus Energy Simulation Software, 2012) is one such tool which was developed by the U.S Department of Energy. During the design phase of a building, EnergyPlus allows the user to precompute the energy usage and thus optimize the building design. EnergyPlus performs a whole building energy simulation.
COMFEN (2013) is a tool designed to support the systematic evaluation of alternative fenestration systems for project-specific commercial building applications. It dynamically simulates the effects of these key fenestration variables on energy consumption, peak energy demand, and thermal and visual comfort. The results presented in graphical and tabular format within the simplified user interface for comparative fenestration design cases help users move toward optimal fenestration design choices for their project. COMFEN uses EnergyPlus as its computational engine.

Many times, architects and designers face the situation where the combinations of Energy Conservation Measures (ECMs) available to them can run in to few millions. Further, larger simulation run time for building simulation model could be exhaustive in terms of cost and time. Also, for large models, higher simulation run time could lead to a delay in the optimization process.

Various building energy optimization tools are currently available to the users. GenOpt (2013), a tool developed by Lawrence Berkeley National Laboratory, can optimize problems where the cost function is computationally expensive and its derivatives are not available or may not even exist. Another tool, BEopt (2013), provides capabilities to evaluate residential building designs and identify cost-optimal efficiency packages at various levels of whole-house energy savings. DesignBuilder (2013) has a parametric analysis facility that is useful for searching ‘optimal’ designs.

To find out optimization solution for their buildings, user needs to have expertise in both optimization tools and simulation tools. There is a need for tools where users can address the problem directly, without learning simulation and optimization tools. During the early design stage, architects are the main performers of energy simulation (Bambardekar et al., 2009). The designs are more conceptual, not specifying the complete details of the buildings. Further, there are large numbers of ECMs to be considered for the building. A few quick simulations need to be performed and optimal choices need to be identified for a sustainable design. In producing the WinOpt tool described here, we have considered some of the key factors involved in the design of a façade and developed a tool that can minimize the operational energy for conditioned buildings and maximize thermal comfort for unconditioned buildings.

To reduce the direct solar heat gain into the building, one needs to optimize the design elements of a window. A few of these factors are:
1. Building orientation of the building with respect to true North
2. Aspect Ratio of the building (Length/Breadth ratio of the building)
3. Window-Wall Ratio (WWR)
4. The type of glass in the windows
5. Details of shading devices such as depth of the overhangs and side-fins

To compute the energy consumption of a building, one needs details such as type of building, operational schedules, internal loads, and Heating Ventilation and Air Conditioning (HVAC) systems. Most of these variables are provided as default values in the simulation model so that a user can directly select their optimization variable, provide an acceptable range of values, and view solutions.

DESCRIPTION OF THE TOOL

WinOpt is a tool that performs a multi-parameter optimization for reducing the energy consumption of a building. WinOpt achieves this by using EnergyPlus to compute the energy consumed by the building and using GenOpt for optimizing the user-selected design parameters. The algorithm chosen for optimization by GenOpt is a hybrid of the Generalized Pattern Search (GPS) algorithm and the Particle Swarm Optimization (PSO) algorithm, which is used to initialize the search. These algorithms can perform optimization for both continuous and discrete independent variables. The continuous independent variables are Azimuth angle, WWR, Overhang depth, and Aspect ratio, and the discrete...
independent variable is the glass type of the window.

WinOpt is being developed as a web-based application. The tool is developed on Apache/2.2.16 (UNIX) and Web pages are developed in PHP and use JavaScript/jQuery Technologies. At the back end, socket programming has been implemented, the code for which is written in the C language. The inputs submitted from the User Interface (UI) are pre-processed by a PHP script that generates the corresponding EnergyPlus Input Data File (IDF) for the simulation. The IDF name and the weather file name are then sent to a bash script that manages the simulations while the front end shows the progress of the simulations. Once the simulations are done, the UI is redirected to the results page, which shows the results. The architecture of the tool is shown in Figure 1.

![Figure 1 Work flow diagram of WinOpt](image)

First, the tool takes the static parameters, which are the location of the building and HVAC type to be used in the building, as input. After the static parameters, it takes the ranges of the various variable parameters for which the building design is to be optimized. It then uses EnergyPlus and GenOpt to perform simulations in order to get an optimal output. There is also an option to perform parametric simulations on user specified values without any optimization, to give the user a complete spectrum of possible outputs for analysis.

In the tool, four different types of HVAC systems are available for selection – Packaged Terminal Heat Pump (PTHP), Packaged Single Zone (PSZ)-HP, Central Air Conditioning with a water cooled chiller, and Central Air Conditioning with an air cooled chiller. Each building type can be selected with any one of the available HVAC options listed in Table 1.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Parameter</th>
<th>PTHP</th>
<th>PSZ-HP</th>
<th>Central AC Water cooled</th>
<th>Central AC Air cooled</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Cooling Type</td>
<td>Direct Expansion coil</td>
<td>Direct Expansion coil</td>
<td>Water cooled screw chiller</td>
<td>Air cooled chiller</td>
</tr>
<tr>
<td>3.</td>
<td>Fan Control</td>
<td>Constant Volume</td>
<td>Constant Volume</td>
<td>Variable Air Volume</td>
<td>Variable Air Volume</td>
</tr>
<tr>
<td>4.</td>
<td>Coefficient of Performance (COP)</td>
<td>2.8</td>
<td>3.0</td>
<td>5.5</td>
<td>3.1</td>
</tr>
<tr>
<td>5.</td>
<td>Heating Seasonal Performance Factor (HSPF)</td>
<td>1.91</td>
<td>1.91</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>6.</td>
<td>Air-side economizer</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>
When GenOpt is used in the optimization mode, a series of random variable combinations are generated and simulations are performed to identify the low energy combinations. The optimization algorithm narrows down its search to the least energy consuming combinations from the above step. This leads to a clustering of variable combinations that produce low energy use. This could mislead a user about the range of solutions that are available. In order to make the user be more aware and cautious about the solution sets that are available, the option of performing a parametric simulation is also provided. Parametric simulation is a brute force method for performing simulations for all the possible combinations. This is time consuming but provides a full spectrum of results. Therefore, it would be useful for the user to be able to choose a limited set of variables for use in the parametric simulation based on the results from the optimization mode. Both these methods are compared in Table 2.

**Table 2: Comparison of optimization and parametric mode**

<table>
<thead>
<tr>
<th></th>
<th>Optimization mode</th>
<th>Parametric mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of simulations</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Time</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Knowledge about ECMs applicable for the given design</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

A case study that illustrates the operation of GenOpt and the difference between parametric and optimization results is presented in the following section.

**CASE STUDY**

Location – Hyderabad, India  
Building Type – Office  
Building Footprint – 100 sq.m  
Operation schedules – Mon – Fri (09:00 AM – 06:00 PM)  
HVAC system – PTHP

**Table 3 Input variables for optimization**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Step Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Building Orientation (°)</td>
<td>0</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Window Wall Ratio (%)</td>
<td>20</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Overhang Depth (m)</td>
<td>0.2</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
<td>Aspect Ratio</td>
<td>1</td>
<td>2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Input parameters and ranges used in the optimization mode are listed in Table 3 and the four different values of glass types used are listed in Table 4.
Table 4 Glass types for optimization

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Glass type</th>
<th>U-value (W/sq.m-K)</th>
<th>Solar Heat Gain Coefficient (SHGC)</th>
<th>Visible Light Transmittance (VLT) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Type-1</td>
<td>1.5</td>
<td>0.25</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>Type-2</td>
<td>3.72</td>
<td>0.28</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>Type-3</td>
<td>1.5</td>
<td>0.20</td>
<td>35</td>
</tr>
<tr>
<td>4</td>
<td>Type-4</td>
<td>5.7</td>
<td>0.67</td>
<td>67</td>
</tr>
</tbody>
</table>

Input parameters and ranges used in the parametric mode are listed in Table 5 and different values of glass types used for performing the simulations for parametric mode are listed in Table 6.

Table 5 Input variables for the parametric simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>Value 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Orientation (°)</td>
<td>0</td>
<td>45</td>
<td>90</td>
<td>135</td>
<td>180</td>
</tr>
<tr>
<td>Window Wall Ratio (%)</td>
<td>20</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>Overhang Depth (m)</td>
<td>0.3</td>
<td>0.5</td>
<td>0.8</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>0.6</td>
<td>1.0</td>
<td>1.3</td>
<td>1.5</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 6 Glass parameters used for the parametric simulation

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Glass type</th>
<th>U-value (W/sq.m-K)</th>
<th>SHGC</th>
<th>VLT(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Type-1</td>
<td>3.3</td>
<td>0.15</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>Type-2</td>
<td>3.3</td>
<td>0.25</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>Type-3</td>
<td>3.3</td>
<td>0.40</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>Type-4</td>
<td>3.3</td>
<td>0.60</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>Type-5</td>
<td>3.3</td>
<td>0.85</td>
<td>85</td>
</tr>
</tbody>
</table>

The results can be broadly categorized in two formats:

1. An 'N' dimensional interactive graph as shown in Figure 2 and 3. Using this graph, the user can get insights such as which combination of variable parameters produces the best performance in terms of energy use. The user can also study the impact of various parameters on the performance of the building.

2. A 'Bitmap' visualization of the data as shown in Figure 4. This visualization is available only for parametric simulations. This visualization is useful for finding and understanding clustering (if it exists) in the energy consumption of the building. Therefore, using this visualization, the user can study the parameters that have a major impact on the energy consumed by the building.
Figure 2 Near-optimal solutions obtained using GenOpt, which are used to inform the selection of parameters for use in the parametric study.

Figure 3 Results obtained by performing parametric simulations.

Figure 4 Bitmap visualization of the data.
The following observations can be made from the Bitmap Visualization from Figure 4 & 5:

1. The **Green Region** in the graph shows the areas that are close to the minimum energy as given by parametric simulations (within 5%). As can be seen, this could be achieved by diverse combinations.

2. The **Black Point** in Figure 5 shows the minimum energy value obtained by parametric simulations.

3. The **Red Region** shows the area of maximum energy consumption which appears to be highly clustered in regions of high WWR and high SHGC.

4. The color gradient in graph goes from Green to Blue to Red, where green represents the minimum energy consumption, with blue color depicting medium energy consumption and red depicting high energy consumption.

Also, from the visualizations, we can see that GenOpt performs only an optimal number of simulations to find the most energy efficient configuration and the solutions begin to cluster around the local minima. The energy ranges from 12,841 kWh to 21,044 kWh in the graph showing the results of parametric simulations, performed only on specific values of variable parameters as shown in Figure 3. Hence, this gives a broader spectrum of energy consumed by the building, as compared to performing optimized simulations, in which energy ranges from 12,920 kWh to 18,093 kWh. We can also see that the minimum energy found by performing an optimized number of simulations using GenOpt is very close to the minimum energy obtained by performing parametric simulations on specified inputs.

Also, from Figure 4, it is seen that, as the WWR increases, the clustering in the lower right corner increases. This shows that with increasing WWR, the energy consumption of the building also increases. This observation is in accordance with what one would expect of energy consumption in hot areas. Therefore, using the visualization presented in Figure 4, we can analyze the clustering in the energy consumption statistics of the building.

**CONCLUSION**

WinOpt optimizes the design parameters of the windows for minimal operational energy consumption of a conditioned building. It helps in reducing the total number of simulations to be performed and also has visualization tools embedded within it for easier and faster analysis. This tool can therefore be useful in reducing the time and cost for the early stage design.

From the case study, it was found that the total number of simulations performed by WinOpt was 311. However, if each and every possibility has been simulated individually, the simulation count would have been 246,848 (19 x 7 x 29 x 16 x 4). Here 19 different values of azimuth, 7 different values of WWR, 29 different values of Overhang Depth, 16 different values of Aspect Ratio, and 4 different values of Glass Type are considered. The 311 simulations are then only 0.12% of the total possible simulations.

The parametric option in WinOpt is helpful for the users to understand the spectrum of design solutions. With the help of different visualizations that the tool provides, the users can get useful insights about the energy consumed by the building, which can help them in making rapid design decisions for their buildings.

Since the backend of WinOpt uses EnergyPlus as an engine for simulations, the tool could be
modified to support simulation for free running / naturally ventilated buildings by evaluating thermal comfort conditions instead of the energy consumption of the building; WinOpt could then also help in design decisions for low energy/ net zero energy buildings.

ACKNOWLEDGEMENT

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REFERENCES


The Four Sustainable Design Perspectives

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ABSTRACT
This paper, illustrated with built examples, uses Integral Theory to map four distinct yet ever-present perspectives on Sustainable Design, each with fundamentally different methods, criteria for value, and definitions of good form. The perspectives are articulated by intersecting two primary distinctions: 1) subjective (interior) vs. objective (exterior) ways of knowing and 2) perspectives of individuals (parts, persons, members) vs. collective systems ( wholes, networks, societies). This yields four different viewpoints: Behaviours (singular-objective) [the “IT” prospects], Systems (collective/inter-objective) [the “ITS” prospects], Experiences (singular-subjective) [the “I” prospects], and Cultures (collective/inter-subjective) [the “We” prospects]. From each of these varied perspectives on design, the nature of Sustainable Design and that of Nature itself show up quite differently. Yet many Sustainable Design approaches are primarily grounded in the singular-objective Behaviours Perspective. The expanded multi-perspectival view presented here can enable designers to more comprehensively address the complexity of today’s ecological challenges by including the individual, cultural and social dimensions that contribute to the creation of a sustainable world.

Keywords: integral theory, performance, systems, cultures, experiences, sustainability

1 INTRODUCTION
Perhaps because of the dominance of empirically-based sustainability perspectives, and the culturally predisposed listening that many of us have for it, designers commonly equate sustainability with technology and sustainable technology with quantifiable energy efficiency or its visible hardware, such as photovoltaic collectors. While Sustainable Design is increasingly associated with performance measures, the wider profession is, on the other hand, increasingly ideologically pluralistic. Despite this pluralism, the design fields, and Sustainable Design in particular, seem to have no collective framework for navigating and transcending the fragmentation that entrenches both academia and practice.

Subjective perspectives are missing from most Sustainable Design thinking. As an example, in the US, there are no LEED credits for creating experiences of beauty, none for creating or fitting to ecological order and none for placing people into rich symbolic relationships with Nature. Quality and subjectivity do not appear on this horizon. This is not to argue for devaluing this approach: the technological view of Sustainable Design has done great things for our awareness of the limits of resources and environmental sinks—and the relationships of building design to these.

Similarly, environmentalism based on scientific rationalism has not been very effective. The message goes something like this: ‘Look, we have the facts … the sky is falling, we’re running out of everything you need, the climate is going crazy and Nobel laureate Al Gore (former US Vice-President) has pictures of the polar caps that should scare the pants off of all of us.’ Well, if that does not work to get our collective profession in action, statistics about the contribution of buildings to landfill waste, water consumption and CO₂ production probably will not work too well with a broad audience either—that is, when that’s the only argument we are making. To address these issues, this paper expands on the
theoretical views introduced in Integral Sustainable Design [1, 2] which was the first work to apply Integral Theory [3, 4] to design, and in particular to the field of Sustainable Design.

2 INTEGRAL THEORY’S FOUR PERSPECTIVES

Integral Theory is an emerging theory base that the author has found to be helpful in teaching and thinking about the complexity of Sustainable Design. An integral theory begins with the assumption that everyone is right—at least partially—and seeks to fashion an intellectual framework that both transcends and includes differences. An integrally-informed approach to Sustainable Design (or anything else) challenges us to hold *multiple simultaneous perspectives* and to address different levels of awareness across the spectrum of human development. Integral Theory is a model that could help design educators and practitioners reconsider the scope, breadth, and multifaceted aspects of sustainability. Integral Theory, as developed by the philosopher Ken Wilber, is based on a cross-cultural comparison of human knowledge, experience, and inquiry [3, 4].

This paper is limited to the study of one of the most fundamental aspects of the integral model: *quadrants*. At its most essential level, Integral Theory organizes variables for any problem into a matrix of *quadrants* that intersect individual and collective phenomena with objective and subjective knowledge. These combined variables reveal the following considerations (See Fig. 1): 1) *Experiences*: self and consciousness; 2) *Behaviors*: science, mechanics and performance, 3) *Cultures*: meaning, worldviews, and symbolism, and 4) *Systems*: social and natural ecologies and contexts.

The four quadrants are not separate phenomena, but rather four simultaneous perspectives on any event. For this reason, this paper uses the term *perspectives* in place of *quadrants*. Each quadrant or dimension of reality is ever-present and co-arises with the others. The philosopher Michael Zimmerman notes that “The quadrant perspectives correspond generally to the four ways in which universities divide research methodologies (that is, truth-claim generating practices or paradigms): fine arts (UL), humanities (LL), natural sciences (UR), and social and systemic natural sciences (LR)” [5].

Often the two right-hand quadrants, both objective, are considered together, yielding *three value spheres*, associated with *Self* (UL), *Culture* (LL) and *Nature* (UR/LR), or alternatively, *Art, Morals, and Science*. Wilber refers to these as “The Big Three,” noting that each domain can be associated with the fundamental language distinctions of *I*, *WE*, and *IT/ITS*, or first, second and third person perspectives. This indicates that the perspectives are not opinions or speculative theory, but rather, are so fundamental as to be embedded in all natural languages. The Big Three are the classic value domains of *Beauty, Goodness* and *Truth*. The point is that every event in the manifest world has all three (or four) of those dimensions. You can look at any event from the point of view of the ‘I’ (how I personally see and feel about the event); from the point of view of the ‘we’ (how not just I but others see and understand the event); and as an ‘it’ (the objective facts of the event) [6]. The four fundamental perspectives on any occasion (or the four basic ways of looking at anything), turn out to be fairly simple: they are the *inside* and the *outside* of the *individual* and the *collective* [6].
3 THE FOUR INTEGRAL SUSTAINABLE DESIGN PERSPECTIVES

Figure 2 shows ‘The four Sustainable Design perspectives.’ The proposition is that each type of perspective is ever-present in all languages and cultures; each both discloses and occludes certain phenomena. An Integral approach to design is one that unites the beautiful, the art of design, and the good, the ethics of design, with the true, the science of design. We can also think of design as having four primary dimensions (the four perspectives of the quadrants), each requiring different perspectives on the practice and products of design:

- **Behaviours Perspective**: individual parts or members with their performance characteristics, activities, and functions;
- **Systems Perspective**: patterns of forms and flows of energy, information, people, and materials that order ecological and social relationships;
- **Experiences Perspective**: systemic members (human and non-human) with various forms of perception, sentience, and awareness;
- **Cultures Perspective**: shared meaning and understanding at various levels of complexity arising from individual members interacting with each other.

Applied to the consideration of Sustainable Design, the framework reveals that much of the current dialogue takes the Perspective of Behaviours [UR] and is concerned primarily with performance that can be ‘measured and weighed,’ an important, yet partial view. The Perspective of Systems [LR] reveals that eco-efficiency is not enough by itself to create healthy ecological pattern, and that a logic of ‘systems and relationships’ can be used to organize the UR logic of ‘parts and performance,’ either of which can constitute a reduction to ‘flatland’ (Fig. 3). High-performance design collapses everything to the upper right quadrant. Green, ecological approaches collapse reality to the lower right quadrant, or to the right side of the four-quadrant matrix (the web-of-life). Wilber calls this subtle reductionism as contrasted with the gross reductionism of the upper right. It may be that paying more attention to the perspectives of Experiences [UL] and Cultures [LL] has the potential to vastly expand the effectiveness of the objective arguments for ‘design with nature.’ Objective, mental arguments often fall on deaf ears for people oriented primarily with values from the subjective (what it feels like to me) and the inter-subjective (what is means to us) perspectives.

4 INTENTIONS AND CRITERIA FOR GOOD FORM FROM THE FOUR PERSPECTIVES

Architectural design is a discipline that requires the shaping of form; in the end, something is built or it is not a building. We can then ask the following questions: 1) **Thinking as designers, how shall we shape**
form for sustainability from each perspective? and, 2) From each quadratic perspective, what is the designer’s intention and what are the criteria for good form relative to sustainability?

From the Behaviours Perspective [UR] the design question is: How shall we shape form to maximize (eco)performance? Good form minimizes resource consumption and pollution while maximizing preservation and recycling.

From the Systems Perspective [LR] the design question is: How shall we shape form to guide ecological flows? Good form solves for ecological pattern by creating structure in the built environment that best accommodates ecological processes through mimicry of and fitness to the context of natural ecosystems.

From the Cultures Perspective [LL] the design question is: How shall we shape form to manifest the meanings of ecological systems and our relationships to them? Good form reveals and expresses ‘the patterns that connect’ in ways that celebrate the beauty of natural order, place inhabitants into relationships with living systems (or their idea of Nature) and situate human habitation in bioregional place.

From the Experiences Perspective [UL] the design question is: How shall we shape form to engender experiences of Nature and process? Good form orchestrates rich human experiences of Nature and its phenomena and creates centring places conducive to self-aware transformation to higher levels of (ecological) consciousness.

5 NEW PRINCIPLES FOR INTEGRAL SUSTAINABLE DESIGN

Given the heterogeneous ideas of Sustainable Design, the following illustrative principles have been defined in Figure 4 for each perspective. A principle is a statement of the fundamental basis of something, a truth or proposition, as an injunction, that makes ideas portable. Principles serve as the basis of a system of belief or reasoning, and they can be applied across a range of situations. There could be more or less than those given. The principles below follow as articulations of what can be called “an Overarching Principle of Integral Sustainable Design”: Design for sustainability by considering multiple levels of developing complexity in the intersecting domains of self, culture and Nature.

Experiences perspective [UL]
- Design profound aesthetic experiences of natural processes and a living world, accessing multiple senses.
- Design to access human psychological connections to place, at multiple levels from archetypes to the Transpersonal.
- Design centring places conducive to self-aware transformation to higher levels of Nature consciousness.

Behaviours perspective [UR]
- Design high-performance buildings that maximize efficient use of water, energy and material resources while minimizing waste and pollution.
- Design with on-site renewable resources of sun, wind and light.
- Design to create safe, healthy places with long-term value, eliminating toxicity to present or future generations.

Systems perspective [LR]
- Design at three levels of holarchy: to build a larger whole, to create a whole and to organize smaller wholes.
- Design living systems using ecology as the model. Fit flows to local renewable systems while also supporting techno-industrial ecosystems.
- Design solutions fit to particular places, considered as local site, larger neighbourhood and region.

Cultures perspective [LL]
- Design based on a high and conscious environmental ethic in which humanity and Nature both thrive in regenerative human ecosystems.
- Design to place people into significant relationships with Nature by making visible how culture is interconnected with living systems.
- Design for cultural communication by using the symbolic languages of design to make evident the meaning of ecological systems.

Figure 4  Design principles from the four perspectives

6 THINKING AND BUILDING FROM THE FOUR PERSPECTIVES

Each of the four foundational perspectives require a different way of thinking. These distinctions in
thinking yield different concerns for Sustainable Design and a different sustainable architecture. They can also be combined. At an Integral level of complexity, a design might consciously employ all four.

6.1 Thinking and Building from the Behaviours Perspective

The Behaviours Perspective employs an analytic logic of parts and performance that allows designers to dissect projects, measure performance and assess results. It assures efficiency of the constituent building parts. We understand the order of the whole in terms of our knowledge of individual elements. It is the most clear and certain way of design thinking. Behaviours Perspective methods depend on observation and on what can be derived from observation. They require us to look scientifically and objectively at observable phenomena, the behaviours of things and people and at the relationships that are seen and quantifiable. Out of this measuring of things one arrives at high-performance buildings as a goal. Its logical extension is plus-energy buildings, zero-emissions buildings, and so on. This perspective reveals that we are running out of many resources and polluting at rates faster than Nature can absorb. It implies a shift from finite to renewable resources. It’s also the perception that takes our vital signs and the planet’s and researches what is healthful and what is not. Thus, in addition to net-zero resource use, infinite recycling and the transition to design with renewables, it promotes a non-toxic environment. Who can argue with that?

Figure 5  Santa Clarita transit maintenance facility, Santa Clarita, California, 2008; © HOK

The first LEED Gold certified straw bale building (Fig. 5), this super-insulated building utilizes photovoltaics to provide half of the operational energy needed and reacts automatically to changing climatic conditions of its desert climate. It uses under-floor air distribution and high-performance glazing. The combination of high- and low-tech solutions helps this building to exceed stringent California energy efficiency standards by 40 per cent.

6.2 Thinking and Building from the Systems Perspective

The Systems Perspective uses a logic of systems and relationships. It is concerned with finding patterns as a basis for making effective design decisions. It is an associative logic that allows designers to see relationships between facts, forces, processes and form. Whereas the Behaviours Perspective tends toward thinking about the ‘application of technology’ and uses quantity as the criteria for success, this perspective embeds technology in architectural patterns, fitting design to its contexts. The Systems Perspective is inter-objective, a third person perspective on social and natural systems. Integration is its most prized value.
In buildings, energy-efficient elements can be combined in intelligent ways to make buildings as energy systems. An example is a passive solar-heated building that can be combined with efficient envelopes and with spatial organizations, orientations and materials to collect, store and redistribute solar energy in complex diurnal and seasonal patterns. The systems of the passive solar-heated building can be combined with those of the naturally ventilated and daylighted building systems. These can be integrated with active mechanical systems, on-site green power systems, and so on. These energy systems can be further integrated with spatial systems, with patterns of use and social order, the order of structural, material and construction systems, with hydrologic systems in the building and site, natural habitat on site, larger contextual urban systems, and so on.

![Figure 6 Solar Farmhouse, Fox, Arkansas, © Gary Coates, with Kansas State architecture students](image)

In the Solar Farmhouse (Fig. 6), the vernacular dogtrot type meets an atrium and solar greenhouse in a traditional Ozark mountain farmhouse language. The building is organized a series of interrelated design patterns, both social and climatic [7]. The "Dog-Trot Atrium" pattern as a transformation of Alexander's pattern, "Common Areas at the Heart," functions also as a stack-ventilation room and a toplight room. The house is heated by direct gain rooms with solar collection from individual windows and a ridge-top skylight, combined with a substantial two-storey sunspace. Translucent, cylindrical water-filled fiberglass tubes located between the sunspace and the great room serve as thermal mass (and as a food-producing greenhouse), with additional mass in an under-floor rock bed and in the stone walls of the greenhouse stair. The open plan and section allow warm air to rise and enter upper rooms via interior windows, while stratified air is recovered from the top of the atrium and returned to ground level.

6.3 Thinking and Building from the Experiences Perspective

In thinking about the Experiences Perspective, we are concerned with the interior experiences and intentions of designers and with the experiences of the occupants of a sustainable design. For Sustainable Design to be more effective, designers can address the fundamental reality and richness of our human interior experiences. Essentially, if people are to love sustainably designed environments, by necessity designers will have to create loveable places! This means we may choose to design rich full-person experiences, including a range of aesthetic experiences, because responsible action flows most freely from affection, which of itself requires an engaged relationship. A mature Integral Sustainable Design fully engages the human experience of Nature and the subtleties and richness of human feeling in space and place. It is also time for the cultivation of a highly developed theory and practice of Integral Sustainable Design aesthetics that is developmental and multi-perspectival.

To have meaningful discourse about ecological relationships in designed things, individuals must be able to perceive and experience these relationships. Sustainable Design can then ask the design question: How can important ecological relationships—and the ways design creates relationships to these—be made into significant human-felt experiences?
Through extensive design for natural ventilation, the Marie Short House (Fig. 7) creates the experience of the process of ventilative cooling. Adjustable steel louvers in the walls control the flow of wind-driven cross-ventilation, while fixed wood louvers allow airflow beneath gables and above open porches. Wide eaves protect from the sun; open plans align space and moving air. And the building communicates the relationship of form to these processes. In its passivity is the occupant’s experience of connection to process and place.

Think of the building as an instrument that’s picking up all these sounds..... It’s addressing the topography, the wind patterns, light patterns, altitude, latitude, the environment around you, the sun movements. It’s addressing the summer, the winter and the seasons in between. It’s addressing where the trees are, and where the trees are will tell you about the water table, the soil depth, climatic conditions.’ —Glenn Murcutt [9]

6.4 Thinking and Building from the Cultures Perspective

Designers understand that both the relationships of the natural world (gravity, climate, energy, ecology, etc.) and human relationships (social interactions and human interactions in culture) must be solved for. Seeing Sustainable Design from the Cultures Perspective asks designers to look at how any design places us into relationship with Nature in ways that embody meaning. Anything we design creates or modifies a system of ecological relationships and places humans into an inhabited system in which our relationships to natural forces and processes are tightly bound.

Looking at design from this perspective, designers can ask, How can Sustainable Design be appropriately ordered to fit its cultural context? and How can the patterns of ecological relationships in which the building participates be made culturally significant and appropriate?

Serving as a place to educate visitors on native ecosystems, the Shangri La Botanical Gardens (Fig. 8) use the surrounding site as part of its regionalist architecture. This LEED Platinum project serves primarily as an interpretive centre for the site’s native ecosystems (cypress and tupelo swamp, wooded

Figure 7  Marie Short House, Kempsey, New South Wales, Australia, 1975, Glenn Murcutt [8]

Figure 8  Shangri La Botanical Gardens and Nature Center, Orange, Texas, 2004, Lake/Flato [10]
uplands, and prairie lowlands) as well as a facility for study and research. Nature centres are some of the clearest American expressions of a postmodern Cultures Perspective on Sustainable Design, because they take a clear attitude on what Nature is and tell the story of the human relationship to Nature. While it may perform well, this performance is in service to a cultural ethic.

7 CONCLUSION

A premise of Integral Sustainable Design is that more expansive perspectives on the world are necessary to meet the diverse ecological, social, cultural, ethical, and technological challenges of the twenty-first century. Species interdependence and humans’ role in shaping a sustainable future require new approaches that include, yet expand the current emphasis of Sustainable Design on scientific-objective measures. The implication for design is not that each building should address all four perspectives all the time, but rather, that one can be integrally-informed by this expanded view and thus consider, using the tools and methods of that view, each of the four perspectives to question whether or not the issues embedded in the each are relevant for the project at hand.

In addition to designing high-performance buildings and sites, a more Integral view of Sustainable Design incorporates understandings of problems and their solutions that also address the other three important classes of issues.

The highest levels of performance require a systemic approach using method and concepts revealed only from the Systems perspective. Performance in an ecosystem is about dynamically balanced exchanges of energy, information and materials that bring systemic health. Ecological health trumps green efficiency.

The inclusion of a focus on the Experiential Perspective on Sustainable Design fosters the possibility of direct personal knowledge of Nature. Knowledge always precedes care. Care often gives rise to spontaneous action that benefits the object of care. We humans tend to care more about those we know than those we don’t know. Having groups of people have experiences of ‘Nature-via-design’ gives rise to dialogue and interpretation, the key to cultural transformation. Culture in a sense is the effect of all of our conversations. So as designers, can we give people something to talk about?

When Sustainable Design manifests, reflects and expresses ecological processes (from the Cultures Perspective), such as the water cycle for example, it gives people the opportunity to become more aware of living processes and their relationships to them. The stories of our relationships to Nature as told though ecologically expressive built works are powerful. Such expression could allow Sustainable Design to become as transformative of the settled landscape as was post-war suburbia.

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ABSTRACT

How can the summer behaviour of timber buildings be improved without worsening its seismic performance? The research developed by Fraunhofer Italia, Free University of Bozen-Bolzano and supported by Trees and Timber Institute CNR – IVALSA, focuses on passive features of the building envelope. Combining the classifications of the Italian territory based on climate (equivalent Cooling Degrees Days) and structural indicators (horizontal elastic response spectrum), possible improving strategies with thermal mass for different climatic zones are identified. The research considers both building physics and structure implications and matches two structural typologies (Platform Frame and Cross-Laminated Timber) with different building features. The building physics analysis determines some effective building components whose improved cooling energy performances are evaluated by dynamic simulations under the critical period. The structural analysis is aimed at calculating seismic behaviour and limits of a timber structure with applied additional mass loads. The following paper describes the TIMBEEST research methodology by providing work-in-progress results.

INTRODUCTION

The development of architecture features is significantly influenced by the geographical situation. Timber buildings are mostly widespread in cold climates, because of a good thermal performance and the availability of raw material. In fact, the use of timber constructions, especially lightweight walls, is not common in the Italian building stock. The low thermal inertia of timber buildings is identified as one of the main reasons for the worsening of summer thermal behaviour in comparison with clay block or concrete. Hence, it is a limit during the cooling season in hot climates. Passive design of building envelop considers environmental circumstances such as local climate and site conditions, and adopts suitable passive cooling techniques as thermal mass in order to reduce indoor temperature without the use of HVAC systems. Since 1970s, researchers have studied the effect of thermal mass on energy demand and cooling/heating peak loads. Furthermore, the distribution optimization of thermal mass layer and the effective thickness have been investigated. Baverstock demonstrated that the thermal mass effect...
in a commercial building, located in Perth (Australia), decreased the cooling peak loads of 27%. On the basis of a specific time-dependent method, Shaviv evaluated that the optimum thickness of a concrete thermal mass should be 10 cm for internal partition and 15 cm for external walls. Brown proved that thermal mass applied to walls and floors made possible to achieve cooling demand decrement of 18-20%. Robertson provided recommendations regarding the best use of thermal mass in residential and small commercial buildings: a 5-10 cm mass wall is usable for daily heat absorption, storage, and release, and it is possible to obtain an annual reduction of sensible heating and cooling as high as 40% for the mild climates. Kosny and Kossecka determined that the distribution of thermal mass on internal side of walls is the best solution for U.S. climates in order to decrease the energy demand. Al-Sanea and Zedan demonstrated that for the arid climate of Riyadh (South Arabia) the thermal mass distribution is optimal when split in two parts by insulation layers, placed at inside, middle, and outside. A previous Fraunhofer research project (Paradisi et al., 2012) regarding the improvement of summer thermal behaviour of timber building investigated and prototyped the technology, which integrates aluminium tubes filled with sand and water on internal side of wall. It has been used in the “Med in Italy House” during the Solar Decathlon Europe 2012 competition, held in Madrid. The thermal assessments, carried out by both dynamic simulation and monitoring campaign, confirm that thermal mass in direct contact with the indoor environmental notably influence thermal comfort and cooling peak loads. TIMBEEST research project aims at understanding the possibility of improving the summer behaviour of timber buildings across the Italian territory by using thermal mass without worsening its seismic performance. This because Italy is a country characterized by an intense and widely spread seismic activity (Civil Protection Department) and high temperature during summer (Pinna, 1978), especially in southern areas. Timber technology presents an excellent structural behaviour in seismic zones, but its low thermal inertia (compared to clay block or concrete buildings) is one of the reasons for worsening the energy performance in cooling period. Since timber technology is rare or even absent in Central and Southern Italy, it is an opportunity to investigate the technological feasibility and effectiveness of timber buildings, considering both thermal performance and structural implications. Three research entities – Fraunhofer Italia for technological development and thermal assessments, Free University of Bozen-Bolzano for dynamic simulation, and Trees and Timber Institute CNR – IVALSA for structural aspects – are trying to answer this question thanks to the Autonomous Province of Bolzano-Bozen which supports the research project.

METHODOLOGY

In order to achieve the mentioned goal, the research is structured in three phases as follows:

1. Maps of the Italian territory visualize physical features regarding external restraints such as climate and seismic indicators (equivalent Cooling Degree Days CDD and horizontal elastic response spectrum Se, respectively). The combination of these indicators allows creating a Synthesis Map, which pinpoints the critical areas for timber buildings in terms of summer thermal and seismic behaviour.

2. In order to evaluate energy and structural performances, the most common sample of standard buildings components (walls, roofs, slab/floors) in Platform Frame (PF) and Cross-Laminated-Timber Panels (CLT) with different types of insulation materials is identified. These building components are applied to a reference model, used for dynamic simulations.

3. Based on scientific literature review on thermal mass, on dynamic simulation output data and on linear static analysis, the standard building components are improved. A multi-criteria analysis is developed in order to find out the solution of thermal mass integration in the building envelope which is optimized for 110 capital cities of Italian Provinces. The output data of this phase will be applied to further dynamic and seismic dynamic simulations in order to define the percentage of improvement and its geographical extent, comparing both standard and improved building components.

First phase: Analysis

The first analysis is focused on external restraints regarding energy aspects. In order to achieve a better evaluation of building energy performance, dynamic simulation tools require more complex and detailed inputs such as hourly weather data (Pernigotto et al., 2013). The Test Reference Year TRY as
defined by the European technical standard EN ISO 15927-4:2005 is considered as weather data. The TRYs are those provided by CTI – Italian Technical Committee at May 2013. In order to qualify the Italian territory by the high temperatures during summer which can affect the cooling energy demand of buildings, the research team of the Free University of Bolzano-Bozen calculates the equivalent Cooling Degree Days (CDD, [K d]) referred to TRY according to Gasparella et al. (2011). The equivalent CDD, also called Climate Indicator (CI), is calculated for the period from May to September considering: 1) monthly average sol-air temperature ($\theta_{\text{sol-air}}$, [°C]) referred to three different horizontal surfaces with absorption coefficient value ($\alpha$, [-]) respectively 0.3, 0.6 and 0.9; 2) setpoint of cooling temperature ($\theta_{\text{in}}$, [°C]) equal to 26 °C. CI indicates the climate characteristic given by temperature and solar radiation of the typical year referred to all Italian capital cities. It is classified in quartiles, as shown in Table 1 and visualized using QUANTUM GIS software, as shown in Figure 1a. The second analysis aims at classifying the Italian territory according to seismic action. Italy is a country characterized by a high seismic activity including areas with low energy earthquakes (e.g. Vesuvius area, Etna area), and areas with seldom earthquakes with higher energy (e.g. Eastern Sicily, Calabria Apennines), as states by the Civil Protection Department. In order to provide a Seismic Indicator (SI), which describes the seismic action on buildings, throughout the Italian territory, the horizontal seismic action on buildings is calculated by the research team from the CNR – IVALSA. To define it, the elastic horizontal ground acceleration response spectrum ($S_e(T)$, [g]) is calculated for 110 capital cities of Italian Provinces according to NTC 2008 and Eurocode 8, assuming the type D of ground classification. Figure 1b represents an example of elastic response spectra: x-axis shows the structural period of the building. It is also possible affirm that the fundamental period of timber buildings presented in this study is typically between 0.1 [s] and 0.5 [s]. The calculation of $S_e(T)$ is carried out using Simqke software [12] developed by the University of Brescia. The SI is ranked in five classes according to the SI previously defined, as shown in Figure 1c and Table 2.

### Table 1. Classification of Climate Indicator in Italian territory for different horizontal surfaces

<table>
<thead>
<tr>
<th>Class</th>
<th>Cooling Degree Days (CDD), $\alpha = 0.3$</th>
<th>Cooling Degree Days (CDD), $\alpha = 0.6$</th>
<th>Cooling Degree Days (CDD), $\alpha = 0.9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (light green colour)</td>
<td>&lt; 225 (K d)</td>
<td>&lt; 560 (K d)</td>
<td>&lt; 950 (K d)</td>
</tr>
<tr>
<td>B (yellow colour)</td>
<td>225–290 (K d)</td>
<td>560–670 (K d)</td>
<td>950–1100 (K d)</td>
</tr>
<tr>
<td>C (orange colour)</td>
<td>290–360 (K d)</td>
<td>670–750 (K d)</td>
<td>1100–1180 (K d)</td>
</tr>
<tr>
<td>D (red colour)</td>
<td>&gt; 360 (K d)</td>
<td>&gt; 750 (K d)</td>
<td>&gt; 1180 K d</td>
</tr>
</tbody>
</table>

### Figure 1

a) Map of CI ($\alpha = 0.6$); b) Examples of elastic horizontal ground acceleration response spectrum of cities in Sicily; c) Map of SI

### Table 2. Classification of Seismic Indicator in Italian territory

<table>
<thead>
<tr>
<th>Class</th>
<th>Horizontal seismic action ($S_e(T)$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non seismic zone (grey colour)</td>
<td>-</td>
</tr>
<tr>
<td>I (yellow colour)</td>
<td>&lt; 0.4 (g)</td>
</tr>
<tr>
<td>II (light green colour)</td>
<td>0.4–0.6 (g)</td>
</tr>
<tr>
<td>III (green colour)</td>
<td>0.6–0.8 (g)</td>
</tr>
<tr>
<td>IV (dark green colour)</td>
<td>&gt; 0.8 (g)</td>
</tr>
</tbody>
</table>

In order to characterize the territory according to the environmental indicators (EI and SI), which influence the thermal and structural behaviour of buildings, the Synthesis Map using QUANTUM GIS
software is created, as shown in Figure 2. The Synthesis Map is the result of the overlapping CI and SI maps, identifying nineteen combinations. Each of these maps is referred to the horizontal surface with all three absorption coefficient. Considering the typical use of tiles on roofs, the map with the absorption coefficient value $\alpha = 0.6$ is the reference for any further evaluation. The Synthesis Map highlights the critical areas, in which contemporary risks of overheating and earthquake occur. This analysis is fundamental for further development of the research, especially for the definition of the improved building components.

**Second phase: Energy and structural performance of standard building components**

Based on the most common technological solution of timber construction (Benedetti et al., 2010), the research team of Fraunhofer Italia Research individuates samples of standard buildings components (walls, roof, external slab and floors) in two timber technologies – Platform Frame (PF) and Cross-Laminated-Timber Panels (CLT). The dimensions of beams and studs, distance between elements and thickness of panels are calculated by a structural pre-analysis made by CNR-IVALSA according to NTC2008 taking into account the most severe load configuration. The following building components are combined with different types of insulation materials: 1) walls with natural, mineral and synthetic insulation; 2) double-pitch roof with natural, mineral and synthetic insulation; 3) flat roof with synthetic insulation; 4) external slab with synthetic insulation; 5) indoor floors with acoustic insulation. Material characteristics of each layer refer to the database within WUFI software developed by Fraunhofer IBP and UNI 10351:1994. In order to evaluate building thermal performance in the summer period, twenty standard building components have been designed. The evaluated quantities are: 1) thermal transmittance (U-factor, [W m$^{-2}$ K$^{-1}$]); 2) periodic thermal transmittance ($Y_{ie}$, [W m$^{-2}$ K$^{-1}$]); 3) time shift ($\phi$, [h]); 4) decrement factor ($f$, [-]); 5) internal areal heat capacity ($k_i$, [kJ m$^{-2}$ K$^{-1}$]); 6) long term thermal capacitance ($d^*\rho^*c$, [kJ m$^{-2}$ K$^{-1}$]). Building physics quantities of all components are verified for five climatic zones of the Heating Degree Days (HDD), established by D.P.R. n. 412 26/08/93 – B, C, D, E, F (zone A in not consider, because no capital city is located there), according to Italian Regulation D.P.R. 59/2009 and UNI EN ISO 13786:2008. The total evaluation of standard building components is equal to 100 combinations.

![Figure 2](image)

Based on parameters $Y_{ie}$ and $\phi$ as assessment criteria, Fraunhofer Italia Research identifies the building components with best and worst summer performance. In all cases the best thermal parameters are registered in walls and double-pitched roofs with natural insulation and in flat roofs with synthetic insulation. The worst thermal performance occurs in building components with synthetic insulation and in case of PF walls with mineral insulation. Synthetic insulation in PF are excluded from the analysis since it is rarely applied. Due to the huge number of calculations, thermal parameters of the best components with lower structural thickness (PF – 8x12 cm; CLT – 10 cm) in climatic zone B are reported only, as shown in Table 3.
These standard building components are combined to a reference model (Pernigotto et al., 2014) with a surface floor of 100 m² and 3 m of internal height located in four cities — Messina, Taranto, Firenze, Verona, in order to run dynamic simulations using TRNSYS software. These cities are chosen for two reasons: 1) they belong to D class of equivalent CDD ($\alpha = 0.6$), being thence under severe summer conditions; 2) they concurrently fall under B, C, D climate zones respectively, which refer to HDD and Italian regulation, and thence consider different winter stress. Table 4 summarizes the input data used for the dynamic simulations. For each four capital cities Free University of Bolzano-Bozen carries out 34 dynamic simulations (total 256) considering all combinations of input data. The following output data for the period from May to September are given: 1) cooling energy demand ($Q$, [kWh m⁻²]); 2) number of days in which the operative temperature ($t_{\text{op}}$, [°C]) is above 26 °C; 3) number of days in which the operative temperature ($t_{\text{op}}$, [°C]) is above 28 °C. Table 5 shows some extract of output data for Messina (HDD zone B) considering the following input data: 1) window surface 25.74 m²; 2) Solar Heat Gain Coefficient, SHGC = 0.6; 3) Surface Area to Volume ratio, S/V = 0.73 and S/V = 0.4. Simulation results for Messina show that building components with both timber technologies assure already a quite good thermal performance in terms of indoor comfort. The indoor temperature does not reach 28 °C, being almost above 26°C. However, PF building components may have huge improvements, especially in southern areas, where actually the standard technology requires 15 cm of insulation. Traditional massive structure (vertically perforated bricks) requires an insulation thickness of about 4 cm to comply with Italian regulation for the winter season. Therefore, the thermal mass integration in PF structures might decrease notably the insulation thickness. Since CLT components have a massive structure, huge optimization are not required: the thermal mass activation on interior side of wall might be evaluated as an improvement.

### Table 4. Simulation input data

<table>
<thead>
<tr>
<th>Category</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate input:</td>
<td></td>
</tr>
<tr>
<td>Climate data</td>
<td>TRY (source: CTI – 05/2013)</td>
</tr>
<tr>
<td>Location</td>
<td>Messina, Taranto, Firenze, Verona</td>
</tr>
<tr>
<td>Virtual residential building input:</td>
<td></td>
</tr>
<tr>
<td>S/V ratio</td>
<td>S/V 1: 0.73 (one adiabatic surface – floor) and S/V 2: 0.40 (two adiabatic surfaces – floor and roof)</td>
</tr>
<tr>
<td>Dimension of reference case</td>
<td>Volume: 10x10x3 (m)</td>
</tr>
<tr>
<td>Building components</td>
<td>- the best and worst configurations of standard components in CLT</td>
</tr>
<tr>
<td>Window position</td>
<td>East, West, South and All without solar shading system</td>
</tr>
<tr>
<td>Window surface</td>
<td>Size 1:12.90 m² and Size 2: 25.74 m²</td>
</tr>
<tr>
<td>Window characteristics</td>
<td>$U_g = 1.2$ W/m²·K; SHGC = 0.6 and $U_g = 1.2$ W/m²·K; SHGC = 0.4</td>
</tr>
<tr>
<td>Interior gains (W/m²)</td>
<td>4 W/m² according to UNI/TS 11300</td>
</tr>
<tr>
<td>Natural ventilation rate</td>
<td>0.3 vol/h</td>
</tr>
<tr>
<td>Interior partition</td>
<td>PF: $d = 19$ cm; CLT: $d = 23$ cm (not insulated)</td>
</tr>
<tr>
<td>Cooling period</td>
<td>May 1¹ – September 30¹</td>
</tr>
<tr>
<td>HVAC system</td>
<td>Ideal system</td>
</tr>
</tbody>
</table>

### Table 5. Comparison of best and worst output of thermodynamic simulation for Messina

<table>
<thead>
<tr>
<th>Platform Frame</th>
<th>CLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/V = 0.73</td>
<td>S/V = 0.4</td>
</tr>
<tr>
<td>Worst case</td>
<td>Best case</td>
</tr>
<tr>
<td>$Q$ [kWh m⁻²]</td>
<td>47.61</td>
</tr>
<tr>
<td>$N^o$ of hours &gt; 26 °C</td>
<td>3532</td>
</tr>
</tbody>
</table>
Third phase: Improvement of building components

On the basis of literature review outputs, some technological solutions for Italian climate have been adopted, particularly the one proposed by Al-Sanea and Zedan (2001), which splits thermal mass in two layers. The limit to the mass integration is that it is possible to increase the wall weight up to 1kN per 1m² of wall, namely correspond to 20% of the total weight of the considered building model. Such structural constraint comes out of a case study made by CNR-IVALSA. It is a three storey residential building made of two units of the building model described in Table 4; 10 [m] x 20 [m] dimension in plan; structural walls and seismic weight are referred to the same building components evaluated with dynamic simulations of the second phase. A linear static analysis is performed according to NTC 2008 and to EC8 in order to define the seismic load and the total base shear force in particular. It is demonstrated the possibility of designing structural walls with increased weight by using standard connectors as hold downs and angular brackets. Taking into account such consideration, Fraunhofer Italia Research designs the improved building components with applied additional thermal mass, as shown in Figure 3. The materials considered for the improvement of building components are as follow: 1) double panel of gypsum fibreboard (d = 2x1.5 [cm], ρ = 1800 [kg m⁻³], λ = 0.32 [W m⁻¹ K⁻¹], c = 1200 [J kg⁻¹ K⁻¹]); 2) brick (d = 5 [cm], ρ = 1800 [kg m⁻³], λ = 0.8 [W m⁻¹ K⁻¹], c = 850 [J kg⁻¹ K⁻¹]); 3) clay panels (d = 2.5-3.5 [cm], ρ = 1600 [kg m⁻³], λ = 0.73 [W m⁻¹ K⁻¹], c = 1000 [J kg⁻¹ K⁻¹]). The evaluated solutions for walls are: 1) three types of integration for PF external walls; and 2) four types of integration for CLT external walls. CLT double pitched roof has not been considered as a standard solution because the quantity of timber does not reflect any structural needs. Since it has a better summer thermal performance, CLT double pitched roof is chosen as an improved solution for PF double pitched roof. Due to its better structural behaviour, the indoor floor in CLT technology is preferred to the PF solution. The external concrete slab remains unchanged. The insulation used in all improved walls and roof is a natural one and synthetic one for external concrete slab.

In order to find the best solution amongst the proposed improved walls for 110 capital cities, Fraunhofer Italia Research develops a multi-criteria analysis. The three alternatives of integration for PF

---

### Table 4

<table>
<thead>
<tr>
<th>Platform Frame</th>
<th>CLT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S/V = 0.73</td>
</tr>
<tr>
<td>N° of hours &gt; 26 °C</td>
<td>3532</td>
</tr>
<tr>
<td>% of hours &gt; 26 °C</td>
<td>96,19%</td>
</tr>
<tr>
<td>N° of hours &gt; 28 °C</td>
<td>0</td>
</tr>
<tr>
<td>% of hours &gt; 28 °C</td>
<td>0%</td>
</tr>
</tbody>
</table>
external walls and the four ones for CLT external walls are compared by four indicators: 1) the average of the percentage difference between $Y_{ie}$ of the improved wall and $Y_{ie}$ of the standard wall with best performance, referred to $Y_{ie}$ of the standard wall with best performance; 2) the percentage difference between U-factor of the improved wall and U-factor of the standard wall with best performance, referred to U-factor of the standard wall with best performance; 3) the percentage difference between total thickness of the improved wall and total thickness of the standard wall with best performance, referred to total thickness of the standard wall with best performance; 4) the percentage difference between insulation thickness of the improved wall and insulation thickness of the standard wall with best performance, referred to insulation thickness of the standard wall with best performance. These four percentage values are weighted by 1-to-3 scale which varies as the combination of climatic zone based on HDD and of class based on equivalent CDD. The multi-criteria analysis supports the selection of the following improved solutions for PF walls: 1) type c in areas D, C x B, C, D, E (CDD x HDD) and areas B x C; 2) type b in areas B, A x D, E; and for CLT walls: 1) type d in areas D, C x B, C, D, E and areas B x C; 2) type b in areas B, A x D, E. Table 6 shows the extract of the multi-criteria analysis referred to class D (CDD) and climatic zone B (HDD) and the selected improved solutions for PF and CLT. GIS-maps of Italy in Figure 4 represent the percentage improvement or worsening of the indicators which were used for the comparison and selection of the improved building components – insulation thickness, $Y_{12}$, $\phi$, U and total thickness – referred to the chosen improved building components. Thermal parameter values for the chosen improved building components in PF technology referred to class D (CDD) and climatic zone B (HDD) are provided in Table 7, while the percentage range of the improvement/worsening of thermal parameters for both technologies are summarized in Table 8. There is a huge improvement in terms of decrement of insulation thickness in particular for the PF technology beside an improvement of the thermal parameters which impacts the summer performance.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Class D (CDD, $\alpha = 0.6$)</th>
<th>PF alternatives</th>
<th>CLT alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight</td>
<td>Type a</td>
<td>Type b</td>
</tr>
<tr>
<td>Average $Y_{ie}$ and $\Delta \phi$</td>
<td>3</td>
<td>-0.04 (3)</td>
<td>-0.07 (2)</td>
</tr>
<tr>
<td>U</td>
<td>1</td>
<td>0.43 (2)</td>
<td>0.28 (1)</td>
</tr>
<tr>
<td>Total thickness</td>
<td>1</td>
<td>0.07 (3)</td>
<td>- (2)</td>
</tr>
<tr>
<td>Insulation thickness</td>
<td>1</td>
<td>-1.40 (2)</td>
<td>-1.00 (3)</td>
</tr>
<tr>
<td>Sum</td>
<td>-0.94 (2)</td>
<td>-0.79 (3)</td>
<td>-1.16 (1)</td>
</tr>
</tbody>
</table>

Figure 4 Comparison maps, the percentage improvement or worsening of thermal parameters: a) $Y_{ie}$ for PF technology; b) U-factor for PF technology; c) Insulation thickness for PF technology.

<table>
<thead>
<tr>
<th>Building component</th>
<th>Total thickness (mm)</th>
<th>Insulation thickness (mm)</th>
<th>U-factor (W m² K⁻¹)</th>
<th>$Y_{12}$ (W m² K⁻¹)</th>
<th>$\phi$ (h)</th>
<th>f (-)</th>
<th>$k_t$ (kJ m² K⁻¹)</th>
<th>$d^{<em>}\rho^{</em>}c$ (kJ m² K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF Type c</td>
<td>195</td>
<td>9%</td>
<td>60</td>
<td>40</td>
<td>60%</td>
<td>30%</td>
<td>0.48</td>
<td>0.11</td>
</tr>
<tr>
<td>CLT Type b</td>
<td>260</td>
<td>16%</td>
<td>50</td>
<td>40</td>
<td>16%</td>
<td>25%</td>
<td>0.40</td>
<td>0.09</td>
</tr>
</tbody>
</table>

N.B. Positive value of $\Delta$ represents improvement and negative value worsening.
Table 8. The range of percentage improvement/worsening of thermal parameters in Italy

<table>
<thead>
<tr>
<th>Timber technology</th>
<th>Type of wall</th>
<th>Insulation thickness</th>
<th>V_{12}</th>
<th>( \phi )</th>
<th>U-factor</th>
<th>Total wall thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF</td>
<td>Type b</td>
<td>33%</td>
<td>1%</td>
<td>6%</td>
<td>-28%</td>
<td>No change</td>
</tr>
<tr>
<td></td>
<td>Type c</td>
<td>40-60% S(^<em>); 33-40% N(^</em>)</td>
<td>10-34%</td>
<td>5-15% S(^<em>); -2% N(^</em>)</td>
<td>-29 - -39% N(^*)</td>
<td>No change or decrement of 9%</td>
</tr>
<tr>
<td>CLT</td>
<td>Type b</td>
<td>0%</td>
<td>26%</td>
<td>18-20%</td>
<td>2%</td>
<td>Decrement of 14-16%</td>
</tr>
<tr>
<td></td>
<td>Type d</td>
<td>-14%(^*)</td>
<td>15-27%</td>
<td>15-16%</td>
<td>-4%</td>
<td>Increment of 4%</td>
</tr>
</tbody>
</table>

N.B. Positive value represents improvement and negative value worsening.

\(^*\) S refers to the Southern Italy; N refers to the Northern Italy; \(^*\)\(^*\) increment of insulation only in climatic zone E (HDD)

DISCUSSION AND CONCLUSION

TIMBEEST project has been described as well as its intermediate results. Typical timber building components of the two main technologies (PF and CLT) have been designed and building model performance made out of their combination has been evaluated. Timber buildings have an acceptable performance even in southern Italy but their environmental footprint is high due to the thickness of the required insulation. On the basis of a climate and structural evaluation of the Italian territory, some timber building improved components have been designed. PF walls allow mass to be combined in more solutions than CLT ones as well as mixed technologies better face the seismic challenge. Further steps of the project will simulate and evaluate the percentage of gained improvement in structural and energy fields. It is expected to define the geographical extent of such technology, to determine the environmental footprint of the improved components and to highlight the most promising technological change towards the improvement of timber building performance during the cooling season.

Beyond the limits of the project, it will be interesting to deepen the evaluation of climate indicators as equivalent CDD and to define synthetic indicators combining structure and energy. There are many mixed timber technologies even coming from the past which should be evaluated as PF and CLT as well as the optimization of the mass quantity and position, considering other passive cooling strategies.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the supportive sponsorship provided by the Autonomous Province of Bolzano-Bozen.

REFERENCES


WUFI software, Fraunhofer IBP. Web site:http://www.wufi.de/index_e.html.
The Triple Bottom Line Benefits of Climate-Responsive Dynamic Façades

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Rajan Rawal, Agam Shah

1. Center for Building Performance and Diagnostics (CBPD), Carnegie Mellon University, Pittsburgh, PA
2. Center for Environmental Planning and Technology, Ahmedabad, India

ABSTRACT
To achieve net zero energy, façade designs must move from static dark glass monoliths to dynamic, climate responsive layers for balancing daylighting and shading, natural ventilation and mixed mode conditioning. While 5-15 year energy paybacks are sufficient to prompt some level of increased investment in facades, dynamic facades require the addition of triple bottom line (TBL) calculations that capture the economic, environmental and human benefits of high performance buildings. This paper introduces an approach to TBL justifications of climate-specific high performance building façade solutions, to provide professionals and manufacturers compelling arguments for inspiring building investment that will improve the quality of the indoor environment. Given that lighting and space conditioning are 80% of office energy loads in India, arguments for investing in façades that optimize daylighting and shading, natural ventilation and mixed mode conditioning are critically needed. This paper illustrates the triple bottom line of five climate-responsive façade and related system improvements – high visible transmission/low solar glass, internal light shelves/inverted blinds, daylight dimming, external overhangs/shades, and operable windows - that demonstrate TBL paybacks of less than two years for new and retrofit construction. This ongoing project is funded by the US Department of Energy and LBNL, and undertaken in collaboration with CEPT, India through the Center for Building Energy Research and Development (CBERD).

INTRODUCTION
The development of TBL life cycle data sets for building decision-makers is critical to overcome first-least-cost decision making patterns that prevent owners and tenants from investing in high performance, energy efficient building solutions. While the completion of five to fifteen year energy payback calculations (first bottom line) can prompt increased investments, the addition of environmental and human benefits (second and third bottom line) provides the ‘tipping point’ for the level of design, engineering and investment needed for high performance facades that save energy and improve the quality of the indoor environment for workers.

The challenge for TBL calculations is the quantification of environmental and human gains, including health, productivity, and organizational performance. This paper develops TBL justifications for five climate-specific building façade solutions that improve the quality of the indoor environment while optimizing energy effectiveness. For each technology, the first bottom line relates to the known Indian costs and literature identified benefits of energy and facility management savings resulting from the investment. The second bottom line relates to the Indian environmental benefits that are directly linked to electric energy savings: reductions in CO2, SOx, NOx, particulates, and water. The third bottom line is based on available international studies that have identified the human benefits directly
linked to improved indoor environment quality in terms of human health and productivity.

Carnegie Mellon’s studies of daylighting/ lighting retrofits in the U.S., completed for the DOE EEBHub, revealed that with energy savings ranging from 13-85%, simple paybacks will be from 2-8 years - if only energy savings are included in the life cycle calculation. However, when the environmental benefits of electricity savings are included, paybacks are much faster, from 1.5-5 years. Most strikingly, when human benefits identified in international research are included - from reduced headaches and absenteeism to improved task performance or productivity - paybacks for investments in daylighting and lighting retrofits in US offices are less than 2 years (Loftness, Srivastava et al, 2013). Building on these earlier studies, through support from the US Department of Energy and Lawrence Berkeley National Lab, this on-going research advances the TBL evaluation of high performance façade investments for office buildings in each of the five Indian climates identified in the National Building Code.

WHY INVEST IN FACADES?

India is the world’s fourth largest energy consumer (EIA, 2013) and fifth largest source of greenhouse gas emissions (GOI, 2010). With the building sector contributing 35% of the total electricity consumption (Rawal et al, 2012), and a projected five-fold growth in the constructed area anticipated by 2030 - from a 21 billion square feet in 2005 to 104 billion square feet, building energy efficiency plays a major role in managing energy use in India (Seth, 2010, Figure 1a).

India’s national Energy Conservation Building Code (ECBC, 2008) was revised in 2008, but remains voluntary and has not been adopted by most of the Indian states. To encourage adoption of ECBC, a three-tier approach has been proposed which advocates implementation of the ECBC codes in phases, and allows time for training and capacity building (Rawal et al., 2012). Tiers are categorized based on: ease of implementation within current practice, the energy savings potential, and the ROI offered. Tier one focuses on envelope-related measures, tier two on HVAC, while the third tier regulates lighting measures.

![Electricity End Use in commercial buildings](image)

Figure 1 (a)Forecasted five-fold growth for building sector in India; (b) Lighting and Air Conditioning loads account for 80% of the commercial building energy use (Singh et al,2013)

Given the rapid growth in the Indian construction sector, the national government’s efforts to improve energy-efficiency in buildings are based on significant reductions in air-conditioning, ventilation, lighting and plug loads. Building façade design and engineering is critical to: air conditioning loads through solar heat control; to natural ventilation and night cooling; to effective daylighting; and even free passive solar heating in cooler climates. High performance, climate responsive facades can significantly reduce both annual and peak electricity demand, and ensure “resiliency” in the face of power outages. Equally critical, high performance facades are critical to occupant health and productivity. This paper explores TBL arguments for five high performance facade measures that can provide up to 25% total energy savings in typical Indian office buildings, reducing the environmental costs of electricity and improving indoor environmental quality for human health and productivity.
Design priorities for new and existing façades

The research team employed a range of techniques to identify climate responsive façade guidelines for Indian climates. A climate analysis using a combination of Koppen climate classifications (Rubel and Kottek, 2010), the National Building Codes (BIS, 2005), Climate Consultant (Milne et al., 2007) and simulation tools (Comfen; NIST Climate Suitability tool; PPG, 2014) supported the identification of representative cities for each of the five Indian climate zones (Table 1) and climatically similar U.S. cities. The companion cities were included to support the development of high performance façade guidelines and provide strong illustrations, quantifications, and product choices. The city of Mumbai was matched with the city of Singapore since there was no climate-comparable city in the US.

The research team then reviewed business-as-usual and advanced Indian office building practices in the five climates, classifying critical characteristics of existing and advanced building facades. Then, the review of existing research, codes and standards, field and simulation studies, was combined with the use of simulation tools to help refine a set of climate specific façade strategies. An illustration of façade design recommendations is shown in Table 1, drawn from a longer list, with 0-3 dots indicating the relative importance of each recommendation for the given climate.

<table>
<thead>
<tr>
<th>Façade Recommendations</th>
<th>HOT &amp; DRY Ahmedabad (Phoenix)</th>
<th>WARM &amp; HUMID Mumbai (Singapore)</th>
<th>TEMPERATE Bangalore (Miami)</th>
<th>COMPOSITE New Delhi (Dallas)</th>
<th>COLD Shingling (San Francisco)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daylighting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High VLT glass</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●</td>
</tr>
<tr>
<td>Light shelf/ Inverted blind</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
</tr>
<tr>
<td>Daylight dimming</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
</tr>
<tr>
<td>Shading</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow Building Plan</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
</tr>
<tr>
<td>Avoid E/W Glazing</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●</td>
</tr>
<tr>
<td>Low SHGC</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
</tr>
<tr>
<td>Shading Devices</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
</tr>
<tr>
<td>Natural Ventilation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windows for natural vent.</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
</tr>
<tr>
<td>+ mass for night cooling</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
<td>●●●</td>
</tr>
</tbody>
</table>

From the set of shortlisted guidelines in the above table, five strategies were selected to demonstrate the TBL cost benefit analyses that could be applied across all five climates - with climate specific variations:

1. Invest in high visible transmission glass with climate appropriate shading coefficients
2. Invest in light shelves or light redirection louvers in clerestory glass areas
3. Invest in high performance ballasts with daylight sensors in perimeter office lighting
4. Invest in external overhangs or canvas awnings for summer shading
5. Invest in operable windows for natural ventilation and night cooling

Each of the selected recommendations are outlined in the following sections, alongside preliminary information on product or assembly costs, as well as literature studies on occupant health and productivity benefits, in order to complete Triple Bottom Line calculations for each action.

THE TRIPLE BOTTOM LINE FOR FIVE FAÇADE INVESTMENTS

The TBL calculation approach was refined using the United Nations ICLEI Triple Bottom Line Standards, in which benefits are categorized in one of the three categories – (1) Economic/Profit (2) Environmental/Planet (3) Equity/People. The TBL life cycle benefits for each category are illustrated using successive “return on investment” ratios and NPV calculations. For each façade retrofit, the first cost was evaluated against a 15-year life cycle savings calculation. For the range of selected façade technologies, Indian costs were collected from literature and communications with manufacturers and professionals, acknowledging that there are significant variations in the product and labor market across regions. Where the Indian costs for the technologies were not available, the US market prices were used for this paper. The project team collected average technology and labor costs for each recommendation.
assuming a medium size office of 50,000 square feet on six floors. The energy savings calculations are based on a national baseline of 200 kWh/sqm-yr (approx. 19 kWh/sqft-yr). Load breakdowns are assumed to be: 60% of the total load for HVAC energy use or 120 kWh/sqm-yr; 20% of the total load for lighting energy use or 40 kWh/sqm-yr; with the remaining 20% of energy used for plug loads (Singh et al., 2013). The long-term objective is to build an on-line calculator for building decision-makers to enable the substitution of their own assumptions and numbers.

The first bottom line calculation includes the economic cost benefits of energy and potentially facility management savings resulting from each of the façade actions. The cost of energy was set at $0.18/kwh, the average all inclusive commercial fixed rate in India (RIL, 2012), which may vary by region (Wilson, 2013). The second bottom line line calculations capture the environmental cost benefits that are directly linked to electric energy savings: reduction in CO2, SOx, NOx, particulates (PM) and water demands. These four pollutants are regulated and even taxed in leading countries to reduce global warming, respiratory illnesses, cancers and developmental impairment. Given India’s high reliance on coal fired electric power, the societal costs of environmental abatement could range from $ 0.014 – 0.021/kwh (Table 2), estimated based on EPA (2010), Goodkind and Polasky (2013), Levy (1999) and Ghodke et al. (2012).

<table>
<thead>
<tr>
<th>Table 2. India’s estimated environmental cost impacts of power generation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO2</strong></td>
</tr>
<tr>
<td>India range of emission from coal plant (g/kWh)</td>
</tr>
<tr>
<td>India Average Emission Coefficients (lb/kWh)</td>
</tr>
<tr>
<td>Est. Environmental Cost Premium (/kWh)</td>
</tr>
</tbody>
</table>

The third bottom line captures the human benefits that are linked to improved thermal, lighting and air quality as a result of the building improvement, drawn from the ongoing work of Carnegie Mellon’s CBPD to link the quality of the built environment to health and productivity outcomes captured in BIDS: the Building Investment Decision Support Tool (BIDS, 2008). In the absence of Indian field studies that link high performance building systems to health or productivity cost-benefits, the research team relies for now on international laboratory and field case studies to support TBL life cycle decision making.

1. Invest in high visible transmission glass with climate appropriate shading coefficients

20 percent of commercial building energy use in India is for lighting buildings, and much of this is during the daytime when daylight is abundant. Electric lighting also contributes to the air-conditioning demand in Indian office buildings, at a significantly higher cost than solar-controlled daylighting.

Four of the five Indian climates in the codes have cooling dominated seasons, where protection from the sun often becomes a priority. To block solar radiation, use of very dark and reflective glazing is a common practice in Indian buildings. In pursuit of low solar heat gain (low SHGC), designers often mistakenly specify low visible light transmission (VLT). While this type of glazing is effective for shading, it seriously compromises daylight penetration and seated views to the outdoors (Figure 2a). It is imperative for future office facades and façade retrofits to replace yesterday’s dark glass (low SHGC and low VLT, see Figure 2a) with today’s high performance glass that maintains low solar transmission while maximizing visible light transmission (low SHGC and high VLT, see Figure 2b) in order to lower both lighting and cooling energy while providing views to the outside. Low .30 SHGC with high .65 VLT glass coatings are readily available in India, with incremental costs less than $1/sqft and paybacks of as low as 39 months (PPG, Saint-Gobain, 2014). For the single heating climate in India represented by Shillong (and companion city San Francisco), the low-solar high-visible glass specification should be replaced by a high-solar high-visible glass specification on southern facades to take advantage of the comfort and free heat provided by direct solar gain.
The CMU team used existing research to calculate the first, second and third bottom lines of high performance glass. In a 1999 multiple building study of 8 office buildings in the UK, the Probe team identifies an average 64% lighting energy savings in buildings with effective daylighting due to clear glass and perimeter access, as compared to buildings with deep floor plans and/or tinted glass (Probe team, 1999). Increasing the effectiveness of daylighting and providing access to views also improves employee productivity and health, also included in the third bottom line. In a 2003 building case study of the Sacramento Municipal Utility District (SMUD) Call Center, Heschong et al. identified an average 6.7% faster Average Handling Time (AHT) for employees with seated access to larger windows and a view with vegetation content from their cubicles, as compared to employees with no view of the outdoors. Other studies reveal the importance of sunshine for health in winter with appropriate orientation and shading for glare control and summer comfort (Benedetti et al., 2001 and Choi, 2005).

2. Invest in light shelves or light redirection louvers in clerestory glass areas

To ensure daylight effectiveness beyond the first few feet of work area, the second retrofit recommendation is to introduce light shelves or inverted blinds/louvers in the clerestory glass area. Light shelves serve critical purposes that include the distribution of daylight deep into the building, glare control and shading. When well designed, they can ensure high levels of daylighting without glare and overheating, and even reduce heat loss on winter nights (CBPD, 2014 a). A study of the existing building stock revealed that a number of Indian offices already have clerestory glass above the view windows (Figure 3a), and the addition of a light shelf or inverted louvers or blinds will greatly enhance daylight effectiveness.

The ideal light shelves would be highly reflective and diffusing. If louvers or venetian blinds are used they should be inverted (curve upwards) to reflect daylight onto the ceiling for diffusion (see Lightlouver™ profile Figure 3b). The inverted blinds can even have a seasonally “smart” W-profile that reflects high sun angles back outdoors, to reduce solar gain in the cooling season, and reflects low sun angles into the space to increase solar gain in the heating season (Retrosolar™). Inverted blinds and louvers in the clerestory, in combination with a highly reflective ceiling, create a daylighting system that can be used on the east, west and the south façade. The most affordable solution for the Indian market is approximately $20 per sqft of building façade, based on manufacturer estimates, given 20% of the baseline building surface area as clerestory to be equipped with light shelves (Skyshade™, 2014).
Given that 25-100% of workstations may be within 15 feet of a window wall in many Indian office buildings, daylighting without glare can save up to 35% of a medium size office building’s total lighting energy (Figueiro et al., 2002; Schrum & Parker, 1996). The electricity savings is calculated in the first bottom line and the environmental benefits of reduced power generation is calculated in the second bottom line.

The human benefits of investing in light redirection/diffusion are related to the spectral quality of daylight, the management of brightness contrast by bouncing light, the improvement of views, as well as the importance of sunshine in winter and shading for comfort in summer. For example, in a 1992 laboratory experiment conducted using 26 subjects, Osterhaus and Bailey found a 3% improvement in visual tasks related to reduced glare (Osterhaus & Bailey, 1992).

3. Invest in high performance ballasts with daylight sensors for perimeter office lighting

The third cost-effective retrofit is the use of high performance ballasts and daylight sensors to support on/off or dimming control of the first and second rows of lights on each building façade (Figure 4a). This investment in new controls for groups of lights ensures up to 30% energy savings through ‘daylight harvesting’ (Lee & Selkowitz, 2006). In a 1984 simulation study supported by meta-analysis, Verderber and Rubinstein identify 64% lighting energy savings in a 30% daylit building given daylight dimming controls, automatic scheduling, tuning, and lamp lumen depreciation, compared to a conventional lighting system with no controls. To ensure that the sensors are not disabled or covered by occupants, critical attributes for the selection of daylight sensors include: programmable thresholds for acceptable daylight minimums, relocatable sensors to address variations in office layout, and assurance of gradual light level changes through dimming or time limited switching. Daylight sensors and switches can be installed without full automation systems, and can be introduced with wireless interfaces to existing fixtures, making them cost effective retrofits.

Figure 4: a, b) Electric lighting ‘on’ most of the time in Infosys and Raheja Tower offices in Bangalore; c) Balanced daylight and daylight harvesting controls in the Packard Foundation offices in California.

Encelium, Lutron, and several other lighting control companies have developed wireless controls that can be added to existing ballasts in combination with well-placed daylight sensors. A web based controller is available for calendar-driven or daylight-sensor-driven switching of each row. Daylight harvesting is a quick and low cost retrofit for the majority of buildings, with costs from $0.45-0.90/sqft.

In many medium sized office buildings, up to 100% of spaces could be (and have been historically) daylit, saving up to 70% of total lighting energy. In deeper section buildings, daylight harvesting can save 10-35% of the lighting energy. The human benefits of daylight contributions in the workspace are also measurable. In a 1995 building case study of Lockheed Building 157 in Sunnyvale, California, Thayer et al identified 50% savings in lighting, cooling and ventilation energy and 15% reduced absenteeism due to the daylighting design which integrates layout, orientation, type of glazing, and light shelves in combination with reflective ceilings. The full spectrum light inherent in daylight also has an influence on human health, with research revealing that the natural changes in day light is critical for melatonin production that regulates our sleep cycle (Figueiro, 2010). An earlier field study conducted by Figueiro et al. (2002) identifies a 15% increase in time dedicated to visual tasks in daylit workspaces. With visual tasks constituting 25-30% of time spent at work, there is a potential performance...
improvement of 3.75% linked to the benefits of daylight. Daylighting should be a priority in the workplace, particularly since higher light levels can be achieved at a lower energy cost.

4. Invest in external overhangs or canvas awnings for summer shading

In four of the five climates of India, shading the facade is a high priority to avoid overheating in summer. While modern office buildings in the past century were often sleek glass towers, today’s design community is rediscovering the power of facades articulated by static fins, louvers, and screens as well as the highest performing dynamic awnings. These dynamic shading devices can be daily or seasonally adjusted to reflect sunlight when required, while allowing effective daylight penetration and solar gain during the winter (Lechner, 2009). Today, awnings are made of synthetic fabrics which are fade resistant, water repellant and require less maintenance than they have historically. Fixed overhangs, horizontal louvers and fins, and dynamic awnings are each effective additions to modern facades. They provide shade with daylight, without diminishing our views, and should replace yesterday’s dark glass, eggcrate shades and scrim layers.

Given that India ranges from 6° to 37° north latitude, horizontal devices should be the norm for southern orientations, combined horizontal and vertical or dynamic devices for east west, and vertical devices for north facades (Figure 5b,c). Openings along the top and sides of the overhang or awning should be provided to prevent heat from being trapped at the window wall.

![Figure 5: a) DLF Center, Delhi with no shading devices vs. b) vertical awnings on the north face of the Phoenix library, and c) horizontal louvers on south face of Stecalite, Noida.](image)

The cost of installing external louvers and awnings varies dramatically based on material and assembly, with $7.50/sqft assumed in the TBL calculations. The use of adjustable awnings as a shading device can reduce solar heat gain and associated cooling loads in the summer by up to 65% on south-facing windows and 77% on west-facing windows, with a 20-25% total cooling energy savings (DOE, 2012; Nagy et al., 2000). The human benefits of light shelves include the value of glare control for productivity and health, as well as shading for improved thermal comfort in summer by reducing direct and radiant solar heat. In a 1998 controlled experiment, Witterseh identifies a 54% increase in mathematics accuracy and a 3.5% typing improvement when subjects feel thermally comfortable, rather than too warm, in quiet office conditions (Witterseh, 2001).

5. Invest in operable windows for natural ventilation and night cooling

The last recommendation for which triple bottom line analysis was completed was to introduce operable windows for natural ventilation and night cooling. The business-as-usual building illustrated in figure 6a, reveals the rising trend of sealing office facades (Figure 6a). This is a serious disadvantage during brown outs or black outs, as the building runs out of air and starts to overheat. Moreover, sealing building facades eliminates the opportunity to use natural ventilation for cooling and breathing, or night ventilation to pre-cool the building to offer hours of free cooling the next day.

To avoid the possibility of rain coming in, and to ensure controlled air flow, the use of awning, drop-kick, and pop-out windows are emerging in modern offices (Figure 6b and 6c). For hot and dry climates like Ahmedabad, natural ventilation can be pursued on moderate days if air quality and noise are not a local issue. More critically, night ventilation cooling can be pursued on nights that are predicted to be cooler than 70°F and combined with thermal mass or phase change materials to store ‘coolth’ for conditioning on the following day.
The cost of natural ventilation is related to the additional costs of window hardware and the manual or automated system for control, while night cooling requires the addition or exposure of thermal mass in the airstream. Mechanical engineers should be carefully selected for their commitment to “mixed mode” conditioning (CBE, 2014), and integrated early into the design process. Consideration of natural ventilation should address the site-specific limits of climate, outdoor air quality, noise, security, and local building codes.

On the benefit side of the equation, the annual energy savings of natural ventilation in the climate of Ahmedabad includes up to 15% of ventilation loads (Milne et al., 2007) and up to 35% pre-cooling load (Emmerich, Climate Suitability Tool). International studies reveal that the human benefits of natural ventilation can be measured in both employee health and productivity. In a 2003 meta-analysis study, Seppänen et al identifies a productivity increase of 4.9% for an eight-hour workday due to night-time ventilative cooling, an energy-efficient method of reducing daytime indoor temperatures by using night-time air to cool a building’s structure and furnishings. In a 1988 multiple building study in Berlin and Heidelberg, Kroeling identifies a 33% reduction in reported headaches, a 28% reduction in reported frequency of colds, and a 31% reduction in reported circulation problems for employees in naturally ventilated office buildings as compared to air conditioned office buildings.

TRIPLE BOTTOM LINE RAPIDLY ACCELERATES PAYBACK FOR DYNAMIC FAÇADES

Given these international studies on the human benefits of high performance façade solutions, the research team completed TBL calculation for five façade investments in the hot and dry Indian climate, to demonstrate the applicability of the framework in the building decision-making process (Table 3). For each facade investment, a 15-year life-cycle calculation is completed with the Indian first costs, energy savings and environmental benefits, and combined with international findings on health and productivity benefits, to generate the triple bottom line results shown in Table 3.

<table>
<thead>
<tr>
<th>Economic Considerations</th>
<th>High VLT Glass</th>
<th>Light Louvers</th>
<th>Dimming Ballasts</th>
<th>Awnings for shade</th>
<th>Operable Windows</th>
</tr>
</thead>
<tbody>
<tr>
<td>First cost per employee</td>
<td>$45</td>
<td>$114</td>
<td>$70</td>
<td>$330</td>
<td>$120</td>
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<td>Energy Savings (%)</td>
<td>35%</td>
<td>35%</td>
<td>30%</td>
<td>20%</td>
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<tr>
<td>Energy savings per employee</td>
<td>$24</td>
<td>$23</td>
<td>$20</td>
<td>$40</td>
<td>$70</td>
</tr>
<tr>
<td>ROI (Economic)</td>
<td>52%</td>
<td>20%</td>
<td>28%</td>
<td>12%</td>
<td>58%</td>
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<tr>
<td>Payback in years</td>
<td>2</td>
<td>&lt;5</td>
<td>3.5</td>
<td>8</td>
<td>&lt;2</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Environmental Considerations</th>
<th>High VLT Glass</th>
<th>Light Louvers</th>
<th>Dimming Ballasts</th>
<th>Awnings for shade</th>
<th>Operable Windows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Environmental Benefits:</td>
<td>$6.7</td>
<td>$6.7</td>
<td>$5.8</td>
<td>$11.4</td>
<td>$20.0</td>
</tr>
<tr>
<td>Air pollution emissions (CO2, SOX, NOX = $0.051/kWh)</td>
<td>$0.3</td>
<td>$0.3</td>
<td>$0.2</td>
<td>$0.4</td>
<td>$0.8</td>
</tr>
<tr>
<td>Water Savings ($0.002/kwh)</td>
<td>68%</td>
<td>26%</td>
<td>38%</td>
<td>16%</td>
<td>76%</td>
</tr>
<tr>
<td>ROI (Eco + Env) in years</td>
<td>1.5</td>
<td>&lt;4</td>
<td>&lt;2.5</td>
<td>&lt;6.5</td>
<td>&lt;1.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equity Considerations</th>
<th>High VLT Glass</th>
<th>Light Louvers</th>
<th>Dimming Ballasts</th>
<th>Awnings for shade</th>
<th>Operable Windows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Human Benefits</td>
<td>$320</td>
<td>$240</td>
<td>$300</td>
<td>$100</td>
<td>$240</td>
</tr>
<tr>
<td>Productivity increase (1-4%)</td>
<td>$24</td>
<td>$24</td>
<td>$24</td>
<td>$24</td>
<td>$10</td>
</tr>
<tr>
<td>ROI (Eco + Env + Equity)</td>
<td>825%</td>
<td>258%</td>
<td>500%</td>
<td>52%</td>
<td>284%</td>
</tr>
<tr>
<td>Payback (Eco + Env + Equity) in years</td>
<td>&lt;0.5</td>
<td>&lt;1</td>
<td>&lt;0.5</td>
<td>2</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

*Awnings have a lifetime of 5 years; first cost includes prices for three changes.
The development of Triple Bottom Line life cycle data sets for building decision-makers is critical to overcoming first-least-cost decision making patterns that prevent owners and tenants from investing in high performance, energy efficient building solutions. For example, the investments in high visible transmission glass with climate appropriate shading coefficients shift from 2 year paybacks based on energy savings alone, to 1.5 years including environmental benefits, to less than 6 months given the human benefits. Investments in the most affordable light redirection louvers in clerestory glass areas, high performance ballasts and daylight sensors, canvas awnings, and controls for operable windows also demonstrate reductions in paybacks from 8 years to less than a year as energy, environmental and human benefits are cumulatively calculated. It is critical for building owners and their design-engineering teams to embrace layered and dynamic facades for daylight, shade, natural ventilation and night cooling to significantly reduce India’s lighting and cooling loads in commercial offices and improve indoor environmental quality.

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The *Bundle-Up! Game*: a collaborative learning tool for net-zero energy design

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**ABSTRACT**

The purpose of the Bundle-Up! game is to make learning climatic design strategies and their complex interrelationships fun and easy. The project uses the concept of Bundles developed in the research project, “A New Knowledge Structure for Net-Zero Design.” The idea of design strategy bundles is to resolve conflicts and tensions among strategies by proposing related sets of design strategies that address recurring problems designers face. A Bundle identifies several discreet design ideas that apply in a particular situation across three scales. The game outlines a set of rules for users to create their own bundles specific to a particular project. Bundle-Up! is used with a set of instructions like a typical board game. It is designed to use design strategies from the book *Sun, Wind & Light*, 3rd edition. There is no one right solution, but some answers are better than others, and solutions that follow the rules are all acceptable. Bundle-Up! can be played by one person or several in collaboration. The game pieces (more than 100) each represent a climatic design strategy, each with a unique graphic and other identifying features and descriptions. A prototype was tested with peer teachers and feedback was very positive. The Bundle-Up! game has since been tested in fifth-year B. Arch design studios and with second-year technology course students. Feedback has helped refine the game and its instructions, along with the curricular exercises that accompany it.

Keywords: passive design, design process, knowledge structure, education, design strategies

1 INTRODUCTION: DESIGN STRATEGY BUNDLES

In the U.S., the American Institute of Architects has adopted ‘Architecture 2030’ goals for all new buildings to be carbon-neutral, operating free of fossil fuels by 2030. Carbon-neutral performance can either be achieved by a wasteful building with huge green power systems and purchase renewable energy or by efficient buildings lighted and conditioned by site-based resources, paired with small on-site green power systems. In other words, passive heating, cooling and lighting strategies reduce net loads, which reduce the need for expensive utility green power, photovoltaics and wind generation. To assist designers with this second more architectural and passive energy approach to carbon-neutral performance, this project uses the concept of design strategy bundles developed in the research project, “A New Knowledge Structure for Net-Zero Energy Design” and further developed and published in *Sun, Wind & Light: architectural design strategies*, 3rd edition (SWL) [1]. Bundles are theoretically a combination and development of Pattern Language theory and holarchic structure, particularly as developed in Integral Theory. The second edition of *Sun, Wind & Light* included 109 discreet analysis techniques and design strategies across a range of scales. These strategies addressed issues of heating, cooling, lighting and power. The strategy bundle was born in part as a result of finding three challenges that surfaced in over a decade of using the second edition in teaching and consulting.
1. **Difficulty in knowing which strategies to use** for a particular design situation, such as designing the building envelope, especially for novice passive designers

2. **Challenges identifying how the strategies were related** to each other—or not related—was sometimes implied, but often opaque, and required substantial practical experience

3. **Difficulty in knowing how major variables, like climate type, changed which strategies to employ or to emphasize.**

The purpose of design strategy bundles is to resolve conflicts and tensions among strategies by proposing related sets of strategies across three scales. A bundle proposes a set of the almost-always-required strategies that come together to form solutions to design situations encountered repeatedly in buildings. Some design situations are recurring, such as the problem of how to bring in light through a roof or how to use the building to collect and store heat from the sun in a cold climate.

When one is able to generalize about these design situations, one can also generalize about the solutions and the characteristics of these solutions that seem to be workable across a variety of conditions. If a problem is encountered thousands of times in buildings, the building community develops particular solution types from which designers can learn.

A **Bundle** is defined here as a set of related strategies working together to resolve commonly occurring design problems. A bundle may address a single energy issue or it may address two or more energy topics (heating, cooling, daylighting, ventilation or power). In general, a bundle has the following four characteristic organizing principles, as illustrated in Figure 1:

1. **A Bundle covers two or more scales** in the hierarchical system for levels of complexity (SWL uses nine scales). Most of the fundamental bundles cover three levels (the gray bars). The black lines connecting the squares represent a particular kind of relationship among the strategies of lower and higher complexity. The levels function to make clear how less complex strategies help to build more complex strategies.

2. **A Bundle has 3–5 invariant core strategies** (the solid black squares) that are always workable in the given design situation. Core strategies are recognized as those that apply to all the bundle’s variations.

3. **A Bundle has two or more situational variations**, each with its own bundle diagram. These variations adapt the bundle to a major variable commonly present (such as the difference between designing in a cool climate versus a hot-arid climate) by the addition of situational strategies (the hollow squares inside the dashed line) beyond the core strategies. Remember that core strategies are common to all of the situational variations, whereas situational strategies are more workable or important in one scenario than in the others.

4. **A Bundle may also identify refiner strategies** (the squares outside the dashed line), which are related to the bundle and are recommended to be considered as the design develops to greater levels of detail. These are most likely workable but are less critical strategies.

Because each strategy has a range of variables and can be adapted to variations in its context, the particular combination of strategies suggested for a bundle can yield thousands of formal outcomes. Similarly, the relationship of one strategy to another in a bundle will influence the way in which each strategy is applied. The designer fits one strategy to the others in the network of design strategies that forms the bundle. This network is a context of other more and less complex strategies.
2. EXAMPLE BUNDLE

The example bundle diagram in Figure 2 for a thick plan PASSIVE SOLAR BUILDING bundle, one of its two variations, illustrates the four organizational principles of a bundle.

1) The bundle organizes design strategies at multiple scales, covering three levels of complexity, from lower complexity level three (L3) Building Systems, to L4 Rooms, to higher complexity L5 Room Organizations. These are named in the range of grey bars on the left side of Figure 2. The scale of L6 Whole Buildings is the contextual scale for this bundle and is the level where its particular “emergent characteristics” are evident. The gray lines connecting the squares represent nesting relationships between strategies. For example, the less complex strategies of SUNSPACES, ROOMS FACING THE SUN AND WIND and THERMAL COLLECTORS are all strategies for designing at the L4 Rooms scale; they help to build the more complex strategy MOVING HEAT TO COLD ROOMS, which operates at the more complex scale of L5 Room Organizations to orchestrate heat distribution between rooms that collect heat and those that do not. SUNSPACES helps build MOVING HEAT TO COLD ROOMS, while the higher, deeper, larger strategy also depends on the lower strategy. Bear in mind that the bundles represent some important associations of strategies, and that many additional strategies may be used. Note that, for simplicity, the relationship lines for refiner strategies are not shown in the diagrams, but they can be seen on the design strategy maps in SWL’s chapter on “Navigation by Design Strategy Maps” [1].

2) The bundle has five core strategies. Each graphic icon represents an individual design strategy in SWL. Core strategies are shown in Figure 2 with a bold outline: HEATING ZONES, ROOMS FACING THE SUN AND WIND, DIRECT GAIN ROOMS, MASS ARRANGEMENT and WELL-PLACED WINDOWS. These will apply to almost all PASSIVE SOLAR BUILDINGS of both Thin Plan and Thick Plan variations.
3) The bundle has two situational variations, one for a thick plan building (shown in Figure 2), in which a significant portion of rooms do not face the sun, and one for a thin plan building, in which access to the sun by each room is easier. The situational strategies are located within the bundle boundary (bold dashed line); their icons have no border, for example: CLUSTERED ROOMS, SUNSPACES and MECHANICAL HEAT DISTRIBUTION. These design strategies will typically apply to one of the bundle variations, but not to all of the variations. The situational strategies are appropriate almost all of the time, yet not every strategy need be used in every project. For example, most Thick Plan Variation buildings will need MECHANICAL HEAT DISTRIBUTION to move heat from rooms or surfaces that collect solar heat to remote rooms that do not have direct access to solar heat, but a Thin Plan building can usually use passive radiation or local passive convective loops to distribute heat.

4) Refiner strategies are less critical to the bundle's success or have less impact on architectural form than core or situational strategies. However, they may still have a large impact on performance in Figure 2. The refiner strategies are located outside the bundle boundary (bold dashed line) and their icons have no borders: ATRIUM BUILDING, INSULATION OUTSIDE and SEPARATED OR COMBINED OPENINGS. For example, in a thick plan PASSIVE SOLAR BUILDING, a light court may be used in an ATRIUM BUILDING arrangement; the atrium may also double as a SUNSPACE to collect heat if its roof or one wall has SOLAR APERTURES oriented to the sun. This refiner strategy will not apply to all buildings, but if used, could improve the performance the bundle offers.

4 THE BUNDLE-UP! GAME

The Bundle-Up! game was developed as a fun way to learn about designing with bundles. It allows players to build their own bundles of design strategies that are more specific to their design’s program, site, and climate than the more generic “fundamental bundles” in SWL. The game board (Figure 3) follows the structure of bundles as described above. Users select “Scale Cards” from among nine options (Figure 4a). Scales must be sequential from smaller to larger. A colored “Bundle Tile” from among nine current options (Figure 4b) is placed in the top position, or, alternatively, a blank tile may be selected and given any original name by players who wish to create a custom bundle for a new problem type. Each fundamental bundle and design strategy (currently 115 total) from Sun, Wind & Light [1] is represented by a “Strategy Tile” (Figure 5). The front of the tile shows its SWL strategy icon, abstracted
from a built example, along with its name, strategy number, and level of complexity designation (L1, L2, etc.). The back side gives more information: the strategy or bundle number, its defining “strategy statement,” the energy issues it addresses (heating, cooling, daylighting, etc.), and its level name.

5 OUTLINE OF INSTRUCTIONS FOR PLAYING BUNDLE-UP!

The game can be played by one person (as solitaire) or several people in collaboration. It can also be played by having different teams create variations on the same bundle. This is a good way to arrive at core strategies (ones that have workability in all of a bundle’s variations). Instructions for play:

1) Place your colored Bundle Tile (or create one) in the dashed bundle square on the top.
2) Each strategy has a scale and can only be used at that scale.
3) Choose critical strategies (or your best guess for candidates) from the deck of Strategy Tiles and place them inside dashed bundle “wrapper.” These will become either core or situational strategies. You may start with any strategy that you think would be very important to the design scheme.
4) Place less critical refiner strategies at their designated scale, but outside the bundle wrapper.
5) Examine your set of strategies for their interactions and add, subtract or substitute strategies to create greater synergy between strategies to solve the bundle’s energy issue(s). Debate the importance of different strategies, moving them inside or outside the bundle wrapper.
6) Now identify the strategies that are the three most critical—at least one at each scale—that are critical to “almost every building” in your situation. Place these in the bold core squares. If desired, you may add up to 2 more core strategies.
7) To test your choice of core strategies, think about whether or not each would still be effective in the other situation(s) of the bundle problem. If playing in teams, debate with the other team. If playing in one group, it is useful to assign different players to advocate for the needs of a particular bundle variation.
8) There is no one right solution, but some are better than others, and solutions that follow the rules are all acceptable. When satisfied with your solution, or your group has reached consensus, record it on the Bundle Capture Form (a reduced version of the game board).
9) HAVE FUN!!! Design. Repeat.

Figure 4: (a) Cards for scale/level of complexity (b) Bundle tile example

Figure 5: Strategy tile examples
6 PROTOTYPES AND TESTING

A rough, limited scope prototype with one bundle and only cooling strategies was created, and an initial test was run with peer teachers at the 2012 annual curriculum meeting of the Society of Building Science Educators. Two teams of architects and design professors debated over and created bundles for hot-humid and hot-arid variations of a PASSIVELY-COOLED BUILDING bundle. Feedback was very positive. The members offered suggestions for improvement, mainly to the instructions and options given to users. Overall, they agreed that the game was a good learning tool and that they had actually learned something themselves in the process of playing. The teachers enjoyed learning in a group together and saw possibilities for transforming the typical architectural technology class that primarily uses individual learning approaches and also noted the potential as a design tool in design studio classes.

The next prototype, with a complete set of bundles and strategies, along with revised instructions, was then tested in two classroom settings: fifth-year undergraduate design studios in Spring and Fall terms of 2013 and a second-year “Introduction to Architectural Technology” course in Spring of 2013 and 2014. The lower level instruction in a class of 65 students made use of an instructional video created by the author with two advanced students. In one semester, upper level students designed housing for a village in Gujarat India, collaborating with Professor Sharad Sheth’s fourth-year students from Sardar Vallabhbhai Patel Institute of Technology, Vasad. University of Tennessee students are shown playing Bundle-Up! in Figure 7a. A team working on housing design for the village of Waghnagar developed a composite bundle for a PASSIVELY-COOLED BUILDING and an OUTDOOR MICROCLIMATE, shown in simplified form in Figure 7b. Their scheme for two variations on low-energy climate-responsive courtyard houses built with local materials and labor skills is shown in Figure 8.

Figure 6: Testing Bundle-Up! with the Society of Building Science Educators

![Figure 6](image_url)

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Figure 7: (a) Bundle-Up! in design studio (b) Hybrid custom bundle for Gujarat housing design

![Figure 7](image_url)
In another semester, fifth-year students used Bundle-Up! to help design a net-zero energy brewpub and beer garden in seven different U.S. cities, each set in a different climate. One team’s design for warm-dry Marfa, Texas is shown in Figure 9. It includes passive cooling, heating, and daylighting strategies from Sun, Wind & Light, 3rd edition [1]. They also used the new SWL Tools spreadsheets to calculate energy demand and size photovoltaics to become a plus-energy project.

The lower-level students used Bundle-Up! as a part of a sequence of passive design exercises that design a net-zero energy bioclimatic residence, again in multiple climates. In all of these cases, students developed their designs in collaborative teams of two to four students. Figure 10 shows an example a PASSIVELY-COOLED BUILDING bundle developed in the exercise, a student team using Bundle-Up! in the design process, and a second-year scheme for a net-zero energy residence in the mixed-humid St. Louis climate. As a result of these and other classroom innovations, the instructor/author was awarded the Chancellor’s Award for Teaching Excellence 2014 at the University of Tennessee.
CONCLUSIONS AND FUTURE PLANS

The next step in testing and revision will be a workshop for practicing architects in October 2014. In theoretical terms, observing users playing Bundle-Up! many times and applying their results in designing buildings have suggested the need to expand the Sun, Wind & Light knowledge structure. Bundles, as defined in SWL, cross a limited range of three scales in the nine-scale system of SWL that ranges from materials to neighborhoods. The development question is, “Can the bundle concept and the Bundle-Up! game be expanded to include mapping the full range of design strategies employed in a specific design?”

While the game is clear and useful as a learning or design activity, it is important to place it for students within a clear design process context. Students need assistance in knowing when to employ the bundle concepts and more specific guidance about what to do with the game results. To this end, future class exercises will guide a more explicit design process that involves multiple uses of the game in a sequence of different problem variations. Examples might include generating building design bundles for passive heating, cooling, and lighting, or using Bundle-Up! to explore a responsive envelope that addresses multiple energy issues.

Perhaps the most common request is for an iPad app or other electronic version of the game tied to its SWL knowledge base. The author is currently seeking technical collaborators and funding.

Through application and feedback in different settings and class types over a two-year period, several conclusions may be drawn. Students have found the Bundle-Up! game useful as a step in the process of designing passive and net-zero buildings. It requires them to choose carefully and to narrow their design options strategically. Via the game, the relatively complex SWL knowledge structure becomes more accessible to both beginning and advanced students. Playing Bundle-Up! seems intuitive and fun. Making more fun of understanding climatic design was the game’s real purpose. One peer teacher found, “It teaches systems thinking across multiple scales with none of the systems thinking jargon.” Another reported, “This really supports integrative ecological thinking in a very concrete architectural way.” Students’ responses from feedback surveys are consistent in their appreciation of learning in collaborative dialogue and the teamwork required by Bundle-Up!, in contrast to many of their other classes. They enjoy learning in a hands-on, project-based setting, working together with their peers, rather than working in competition with them.

Digital files for printing and making Bundle-Up! are available from the author.

ACKNOWLEDGMENTS

The author thanks the following for their important roles in this project: Susanne Bennett for the initial game idea; Jordan Etters, research assistant, for graphics and game production; the AIA Upjohn Research Initiative Award for financial support to develop the underlying knowledge structures; the University of Tennessee College of Architecture and Design for a faculty development award to produce and test the prototypes, and the SBSE and University of Tennessee students for prototype testing and feedback.

REFERENCES

Session 6B : Low energy materials and technology

PLEA2014: Day 2, Wednesday, December 17
14:10 - 15:50, Compassion - Knowledge Consortium of Gujarat
Integrated dehumidification and downdraught evaporative cooling system for a hot-humid climate

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ABSTRACT
Unlike in hot-dry climates, in hot-humid climates evaporative cooling techniques are not readily suitable for space cooling. In order to effectively use evaporative cooling in hot-humid climates, dehumidification of ambient air is necessary before it passes over an evaporative medium for cooling. The present study explores the combined process of dehumidification and evaporation and its effect on thermal comfort in a typical small residential building located in a hot humid climate. A novel system has been investigated with the combination of an Earth Tube Ventilation (ETV) (for pre-cooling of air), a rotary wheel desiccant dehumidifier (for dehumidification) along with a Passive Downdraught Evaporative Cooling (PDEC) tower (for evaporation) in that order. Parametric simulations using the EnergyPlus tool have been conducted in order to determine the critical dimensions and parameters of the proposed system, such as desiccant system sizing, PDEC tower height, and air and water flow rate at various points of the system. Results of indoor air temperature, humidity levels and volumetric air flow rates in the building spaces were obtained to study the influence of the proposed combined system on human thermal comfort. On a typical hot day the results from the proposed system show a relatively constant indoor air temperature of 28 °C (as opposed to peak indoor temperature of 36 °C occurred by means of natural ventilation) and indoor relative humidity in the range of 62 % - 68 %. The volumetric airflow rate from the outlet of the PDEC tower is in the range of 2.97 - 3.41 m$^3$/s which is well within recommended levels for a dwelling unit. The proposed system displays a significant potential for providing space cooling in hot-humid climates as it paves an alternate way to the conventional energy consuming vapour compression Air Conditioning units.

INTRODUCTION
Space cooling techniques become inevitable in extreme hot-dry and hot-humid climates where building form and construction alone cannot ensure indoor thermal comfort. Evaporation of water has been one of the available techniques used for space cooling. Special architectural features such as wind towers were used in hot-dry climates to direct the prevailing winds over a wet body like khuskhus pads, water filled clay pots etc. to enhance evaporation. However, high humidity in the ambient air inhibits the use of direct evaporative cooling in hot-humid climates and dehumidification of the air is necessary before it passes over an evaporative medium for cooling. This study explores an alternate to conventional vapour compression based domestic air conditioning units by using dehumidification and evaporation in a typical residential building in a hot-humid climate in India. A combination of a cooling system Sriraj Gokarakonda is a research fellow at Wuppertal Institute for Climate, Environment and Energy, Wuppertal, Germany. Georgios kokogiannakis is a senior lecturer at the Sustainable Buildings Research Centre (SBRC), University of Wollongong, Australia.
consisting of a rotary wheel desiccant dehumidifier along with a Passive Downdraught Evaporative Cooling (PDEC) tower has been devised. An Earth Air Tunnel (EAT) for precooling of intake air has later been added to the original cooling system after analysing the preliminary results. Simulations were run with EnergyPlus to conduct a parametric analysis of the proposed system and to study its influence on thermal comfort.

PASSIVE DOWNDRAUGHT EVAPORATIVE COOLING SYSTEMS

Evaporative cooling is based on the conversion of sensible heat to latent heat. When water evaporates, it uses up the heat from the surrounding air to change phase from liquid to vapour and this result in lowering the temperature of the surrounding air. A typical configuration of a passive downdraught cooling system has a tower to draw in air into the space. The air is passed over an evaporative medium placed below the tower inlet, gets cooled and enters the space through an outlet at the bottom of the tower. A passive downdraught was thus created through the evaporation of water within this air-stream and the necessary air circulation was achieved through either by buoyancy or by wind assisted natural ventilation.

However, modern PDEC towers include energy intensive components like fans and pumps to enhance downdraught or to increase flow rates and are referred to as Passive and Hybrid Downdraught Cooling (PHDC) (Ford, Phan, & Francis, 2009). To increase the evaporation of water, large droplets of water are sprayed into the air stream (e.g. by a shower tower) or a mist of water is added to the air stream (e.g. by misting nozzles in a misting tower) instead of letting the air passing over wetted pads and clay water pots. In this paper, shower tower configuration of PDEC is selected as it represents a typical system used in practice. A shower tower PDEC (PHDC) proved to be a worthy option in meeting the cooling needs of the Torrent research centre building in Ahmedabad (Leena & George, 1997). The system provided an alternative to the use of conventional Air Conditioning in such hot climates during hot-dry season. However, reliance on conventional air conditioning was recommended for the hot-humid season. This system can also be well integrated to the existing buildings. An example of such an application is in Portugal, where an existing chimney of a building has been modified to be used as a PDEC tower (Melo & Guedes, 2006). Its performance was studied by measuring the thermal parameters and humidity levels and compared against a mathematical model. The results for PDEC were encouraging, but it was concluded that a PHDC was performing better over a PDEC (Melo & Guedes, 2006).

DESICCANT DEHUMIDIFICATION

Desiccant dehumidification is based on the principle of sorption with the use of desiccant chemicals. Sorption occurs due to difference in the vapour pressure exerted by the moisture in the air on the surface of desiccant which offers an area of low vapour pressure (Munters Corporation, 2002). Liquid desiccant dehumidifiers in general are large systems and are used to condition large spaces. Solid desiccant dehumidifiers are available in different sizes, configurations to suit for application in residential buildings. Two popular solid desiccant configurations that suit residential applications are packed bed and rotary desiccant wheel.

Packed bed dehumidifier consists of loosely packed silica gel beads. Ambient air is passed over this desiccant bed and the dry air is circulated into the space. It has found application in residential units in a configuration called desiccant enhanced nocturnal radiation (DESRAD) cooling and dehumidification. Chung et al., 1995, Satio (1993), Techajuntaa et al. (1999) further investigated DESRAD concept in various configurations and concluded it can be used in domestic air-conditioning in tropical humid climates.

Rotary Desiccant Wheel (DW) dehumidifier consists of finely divided desiccant silica gel beads that are impregnated into a semi-ceramic structure, which in appearance resembles corrugated cardboard that has been rolled up into the shape of a wheel. The wheel rotates slowly between two air streams called the process air and reactivation airstreams. The process air flows through the flutes formed by the
corrugations, and the desiccant in the structure absorbs the moisture from the air (Figure 1 process A-B). Re-activation (Figure 1 B-C) is the hot air (blown by a hot air blower) necessary to regenerate the saturated desiccant. Following reactivation, the hot desiccant rotates back into the process air (Figure 1 C-A), where a small portion of the process air cools the desiccant so it can collect more moisture from the balance of the process airstream. (Munters Corporation, 2002). Commercial desiccant products in the HVAC industry are mostly available in rotary desiccant wheel (DW) configuration.

While a rotary DW dehumidifier consumes more energy than a packed bed it has been chosen for the present study because the DW system can be easily and precisely sized with available modelling tools to fit a building case. Modelling a packed bed on the other hand involves dependence either on experimental data or rigorous analytical calculations with assumptions to be made which was beyond the time scope of the study.

METHODOLOGY

Location and Climate analysis

The location selected for the current study is Visakhapatnam city (Lat 17.72, Lon 83.23) in the state of Andhra Pradesh in India and where the climate is categorised as tropical hot-humid climate. In peak summer the temperature reaches as high as 38 °C and in winter it reaches a minimum of 15 °C. The diurnal variation of temperature during hot summers is usually 5-6 °C. The outdoor relative humidity levels are in general above 60% for most of the year. Relative humidity is low at noon and reaches peak during early morning before the sunrise and again drops as the day progresses.

Description of the proposed system and sequence of operation

The proposed system consists of a rotary Desiccant Wheel dehumidifier (DW) which is integrated with a Downdraught Evaporative Cooling shower tower (PDEC tower) through which the air is supplied into the space (Figure 2 a). An Earth Air Tunnel has later been added to the DW+PDEC system after observing the preliminary results in order to pre cool the supply air drawn into the Desiccant Wheel.

The ambient air at temperature \(T_a\) and relative humidity \(R_{h_a}\) is drawn into the EAT and leaves the EAT at a temperature \(T_1\) and relative humidity \(R_{h_1}\). The air at \(T_1\) and \(R_{h_1}\) is then drawn into the inlet of DW from the outlet of the EAT. The air at the outlet of the DW is called the process air and it has been dehumidified and conditioned to a temperature \(T_2\) and relative humidity \(R_{h_2}\). The process air at \(T_2\) and \(R_{h_2}\) is then supplied to the top of the PDEC. \(T_3\) and \(R_{h_3}\) are the air temperature and relative humidity at the outlet of the PDEC tower which is directly supplied for cooling the indoor space. \(T_4\), \(R_{h_4}\) is the final
temperature and relative humidity in the zone and it is expected to be less than the ambient $T_1$ and $Rh_1$ for the system to be able to perform well. The psychrometric representation of the proposed system can be seen in Figure 2 b.

![Graphical representation of the proposed system on a Psychrometric chart](image)

**Figure 2** a) Graphical representation of the proposed system b) System representation on a Psychrometric chart

**Description of a typical dwelling unit to which the proposed system is attached**

A typical dwelling unit has been modelled as three thermal zones (Figure 3). Zone 2 is connected to the proposed system of integrated dehumidifier and PDEC tower and it is referred to as zone henceforth. All rooms have a wall to window ratio of 33% which is typical in the region. The floor to ceiling height is 2.8m. The worst possible scenario is assumed for shading during the cooling period, i.e. there are no shading devices or overshadowing from the surroundings. Typical building materials used in the region are assumed for the constructions and their U-Values (in W/m²K) are: exterior walls - 1.946, interior walls - 1.735, roof slab - 4.6, floor slab - 0.894 and windows 5.71 (with an SHGC of 0.567).

![Typical dwelling unit](image)

**Figure 3** Typical dwelling unit (all dimensions in meters)

**MODELLING THE PROPOSED SYSTEM**

The EnergyPlus whole building dynamic simulation program was used to simulate the EAT, DW and PDEC components. However, the whole proposed system of this study (i.e. ambient air $\overline{EAT}$, $\overline{DW}$ and $\overline{PDEC}$) could not be modelled in one simulation because of the limitations of the tool to assemble such a configuration in a single sequence. For this purpose, a total of four simulations were carried out in a way that is explained below and summarised in Figure 2:
1. Ambient air\textsuperscript{\textdegree} EAT (A in Figure 2): Precooling of air was simulated using an Earth Air Tunnel. The results of the simulation provide the supply air temperature at $T_1$, $\text{Rh}_1$ from the outlet of the EAT. The EAT has been modeled with a fan to provide an EAT outlet flow that matches with the supply flow rate demand of the DW dehumidifier.

2. EAT\textsuperscript{\textdegree} DW (A to B in Figure 2): The DW was simulated in EnergyPlus using a modified weather file with temperature and relative humidity values obtained from the previous simulation i.e., $T_1$ and $\text{Rh}_1$ as inputs. The results of this simulation provide the process air at $T_2$, $\text{Rh}_2$ from the outlet of the DW.

3. DW\textsuperscript{\textdegree} PDEC (B to C in Figure 2): The PDEC tower was modelled in the third simulation. Technically, in the EnergyPlus program the PDEC tower simulation takes the inlet temperature and humidity data at the top of the tower from the original weather file. Therefore, the values of actual ambient air temperature and relative humidity in the original weather file were replaced by the output obtained from the 2\textsuperscript{nd} simulation, i.e., with $T_2$, $\text{Rh}_2$. When this 2\textsuperscript{nd} simulation was run PDEC tower takes $T_2$, $\text{Rh}_2$ as the inlet values at the top of the tower and the tower outlet temperature and humidity $T_3$, $\text{Rh}_3$ are obtained. The conditions in zone 2 ($T_4$ and $\text{Rh}_4$) can in theory be calculated from the same simulation, however in this case the zone conditions cannot be obtained because the temperature and relative humidity values ($T_2$ and $\text{Rh}_2$) in the weather file for the 3\textsuperscript{rd} simulation were modified from the actual ambient temperature and relative humidity (from $T_4$ and $\text{Rh}_4$) to the DW outlet temperature $T_2$ and relative humidity $\text{Rh}_2$ in order to be used as inlet conditions of the PDEC tower. This means that the weather file during the 3\textsuperscript{rd} simulation did not include the actual weather conditions and could not therefore be used to define the boundary conditions of the building.

4. PDEC\textsuperscript{\textdegree} Room (C to D in Figure 2): The fourth simulation was run to obtain the zone temperatures and relative humidity levels ($T_4$ and $\text{Rh}_4$). In this simulation boundary conditions were properly set based on the original weather file with ambient air conditions at $T_a$ and $\text{Rh}_a$. The air supplied into the zone from the PDEC tower outlet (i.e. $T_3$ and $\text{Rh}_3$) has been mimicked by using a customised EnergyPlus component that supplies air into the zone at desired parameters. The results of this simulation provide the zone air conditions at $T_4$, $\text{Rh}_4$.

Parametric studies have been done at each component level to optimise the critical parameters that impact in achieving the lowest temperature and relative humidity of the air at each of the outlets. The focus was on optimising pipe length and depth for EAT, velocity of the wheel for the Desiccant Wheel, and water flow rate and height of the tower for PDEC tower. Table 1 gives a summary of the sequence of optimization of various components, which was done based on the above listed parameters. The physical parameters of the proposed system were optimized based on the conclusions drawn from the parametric results. The highlighted area shows the selected case from each stage, which was then carried forward to the subsequent simulation stage.

<table>
<thead>
<tr>
<th>Table 1 Optimization process</th>
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<tr>
<td>Earth Air Tube</td>
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<td>Pipe length</td>
</tr>
<tr>
<td>Depth</td>
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<tr>
<td>DW</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
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<tr>
<td>PDEC</td>
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<td>Max water flow rate (m$^3$/s)</td>
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<td>PDEC - height (m)</td>
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<tr>
<td>PDEC</td>
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<tr>
<td>Max water flow rate (m$^3$/s)</td>
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<td>PDEC - height (m)</td>
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</table>
RESULTS

A period of two representative weeks during which peak outdoor temperatures occur is taken for study (Figures 4 and 6). It can be observed from Figure 4 that there is a significant decrease in the zone temperature in the range of 3-8 °C after adding the proposed system (without EAT) in comparison to the zone temperature without any system and open to natural ventilation. The addition of the EAT further decreases the zone temperature and brings it close to the comfort limits (in the range of 28 – 30 °C).

![Figure 4 Zone temperature (T₄) after adding EAT (case 5) to pre cool the supply air](image)

A typical warm day chosen from the above two-week period to analyse the diurnal variation in zone temperature and zone relative humidity levels. From Figure 5 it can be seen that zone temperatures during the day are lower than that of the night for the system configuration with EAT (case 5) + DW (case 3) + PDEC (case 6). The zone air temperature increases in the night and at times exceeds the ambient air temperature (see Figure 5).

![Figure 5 Diurnal variations in zone temperature (T₄)](image)
The relative humidity in the zone with the proposed system was lower during daytime and higher during the nights than the relative humidity values of the naturally ventilated case. However, zone relative humidity levels are maintained well below the maximum permissible level of 75% (Figure 6) (CIBSE, 2006) throughout the period of the study.

Figure 6 Zone humidity ($\text{Rh}_4$) after adding EAT to pre cool supply air

Figure 7 shows that the proposed system results in a slightly higher relative humidity (up to 8%) compared to the naturally ventilated zone humidity levels during the day. However, during the nights the system reduces (by up to 7%) the relative humidity in the zone. An air flow rate of 2.97 - 3.41 m$^3$/s was also observed at the outlet of the PDEC tower ensuring the recommended ventilation levels within the space as per ASHRAE (2009) for residential dwellings.

Figure 7 Diurnal variation in zone relative humidity ($\text{Rh}_4$)
CONCLUSION

An integrated cooling system of desiccant dehumidifier and PDEC was evaluated for a typical dwelling in a hot humid climate in India after being combined with an earthtube ventilation system. A process for enabling the simulation of the proposed system has been reported. The system’s performance was investigated with a parametric analysis and it was found that by using the EAT+DW+PDEC system as opposed to using natural ventilation the peak indoor summer temperatures were reduced by about 8 °C while indoor relative humidity remained below 75%. The proposed system could provide space cooling in hot-humid climates and could be an alternative to high energy consuming conventional vapour compression AC units. This study analysed a worst-case scenario of a building without any shading and by assuming typical materials that are not of high thermal standards. With improvements however in building designs, the proposed system could ensure good levels of indoor thermal comfort.

REFERENCES

Thermal Performance of a Passive Cooling Louver System to Form Cool Microclimate in Urban Residential Outdoor Spaces

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ABSTRACT
A passive cooling louver system (PC louver), which is an aluminum louver partition coated with hydrophilic and water absorbing film, was developed in order to form a cool microclimate in urban residential outdoor spaces in hot and humid regions. The combination of hydrophilicity and water absorption of the film enhances water diffusion of the surface of PC louver. Hence, when a PC louver is watered from the top, the entire surface becomes wet, which enhances its evaporative cooling effect. The PC louver was designed to shade direct solar radiation, provide radiation cooling and ventilation cooling with cooled airflow. In this research, the thermal performance of the developed PC louver in outdoor environment was evaluated. As a result, the PC louver’s surface was fully wetted and its surface temperature was approximately the ambient wet bulb temperature throughout the day. Temperature of the air passing through the PC louver decreased 2–3 °C, which achieved the expected cooling performance as a passive cooling system.

INTRODUCTION
In urban cities in hot and humid regions, the outdoor thermal environment has become a serious issue as the danger of heat stroke has increased. In these regions with a large amount of rainfall during the summer, the application of a passive cooling design using solar shading and evaporative cooling is focused (Hoyano et al., 1995). In residential area, it is expected to form cool microclimate in semi-outdoor spaces, so as to improve thermal comfort for both indoor and outdoor spaces.

Therefore, we developed a “Passive Cooling Louver System (PC louver)” as a residential exterior item (Figure 1). Louvers in general are able to shade solar radiation while penetrating air flow. In addition, by wetting the louver’s surface, the surface temperature of the louver is expected to decrease by the latent heat of the evaporating water. Thus by adding the function that enables to wet the louver’s entire surface, the following passive cooling effects can be expected: 1) solar shading, 2) radiation cooling, 3) ventilation cooling with cool airflow.

In this paper we first summarize required performances of PC louver and approaches to satisfy these requirements. Subsequently, we verified the thermal performance of the PC louver through experiments in an outdoor environment. Besides, since it is necessary to predict the cooling effects at the architectural design stage, the thermal performance of the PC louver is evaluated in means of revealing the heat balance of the PC louver, in order to build a heat transfer model. However, this paper describes the achievements of thermal performances of the PC louver compared to the required performances, and the construction of modeling is performed in the next step.
DEVELOPMENT OF A PASSIVE COOLING LOUVER SYSTEM

Cooling Potential and Required Performance of the PC louver

Among hot and humid regions, there are cities that the relative humidity during the daytime decreases significantly. For example Tokyo, Japan is a seasonally hot and humid climate, but while the air temperature is above 30 °C during the day, relative humidity tends to decrease to 40–50 %, and wet bulb temperature at about 20–25 °C, which indicates enough potential as a cooling source (AIJ, 2005).

In the previous research (Hoyano et al., 1995), they developed a moist and void brick wall as a passive cooling wall (PCW), and verified that the wet bricks’ inner surface temperature lowered to almost the ambient wet bulb temperature in an outdoor environment. Moreover, in the previous measurement and simulation of a semi-enclosed space using PCWs, the mean radiant temperature near PCWs were 2–4 °C less than the ambient air temperature and the air temperature passing through the PCW was lowered to 3 °C at the maximum. (Shirai et al., 1997; He et al., 2009).

The high performance of a PCW is well known through the previous research, but since a PCW is a wall of bricks, its form and utilization is more suitable in public spaces rather than in residences. Besides, moist bricks are effective to provide cooling effect continuously, but being moisted constantly is not a good condition for durability. Therefore, as shown in Table 1, we summarized the requirements for the development of the PC louver to satisfy performances as a passive cooling system together satisfying requirements as an exterior item in residences.

Surface Specifications of the PC louver

For the basic material of the PC louver, aluminium was chosen for its strength and durability. For the surface layer, it is important to wet the entire surface of the louver in order to minimize the surface temperature distribution. Thus, a hydrophilic resin with porous particles (Figure 2(a)) and photocatalyst

![Figure 1 Image of passive cooling effects using a PC louver in semi-outdoor space of a residence.](image)

<table>
<thead>
<tr>
<th>Required performances</th>
<th>Methods</th>
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<tbody>
<tr>
<td>1) Shade direct solar radiation to the subject space.</td>
<td>Adjust pitch of the louver’s slats.</td>
</tr>
<tr>
<td>2) Wet the entire surface of the louver and create uniform surface temperature distribution.</td>
<td>Enhance the hydrophilicity of the louver’s surface.</td>
</tr>
<tr>
<td>3) Prevent algae, mold or smudge by letting the louver’s surface dry easily when it is not in use.</td>
<td>Separate surface layer and base layer, and wet only the surface layer.</td>
</tr>
<tr>
<td>4) Enhance heat transfer between cooled louver’s surface and air passing through the louver.</td>
<td>Enhance the surface ratio of the louver’s slat to the louver’s vertical plane.</td>
</tr>
<tr>
<td>5) Lower surface temperature of the louver immediately after watering.</td>
<td>Lower heat capacity of the louver by using the hollow aluminium slats.</td>
</tr>
<tr>
<td>6) Enable to maximize the shape factor to the subject space.</td>
<td>Manufacture the louver with compact depth and flexible width and height.</td>
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(TiO$_2$) was coated to the aluminum base (Figure 2(b)). Hydrophilicity of the resin and the porous particles were enhanced by the photocatalyst, and the capillary force of the porous particles aided the diffusibility of the surface water.

**Form and Sectional Composition of the PC Louver**

The form and the sectional composition of the PC louver were determined mainly with the consideration of water flow and the solar radiation transmittance. The louver’s slats are titled 3° down toward the terrace side in order to drain water mainly to the terrace side. In addition, by cutting the edge of slats toward the center, water is led to drop near the center of the next slat (Figure 3(a)).

Space between slats affects the quantity of solar radiation transmittance, evaporation, air permeability, and heat transfer between louver’s surface and air passing through the louver. Among these factors, we mainly focused on the effect of solar shading because the amount of solar energy is larger compared to other factors. By narrowing a space between the slats to 10 mm, the louver system allows direct solar radiation to transmit only at solar altitude lower than 13°, which corresponds to approximately an hour before and after the sunset and sunrise (Figure 3(b)).

**THERMAL CHARACTERISTICS OF THE PASSIVE COOLING LOUVER SYSTEM**

**Aim of the Experiment**

An outdoor experiment was conducted in order to verify thermal performance of the PC louver in means of clarifying the heat balance of the PC louver’s surface. The heat transfer model is expected to be inserted in a microclimate simulation tool (Asawa et al., 2008), which the authors have developed. In order to analyze the spatial distribution of the microclimate in the simulation, the heat transfer model of PC louver is required to be simplified to reduce calculation load. Therefore, a distribution of the surface temperature of the PC louver is verified at the experiment in order to discuss the possibility to treat PC louver’s surface as a thermally equivalent semi-permeable vertical plane. A description of the PC louver’s heat transfer model is shown in Figure 4.
Measurement Methods

A terrace with the PC louver was constructed in semi-outdoor space of a detached house, facing the southwest direction (220°). The site was open to the predominant wind direction, thus wind flowed into the terrace from the front to diagonal direction of the louver. Two PC louver planes on the front side of the house were attached to the pergola, which the east side louver was wetted during the experiment (the wet PC louver) and the west side louver was kept dried (the dry PC louver) for comparison purposes. The scheme of the PC louver and the measurements are shown in Figure 5 and Table 2.

The measurement was conducted on Oct. 1st 2012 and Aug. 4th 2013 to Nov. 29th 2013. Air temperature at the vicinity of the PC louver was measured using a φ = 0.1 mm T-type thermocouple set inside a forced draft φ = 13 mm polyvinyl cylinder (air velocity of approximately 1.5 m/s), in order to reduce the influence of solar radiation. Ambient dry bulb and wet bulb temperature were measured inside a forced draft φ = 150 mm aluminum cylinder (air velocity of approximately 3 m/s). A water tube with φ = 6 mm was inserted through the strut to the beam of the pergola. The amount of water supplied was measured right below the water drip tube and the amount of water drainage was measured at bottom of PC louver using a tipping-bucket rain gauge. During the experiment, tap water was supplied at approximately 0.04 kg/min per PC louver’s vertical plane. Although, for hot and humid regions with a large amount of rainfall during summer, where the amount of precipitation is enough to cover the evaporation amount, we are working to construct a system to use rain and supply it to the PC louver.

Measurement Results

Wet and Dry PC Louver’s Surface Temperature The distribution of the wet state of the louver was difficult to measure, thus surface temperature distribution was measured using an infrared camera. Figure 6 (a) shows the surface temperature distribution of the terrace side and the outside of the PC louver at 13:00 on Aug. 7th 2013, as a representative day of a clear sunny day. Overall, there was about a 3 °C range in surface temperature distribution of the wet PC louver. As shown in Figure 6 (b), the outside surface of the louver had a large distribution of solar radiation due to its ragged form, but the difference in surface temperature was small. This indicates that the quantity of solar radiation does not determine the surface temperature of the wet louver, but the latent heat, as the quantity of evaporation shown in Figure 9, is the main factor. The small distribution in the wet PC louver’s surface temperature also indicates that the convective heat flux of water flow is small compared to other heat fluxes at the experimented amount of water supply. This is also confirmed by the calculation of He et al., (2008) that only a few centimeters of the wet surface’s temperature are affected by the water’s temperature.

From these results, the small range of surface temperature distribution was confirmed when the entire surface is wet. The range was small enough to use the average temperature as a representative temperature for an equivalent vertical plane, when discussing on the microclimate in residential space.
Figure 5 Section of PC louver and measurement points.

Table 2. Descriptions of the Measurement Sensors.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Measuring point</th>
<th>Sensor type</th>
<th>Resolution</th>
<th>Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient air temperature</td>
<td>GL+9m</td>
<td>Weather Transmitter (WXT520, VAISALA)</td>
<td>±0.3 °C</td>
<td></td>
</tr>
<tr>
<td>Ambient relative humidity</td>
<td>GL+9m</td>
<td>(WXT520, VAISALA)</td>
<td>±3% (&lt;90%RH)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>±5% (&gt;90%RH)</td>
<td>1min.</td>
</tr>
<tr>
<td>Ambient wind direction</td>
<td>GL+2.3m</td>
<td>Wind vane anemometer</td>
<td>±5°</td>
<td></td>
</tr>
<tr>
<td>Ambient wind velocity</td>
<td>GL+2.3m</td>
<td></td>
<td>±0.3 m/s</td>
<td></td>
</tr>
<tr>
<td>Dry bulb temperature</td>
<td>GL+1.5m</td>
<td>Φ0.1mm T-type thermocouple (internal forced draft cylinder)</td>
<td>±0.1 °C</td>
<td></td>
</tr>
<tr>
<td>Wet bulb temperature</td>
<td>1m outside from PC louver</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total horizontal solar radiation</td>
<td>GL+2.6m</td>
<td>Pyranometer (sensitive waveband:0.3-2.8 μm)</td>
<td>±5%</td>
<td>1sec. /</td>
</tr>
<tr>
<td>Total vertical solar radiation</td>
<td>(top of pergola)</td>
<td></td>
<td></td>
<td>10sec. /</td>
</tr>
<tr>
<td>Wind direction</td>
<td>GL+1.5m</td>
<td>3-D Ultrasonic wind sensor</td>
<td>±2°</td>
<td></td>
</tr>
<tr>
<td>Wind velocity</td>
<td>1m outside from PC louver</td>
<td></td>
<td>±0.1 m/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GL+1.5m</td>
<td></td>
<td></td>
<td>1min.</td>
</tr>
<tr>
<td>Air temperature</td>
<td>GL+1.5m, 0.1m in and outside of PC louver</td>
<td>Φ0.1mm T-type thermocouple (internal forced draft cylinder)</td>
<td>0.1 °C</td>
<td></td>
</tr>
<tr>
<td>Surface temperature</td>
<td>GL+1.5m</td>
<td>Φ0.1mm T-type thermocouple</td>
<td>0.1 °C</td>
<td></td>
</tr>
<tr>
<td>Surface temperature</td>
<td>GL+1.5m</td>
<td>Infrared camera (sensitive waveband:8-14 μm)</td>
<td>±2 °C</td>
<td>arbitrary</td>
</tr>
<tr>
<td>Water supply</td>
<td>Below water drip tube</td>
<td>Weight scale</td>
<td>±3%</td>
<td>10min.</td>
</tr>
<tr>
<td>Water drainage</td>
<td>Bottom of PC louver</td>
<td>Tipping-bucket rain gauge (Φ0.2 m)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Terrace side and outside of the PC louver.  
(b) Enlarged diagram of outside.

Figure 6 Surface temperature distribution of the PC louver.
Diurnal surface temperature change of the PC louver is shown in Figure 7. From Aug. 4th to Aug. 7th 2013, water was supplied continuously during the daytime as shown in the white bands in Figure 7. Surface temperature of the dry PC louver exceeded 40 °C, while the surface temperature of the upper side and terrace side of the wet PC louver was only 0–1.5 °C higher than the ambient wet bulb temperature, which indicates the effect of evaporative cooling at the louver’s surface.

Transmittance and Absorption of Solar Radiation The amount of transmitted solar radiation was approximately 50 W/m² during daytime in a sunny day, which is about 5 % of the incident solar radiation (Figure 6). Direct solar radiation was calculated to transmit at an hour before and after the sunset and sunrise, but solar transmittance did not increase, since the quantity of solar radiation was already small at these times. Solar radiation absorption was calculated by the deduction of transmitted solar radiation and reflected solar radiation from incident solar radiation, and the solar radiation absorption was approximately 47% during the daytime.
Evaporation Rate  Evaporation rate per vertical surface plane of a representative sunny day is shown in Figure 9. Water was supplied continuously for 24 hours during this period. From the experimental results, 14 kg/m$^2$ of water evaporated in a day, which is equivalent to 34 MJ/m$^2$ of latent heat flux. This is about two to three times larger than that of standard water retentive pavements.

Air temperature in front and behind the PC louver  Wind direction in Figure 10 is shown by considering the normal direction from outside to PC louver as 0°. When wind speed was larger than 0.5 m/s, air temperature at the vicinity of the PC louver varied depending on wind’s direction. When wind direction is 0° to ±45° at 13:56–13:58, air temperature decreased approximately 2 °C in the terrace side compared to the outside air temperature. When wind direction is ±45° to ±90°at 14:02–14:03, air temperature difference was not significant. Air temperature in terrace side also decreased with a breeze (wind velocity less than 0.5 m/s) at 13:59 and 14:04. Here, the cooling efficiency of wind penetrating
the PC louver is evaluated by the following index $\eta$, based on the ambient wet bulb temperature:

$$\eta = \frac{(T_a - T_l)}{(T_a - T_{wb})}$$

Figure 11 shows the calculated data when wind continuously passed through the louver from the normal direction for more than 3 sec. $\eta$ tended to stabilize at 0.2 when wind velocity is larger than 2 m/s, and distributed between 0–0.4 at breeze. This is a similar feature to the former PCW that the maximum value of $\eta$ is recognized at breeze, but stabilizes at smaller value as wind velocity increases.

CONCLUSION

This study investigated the potential use of an evaporative cooling system during daytime in urban cities in hot and humid regions. A “Passive Cooling Louver System,” coated with hydrophilic resin, porous particles, and a photocatalyst was developed as an exterior material for residences. From the outdoor experiment the following thermal performances were revealed: 1) The surface temperature of the wet PC louver was approximately the ambient wet bulb temperature. 2) The distribution of the wet PC louver’s surface temperature was small enough that it can be modeled as an averaged value of an equivalent vertical plane. 3) Transmittance of direct solar radiance is few. 4) The maximum amount of daily evaporation of the PC louver is approximately 14 kg/m$^2$ ($\approx$ 34 MJ/m$^2$ of latent heat) per vertical plane. 5) Air temperature at the vicinity of PC louver decreased by 3 °C at most. From these results, the required cooling performance as a development of the PC louver was confirmed. For the next step, we will construct a thermal transfer model of the PC louver and incorporate it to a microclimate simulation tool, in order to aid spatial design to form cool microclimate.

ACKNOWLEDGMENTS

The development of the surface layer of the PC louver was jointly carried out AICA Kogyo Co., Ltd. The authors are grateful for the assistance from AICA Kogyo Co., Ltd.

NOMENCLATURE

$\Phi$ = Diameter [mm]  
$\varepsilon$ = Emissivity [-]  
$R_L$ = Long wave radiation [W/m$^2$]  
$\sigma$ = Stefan-Boltzmann constant [-]  
$T_s$ = Surface temperature [$^\circ$C]  
$T_{aw}$ = Air temperature at windward of PC louver [$^\circ$C]  
$T_{wb}$ = Wet bulb temperature [$^\circ$C]  
$T_{al}$ = Air temperature at leeward of PC louver [$^\circ$C]  
$T_w$ = Water temperature [$^\circ$C]  
$\eta$ = Cooling efficiency [-]  
$k$ = mass transfer coefficient [-]  
$\beta$ = Evaporation efficiency [-]  
$\alpha_c$ = Convection coefficient between air and the surface of PC louver [W/(m$^2$ K)]  
$\alpha_w$ = Heat transfer coefficient between water and the surface of PC louver [W/(m$^2$ K)]

REFERENCES

Embodied energy and CO$_2$ emissions of building materials for residential buildings in Jakarta and Bandung, Indonesia

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[Hiroshima University]

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[Hiroshima University]

ABSTRACT

The objective of this study is to evaluate the current building material stock and future demolition waste for urban houses using a material-flow analysis in Jakarta and Bandung. Their embodied energy and CO$_2$ emissions are also analyzed by using an input-output analysis method. The actual on-site building measurements were conducted in Jakarta (2012) and Bandung (2011), focusing on unplanned houses, to obtain building material inventory data. A total of 297 and 247 houses were investigated in Jakarta and Bandung, respectively. These houses were generally classified into the following three categories: simple (45%), medium (39%) and luxurious houses (16%). The results show that overall, the averaged material quantity per m$^2$ used for the houses is 2.14 ton/m$^2$ in Jakarta and 2.06 ton/m$^2$ in Bandung. Two scenarios with zero and maximum reuse/recycling rates were designed to predict future demolition waste and embodied energy/CO$_2$ emissions of building materials in Jakarta. Closed- and open-loop material flows were applied. The maximum reuse/recycling rates not only decrease material waste (0.93-1.22 ton/m$^2$) but also their embodied energy (16.8-151.1 GJ) and CO$_2$ emissions (1.6-14.9 ton CO$_2$-eq). In contrast, the minimum reuse/recycling rates increase environmental burden, and the expansion of unplanned houses is anticipated to cause further urban sprawls and drastic land-use changes by 2020.

INTRODUCTION

One of the obstacles to analyze embodied energy and CO$_2$ emissions of building materials in developing countries such as in Indonesia is considered to be relatively poor data availability of life cycle building materials from material input to material output (waste) including construction and demolition waste (C&D). The majority of urban housing stocks in Indonesia are unplanned houses. These houses are not designed and constructed in a formal way. Therefore, there is a serious lack of building material inventory data which are required for the analysis of material flow and their embodied energy/CO$_2$ emissions.

This study analyzes flow of building materials and their embodied energy/CO$_2$ emissions for urban houses in Indonesia, focusing on unplanned houses, through the material-flow analysis and the input-output (I-O) analysis methods. The actual on-site building measurements were conducted in Jakarta (2012) and Bandung (2011), to investigate building material inventory. The current status of material stock was evaluated. Further, life-cycle material flows, focusing on demolition waste and their embodied energy/CO$_2$ emissions of urban houses are predicted in different scenarios with various reuse/recycling rates.

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METHODOLOGY

Case study cities and houses

Jakarta and Bandung were selected as case study cities. Jakarta, the capital city, had a population of 9.99 million in 2012 (Jakarta, 2013) while that of Bandung had 2.45 million as of 2012 (Bandung, 2013). Both cities experience hot and humid tropical climates. However, the monthly average temperature in Bandung (22.9-23.9 ºC) is not as high as Jakarta (27.1-28.9 ºC) because of its relatively high altitude. On average, Bandung and Jakarta are located at 791 and 7 m above the sea level, respectively.

In most of the major cities in Indonesia, unplanned houses called ‘Kampungs’ account for the largest proportion of the existing housing stocks. These dwellings settled in unplanned and overcrowded urban villages without being provided with basic urban infrastructure and services properly. These unplanned houses accounted for about 74% of the total housing stocks in Jakarta as of 2012 (Jakarta, 2013) and about 89% in the case of Bandung (Bandung, 2013). Moreover, these unplanned houses can be further classified into three house categories based on its construction cost and lot size, namely simple, medium, and luxurious houses (Figure 1) having a lifespan of 20, 35, and 50 years, respectively (SNI, 1989).

A total of 297 and 247 residential buildings were investigated in Jakarta and Bandung, respectively (see Table 1). As shown, the average household size is about 4-5 persons with a small variation between the three categories for both cities. The monthly average household income was also investigated by a multiple-choice question. As expected, the average income increases with house category from simple to luxurious houses. In general, the average income in Jakarta is slightly higher than that of Bandung. The total floor area also increases with house category in both of the cities. The major building materials used are found to be almost the same in both cities among the above three house categories, though slight differences can be seen in terms of materials for floor and roof.

Current material stock in urban residential buildings

The limitations of data for building, economy and environment in Indonesia make it difficult to clarify the current material stock in urban residential buildings, and to design and implement concrete policies to deal with the issues of C&D waste management. In this study, firstly, we attempt to evaluate a) the current building material stock in urban residential buildings in Jakarta and Bandung at the city level respectively, b) the future demolition waste in unplanned urban houses, and c) the future urban expansion due to demolition of unplanned houses in both of the cities, based on the survey results.

The mathematical equations used to estimate the current material stock for urban houses are described as follows. In this analysis, it is assumed that 1) the number of housing stocks are equal with the number of households determined by number of populations and household size, 2) the income distribution in urban settlement areas of Jakarta and Bandung is the same as the status of whole Jakarta city assuming that low, middle and high income people live in simple, medium and luxurious houses, respectively.

\[
TS = \sum_i \sum_j S_{ij} . H_j
\]

(1)

\[
(2)
\]

**Figure 1** Views of sample residential buildings. (a) Simple house; (b) Medium house; (c) Luxurious house
medium houses: 35 years, luxurious houses: 50 years), 4) zero reuse/recycling rates of each material.

houses will not be demolished until 2020, based on the assumption of 2) and buildings’ life-spans (i.e. 4% for high, 73% for medium and 23% for low income class (JETRO, 2011), 3) the medium and luxurious unplanned residential buildings will be changed in proportion to the significant change in income level; Bandung would be 11.6 and 2.9 million in 2020 (UN, 2011), 2) the share of each type of houses in material stock, estimated by Equation (1). It is assumed that 1) the predicted population of Jakarta and urban houses among the total population (Jakarta: 0.74; Bandung: 0.89), 3) current income distribution (low income (living in simple houses): 0.75, medium income (living in medium houses): 0.20, high income (living in luxurious houses): 0.05) (Mizuho, 2010), TP: total population in 2012, $\overline{HS}_j$: averaged household size for each type of houses, $SA_{ij}$: stock of material $i$ per unit gross floor area in house type $j$ (kg/m²), $F_i$: averaged gross floor area in house type $j$ (m²).

The mathematical equations used to estimate demolition waste from unplanned houses until 2020 are described as follows. In this analysis, we only focus on the demolition waste, generated from the current material stock, estimated by Equation (1). It is assumed that 1) the predicted population of Jakarta and Bandung would be 11.6 and 2.9 million in 2020 (UN, 2011), 2) the share of each type of houses in unplanned residential buildings will be changed in proportion to the significant change in income level; 4% for high, 73% for medium and 23% for low income class (JETRO, 2011), 3) the medium and luxurious houses will not be demolished until 2020, based on the assumption of 2) and buildings’ life-spans (i.e. medium houses: 35 years, luxurious houses: 50 years), 4) zero reuse/recycling rates of each material.

$$\overline{HS}_j$$

$$\frac{1}{m} \sum_{i=1}^{5} M_i j$$

$$\frac{1}{m} \sum_{i=1}^{5} M_i j$$

$$TW = \sum_{i=1}^{5} \frac{1}{m} \sum_{i=1}^{5} M_i j$$

Table 1 Brief profile of sample houses in Jakarta and Bandung

<table>
<thead>
<tr>
<th>Sample size (unplanned/planned)</th>
<th>Jakarta</th>
<th></th>
<th>Bandung</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple</td>
<td>125</td>
<td>Medium</td>
<td>57</td>
<td>Luxurious</td>
</tr>
<tr>
<td>Medium</td>
<td>115</td>
<td>120</td>
<td>99</td>
<td>28</td>
</tr>
<tr>
<td>Luxurious</td>
<td>57</td>
<td>120</td>
<td>99</td>
<td>28</td>
</tr>
<tr>
<td>(125/0)</td>
<td>(75/40)</td>
<td>(29/28)</td>
<td>(120/0)</td>
<td>(99/0)</td>
</tr>
<tr>
<td>Household size (persons)</td>
<td>4.3</td>
<td>5.3</td>
<td>5.6</td>
<td></td>
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<tr>
<td>&lt; 100 (USD)</td>
<td>1.6</td>
<td>7.9</td>
<td>4.0</td>
<td>3.5</td>
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<tr>
<td>100-500</td>
<td>16.8</td>
<td>31.3</td>
<td>14.2</td>
<td>38.4</td>
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<tr>
<td>501-1000</td>
<td>16.8</td>
<td>31.3</td>
<td>14.2</td>
<td>38.4</td>
</tr>
<tr>
<td>&gt; 1000</td>
<td>16.8</td>
<td>31.3</td>
<td>14.2</td>
<td>38.4</td>
</tr>
<tr>
<td>Total floor area (%)</td>
<td>71.2</td>
<td>9.6</td>
<td>50.8</td>
<td>6.1</td>
</tr>
<tr>
<td>&lt; 50 (m²)</td>
<td>71.2</td>
<td>9.6</td>
<td>50.8</td>
<td>6.1</td>
</tr>
<tr>
<td>50 - 99</td>
<td>20.0</td>
<td>51.3</td>
<td>39.2</td>
<td>34.3</td>
</tr>
<tr>
<td>100 - 300</td>
<td>8.8</td>
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<tr>
<td>&gt; 300</td>
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<td>2.6</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Major building materials (%)</td>
<td>Structure</td>
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<td>100</td>
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<tr>
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<td>Stone</td>
<td>Concrete</td>
<td>76</td>
<td>37</td>
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<tr>
<td>Foundation</td>
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<td>Concrete</td>
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<td>53</td>
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<tr>
<td>Floor</td>
<td>Cement</td>
<td>80</td>
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<td>75</td>
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<tr>
<td>Floor</td>
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<td>80</td>
<td>0</td>
<td>75</td>
</tr>
<tr>
<td>Walls</td>
<td>Clay brick</td>
<td>100</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>Walls</td>
<td>Clay brick</td>
<td>100</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>Roof</td>
<td>Clay</td>
<td>48</td>
<td>79</td>
<td>74</td>
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<tr>
<td>Roof</td>
<td>Clay</td>
<td>48</td>
<td>79</td>
<td>74</td>
</tr>
<tr>
<td>Roof</td>
<td>Concrete</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>Roof</td>
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<td>0</td>
</tr>
<tr>
<td>Roof</td>
<td>Zinc</td>
<td>6</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>Roof</td>
<td>Zinc</td>
<td>6</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>Roof</td>
<td>Asbestos</td>
<td>46</td>
<td>20</td>
<td>3</td>
</tr>
</tbody>
</table>
| Source: Building material inventory surveys in Jakarta (2012) and Bandung (2011)
Where, $TW$: total demolition waste from unplanned residential buildings until 2020 (kg), $W_{i,\text{simple}}$: demolition waste of material $i$ from a simple house (kg) (equal with material stock of simple houses), $s_{\text{simple}}$: demolition ratio of simple houses by 2020, $S_{i,\text{simple}}$: stock of material $i$, included in a simple house (kg), $\rho$: income distribution of low income group in 2020 (0.23), $WA_{i,\text{simple}}$: demolition waste $i$ per unit gross floor area in a simple house (kg/m$^2$), $F_{\text{simple}}$: average gross floor area of a simple house (m$^2$).

The mathematical equations used to estimate the urban expansion caused by the demolition of unplanned simple houses and the transformation from these simple houses to larger medium houses by 2020 are described as follows. In this analysis, it is assumed that all the demolished simple houses will be reconstructed to be medium houses in the same cities.

$$W_{i,\text{simple}}/F_{\text{simple}}$$

Flow of materials and their embodied energy/CO$_2$ emissions for each type of houses

Secondly, this paper analyzes the per-floor area flow of building materials and their embodied energy/CO$_2$ emissions for each of the house categories by taking Jakarta for example. Embodied energy/CO$_2$ emissions of building materials generally includes energy for productions in several phases, including material extraction, production, construction, maintenance, and demolition phases. However, construction and demolition phases were not considered in this paper due to the data unavailability.

The design records such as building drawings are required for the analysis of embodied energy of building materials. These data were available for most of the planned houses and unplanned luxurious houses only. The other houses including most of the unplanned simple and medium houses were not constructed in the formal way (normally constructed by non-professional neighbors) and therefore the required design records could not be obtained. Thus, the actual on-site measurements by using laser-distance meters and tape measures were conducted for unplanned simple and medium houses in order to acquire the data.

Since it was impossible to trace all the production processes for most of the building materials due to the data unavailability, this study adopted the I-O analysis-based method to calculate the embodied energy of materials and estimate their CO$_2$ emissions, which consistently followed the method described by Nansai et al. (2002). The latest Indonesian nationwide I-O table published in 2005 (Indonesia, 2005) consisting of 175 x 175 sectors was used for calculating the embodied energy/CO$_2$ emissions, which was measured in the form of primary energy. The detailed procedures of the embodied energy/CO$_2$ emissions were described in the previous paper (Surahman & Kubota, 2012).

In this analysis, we assess the effects of policy of promoting reused and recycled material use through a scenario analysis. The first scenario (Scenario 1) assumes that both recycling and reuse rates are set to be zero (minimum) and the second scenario (Scenario 2) is designed under the assumption that both reuse and recycling rates for respective building materials are increased to the maximum values (see Table 2). The effects of the promotion of reused and recycled building materials use are evaluated through the comparison between two scenarios. The per-house material stock and demolition waste for respective house categories are estimated based on the following equations.

$$\frac{W_{i,\text{simple}}}{F_{\text{simple}}},$$

$$\frac{W_{i,\text{medium}}}{F_{\text{medium}}},$$
RESULTS AND DISCUSSION

Current building material stock

This section discusses the current total material stock and future demolition waste in urban houses at the city level in Jakarta and Bandung. The current building material stocks in urban houses in two cities in 2012 were calculated utilizing Equations (1)-(4). Table 3 shows the composition of the current building material input, including those for maintenance, in the two cities. As shown, overall, the average material quantity per m$^2$ is 2.14 ton/m$^2$ in Jakarta and 2.06 ton/m$^2$ in Bandung. The average material quantity slightly varies among the different house categories in Jakarta and Bandung: 2.26 and 1.88; 2.06 and 2.23, and 2.05 and 2.26 ton/m$^2$ for simple, medium and luxurious houses, respectively. Overall, stone accounts for the largest percentage in Jakarta and Bandung (32% and 31%), followed by sand (31% and 30%), clay brick (19% and 19%), cement (8% and 8%), etc. The current total material stock in urban houses of Jakarta is measured at 232.0 million ton, while that of Bandung was 77.2 million ton. The difference between the two cities is mainly due to the number of houses difference.

Future demolition waste from unplanned residential buildings until 2020

If both reuse and recycling ratios are assumed to be zero, then the total demolition waste of unplanned houses (i.e. only simple houses) in Jakarta is found to be 41.5 million ton/m$^2$ until 2020 and all of them go to the landfills (Equations (5)-(7)). Meanwhile, the corresponding amount of waste in Bandung is predicted to be lower (12.6 million ton/m$^2$) due to less households of simple houses. This scenario will cause the waste to landfills would be very huge, thus results in the overload in the landfills. As a consequence, this scenario anticipates that both Jakarta and Bandung would be forced to construct new landfills to deal with the increased waste in the near future.

Urban sprawl caused by the transformation from simple houses into medium houses

The future demolition of unplanned houses and the transformation of these houses to the larger medium houses by 2020 would cause the further urban expansions in both of the cities: at least, the additional area of 20.0 km$^2$ is required for the new constructions in Jakarta while the area of 5.7 km$^2$ is required in Bandung (Equation (8)). These expansions would accelerate urban sprawls.

Scenario analysis: Policy effects of promoting reused/recycled materials use on reduction of building waste and embodied energy/CO$_2$ emissions
Scenario 1; zero reuse and recycling rates. The following section analyze the flow of building materials per-house for each of the house categories by taking Jakarta for example. As described before, we assess the effects of policy of promoting reused and recycled material use through scenario analysis. In this scenario (Scenario 1), the zero reuse/recycling rates are applied to all building materials used for a house. Figure 2 shows the results of flow analysis for average material input and output of urban houses in Jakarta utilizing zero reuse/recycling rates for whole sample as example. As shown, the total average material inputs including those for maintenance for whole sample (‘B’ in the Figure 2) are derived from Table 3. A few materials are imported such as ceramics (37.5 kg/m²) in the case of luxurious houses. There is no materials reused/recycled for other buildings/products (‘E’ and ‘F’) in this scenario. Thus, all materials go to the landfills (‘G’). Equations (9)-(10) were used to calculate demolition waste for each of the house categories. The total average waste to landfills is larger than the average material input due to additional waste of soil derived from the surplus soil extracted in the construction phase (‘C’), accounting for 2,931.1, 3,921.3, 3,771.5 and 2,665.1 kg/m² for simple, medium and luxurious houses as well as whole sample. Overall, mortar accounts for the largest waste (23%), followed by soil (20%), stone foundation (17%), concrete (16%), clay brick (15%), etc.

Scenario 2; maximum reuse and recycling rates. In this scenario (Scenario 2), we apply the maximum potential for reuse/recycling rates (see Table 2). Figure 3 shows the results of flow analysis of building material input and output for urban houses in Jakarta in Scenario 2 for whole sample. As shown, the total average material input including those for maintenance for respective houses in Jakarta are still the same as those in the Scenario 1 (‘B’ in the Figure 3). However, some materials (589.9 kg/m²) were reused for other buildings (‘E’), including stone (77%), wood (11%), clay brick (7%), etc. Meanwhile, several materials (464.0 kg/m²) are recycled (‘F’), including clay bricks (79%), wood (13%), steel (6%), gypsum (1.5%) and zinc roof (0.5%). There is no material composted/burned (‘I’). The rest of materials (soil, mortar, concrete, ceramic and asbestos) are assumed to be reclaimed to other products or infrastructure (‘H’). The total waste used for reclamation accounts for 1,715.3, 1,596.3, 1,412.0 and 1,611.1 kg/m² for simple, medium and luxurious houses as well as whole sample. Overall, mortar accounts for the largest percentage (39%) followed by soil (32%), concrete (27%), and ceramic tile and asbestos (2%). These materials can not be reused/recycled for other building constructions due to difficulty of separation from mixed materials. Thus, it was found that closed-loop material flow is not enough to fully reclaim building materials and eliminate building material waste to the landfills. Nevertheless, these materials can be reused/recycled by crushing them and used to reclaim for infrastructure such as road and building site. In this case, the total waste to the landfills would become zero.

Figure 4 shows the average material waste of respective houses for both scenarios. As shown maximizing reuse/recycling rates would decrease the average material waste dramatically by 41%, 37% and 40% for simple, medium and luxurious houses, respectively.
Embodied energy and CO₂ emissions

Primary building material inputs were obtained by utilizing Equation (11) for analyzing their embodied energy/CO₂ emissions. The total embodied energy and CO₂ emissions were estimated by combining initial, maintenance and recycling embodied energy/CO₂ emissions for respective houses through previously explained I-O analysis-based method. The potential energy saving through recycling was assumed about 50% of embodied energy/CO₂ emissions (Thornmark, 2002).

Figures 5-6 show the total embodied energy/CO₂ emissions in the two scenarios (i.e. zero and maximum reuse/recycling rates). The results indicate that the reused/recycled materials reduce not only material waste but also diminish embodied energy/CO₂ emissions. The maximum reuse/recycling rates are expected to decrease embodied energy by 16.8 (27%), 58.1 (28%), 151.1 (27%) and 58.6 (27%) GJ for simple, medium, luxurious and whole houses, respectively (Figure 5). Meanwhile, the reduction patterns of embodied CO₂ emissions are similar with those of embodied energy (Figure 6).

The results of the above scenario analysis prove that the promotion of reuse/recycling are important to ensure the building material stocks and to reduce not only material waste but also their embodied energy/CO₂ emissions.

CONCLUSIONS

This study analyzed flow of building materials and their embodied energy/CO₂ emissions for urban houses in Indonesia, focusing especially on unplanned houses. The actual on-site building measurements were conducted in Jakarta (n=297) and Bandung (n=247) to investigate building material inventory.

- Overall, the average material quantity per m² was 2.14 ton/m² in Jakarta and 2.06 ton/m² in Bandung.
The average material quantity slightly varied among the different house categories in Jakarta/Bandung: 2.26/1.88, 2.06/2.23 and 2.05/2.26 ton/m² for simple, medium and luxurious houses, respectively. On average, the stone accounted for the largest percentage for all houses (32%/31%), followed by sand (31%/30%), clay brick (19%/19%), cement (8%/8%), etc.

• If both reuse and recycling rates are assumed to be zero, then the total demolition waste of unplanned simple houses in Jakarta was found to be 41.5 million ton/m² until 2020 and the corresponding waste in Bandung is predicted to be lower (12.6 million ton/m²). All of them go to the landfills. Moreover, the transformation of these simple houses to the larger medium houses by 2020 would cause further urban expansion in both of the cities: at least, the additional area of 20.0 km² is required for the new construction in Jakarta, while the area of 5.7 km² is required in Bandung.

• A scenario analysis was conducted for Jakarta to assess the effects of policy of promoting reused and recycled material use. The two scenarios with the zero and maximum reuse/recycling rates were compared in the analysis. The results showed that maximizing reuse/recycling rates would decrease the average material waste dramatically by 37% to 41%. The promotion of reuse/recycling were proved to reduce embodied energy/CO₂ emissions of building materials effectively (27% to 28%).

• The lack of policies for promoting 3Rs (reduce, reuse and recycling) specifically target C&D waste (Indonesia, 2008) at the national level is considered one of the crucial problems in Indonesia.

• The increase in larger landed houses would directly result in the rapid horizontal expansions of the cities, thus accelerates urban sprawls. Provision of mid-to-high-rise apartments to the growing middle class in the cities would be one of the effective housing policies for already crowded Indonesian cities.

ACKNOWLEDGMENTS

This research was supported by a JSPS Grant-in-Aid for Young Scientist (B) (No. 23760551). We also would like to thank Mr. Yohei Ito, Mr. Ari Wijaya, M.SI of Universitas Persada Indonesia, Dr. Hanson E. Kusuma of Institut Teknologi Bandung and the students who kindly supported our survey.

REFERENCES


Urban Climate mapping of an Institutional Campus in Hot-Humid Climate using GIS

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ABSTRACT

Urbanization modifies the built form to a greater extent and exerts extreme heat stress due to the urban heat island (UHI) effect in hot and humid climates. Sathyabama University - an institutional campus in Chennai experiences a UHI intensity of 6°C to 10°C during the day. The students in the campus often use the outdoor spaces for their interactions and discussions. This paper aims to map the urban climate in an institutional campus and analyze the outdoor comfort conditions. The urban climate mapping is done through field measurements and comfort conditions are analyzed through a questionnaire survey. The field measurements include the recording of hourly air temperature and humidity data using HOBO U20 datalogger on a hot summer day. Isopleths are derived using ArcGIS and the heat and cool pockets in the campus are identified. The questionnaire survey records the thermal sensation of the students and is compared with the isopleths to arrive at a climate sensitive design. The survey results can aid in improving the outdoor comfort through increase in vegetation cover in the campus.

INTRODUCTION

Urbanization modifies the built form to a greater extent and exerts extreme heat stress due to the urban heat island (UHI) effect in hot and humid climates. Also the urban land uses and the related activities increase the urban air temperatures. The increased temperatures in urban areas results in the formation of heat pockets and are termed the “Urban Heat Island” (UHI) (Landsberg 1981). This thermal difference between urban and rural areas determines the intensity of heat island. The rate of cooling of open spaces when compared to that of the dense built up spaces, contributes significantly to the intensity of UHI (Givoni 1998).

Studies on climate change due to urbanization have gained momentum, and have become the main focus of research in the recent past. Urban climates are distinguished from those of less built-up areas by differences in air temperature, humidity, wind speed and amount of precipitation. These differences are mainly due to the alteration of natural surfaces with highly reflective parking lots, concrete masses, asphalt roads etc., resulting in higher absorption of solar radiation, thereby affecting the thermal environment. Oke (1981) states that the rate of cooling of urban areas at the micro level depends on two parameters; the street geometry and the sky view factor. Todhunter (1990) explains that at the canyon layer, urban geometry plays an important role in defining the spatial and temporal distribution of the UHI compared to surface materials. Saito et al (1990) found that even small green areas can reduce the temperatures by 3°C, when compared to the built up surfaces in the city of Kumamoto. Akbari et al (1992) identified that large number of trees and urban parks can reduce local air temperatures by 0.5°C to 5.1°C. Unger et al (1999, 2001) found that there exists a strong relationship between urban thermal excess and land use features and built up density in Szeged, Hungary. Johansson and Emmanuel (2006) analyzed the influence of street canyon geometry on the outdoor thermal comfort in Colombo and identified that the differences in air temperatures were higher during the day, especially in the afternoons.
when compared to the night and a maximum difference of 7°C was found between sites. Amirtham et al (2009) investigated the land cover changes due to urbanization in the city of Chennai from 1991 to 2000 and found a significant increase in hot spots in the city mainly attributed to the increase in the urban built up. Rose (2010) found the existence of UHI in Chennai city through the study of historic climate records from meteorological stations and also found a statistically significant increasing trend in the discomfort due to urbanization.

Thermal comfort indices combine two or more parameters into a single factor. Spagolo and de Dear (2003) found the outdoor thermal comfort index OUT SET* in the subtropical Sydney as 26.2°C and that of the indoor SET* as 24°C. Taib (2010) in the assessment of thermal comfort parameters in landscape gardens in high rise buildings identified significant variation in air temperature, humidity, wind speed and radiation; but the survey on users perception revealed differences only in lighting level and wind speed. Also the behavioural adaptations of users in urban open spaces in Taiwan revealed that the attendance in urban parks was influenced by sun and thermal conditions (Lin et al 2013). Yang et al (2013) found that the neutral operative temperature and preferred temperature as 28.7°C and 26.5°C in Singapore. And the study also found that people in outdoors generally have a higher tolerance level to comfort conditions when compared to indoors especially in the tropics. The study also suggested that the combination of lower density spaces with higher building heights would reduce the sky view factor value and the incoming solar radiation thus improving the outdoor thermal comfort.

Chennai, a tropical city characterized by high temperatures and humidities, suffers extensively due to the urban heat island effect which affects the outdoor thermal comfort conditions significantly. Therefore, this study aims at the enhancement of outdoor thermal comfort conditions, through urban climate mapping in an institutional campus in Chennai.

**AREA OF STUDY**

Sathyabama University is an institutional campus in the suburbs of Chennai experiencing hot humid climate (Figure 1a). The maximum air temperatures during summer (May and June) varies between 38°C and 42°C and the minimum air temperatures during winter (December and January) varies between 18°C and 20°C. The average monthly relative humidity ranges from 63% (June) to 80% (November) and the vapour pressure varies between 22.6hpa and 32hpa. The institution houses several academic blocks of varying street geometry. Five different locations in the campus were selected considering various parameters such as the percentage of vegetation, orientation of streets and canyon geometry (H/W ratio). The thermal properties of the built surfaces were similar in all locations. Figure 1b shows the measurement locations in the campus.

**Figure 1** a) Sathyabama University Campus, Chennai b) Measurement locations in the academic zone

**Figure 2** Images of Measurement locations (1-5)
The data loggers placed at five strategic locations within the academic zone were based on the percentage of vegetation, orientation of streets and canyon geometry as shown in figure 2. Logger 1, 3 & 5 is placed in the N-S orientated streets with canyon geometry of 1, 2 and 1.67 respectively. Logger 2 & 4 has been positioned in the E-W streets with canyon geometry of 0.5 each.

METHODOLOGY

The air temperature and relative humidity data were measured continuously on an hourly basis using HOBO dataloggers (HOBO U20 Temp/RH) in the selected locations. The wind speed and the cloud cover data from the Nungambakkam Meteorological station were used for the study. The urban climate mapping of the campus was derived using ArcGIS. Temperature isopleths on a typical summer day are derived for 02:00 hrs, 06:00hrs, 10:00hrs, 14:00hrs, 18:00hrs & 22:00hrs. The analysis of the daytime and night time isopleths reveals the temperature distribution pattern in the campus. Also, a questionnaire survey on thermal sensation in the selected locations was conducted to study the subjective response of students to the outdoor thermal environment during daytime. The sample questionnaire used for survey is shown in appendix 1. The subjective response of the respondents and the temperature isopleths during daytime were compared to identify the appropriate built geometry for a thermally comfortable environment.

RESULTS AND DISCUSSION

Analysis of the Daytime and Night time Isopleths

The campus has various functional spaces and the present study is confined to the academic zone where most of the student interaction takes place, thus highlighting the need of a thermally comfortable outdoor environment. Table 1 shows the ambient air temperature on a typical summer day and Table 2 shows the recorded relative humidity.

### Table 1. Daily Air Temperatures at Various Locations

<table>
<thead>
<tr>
<th>Location / Logger</th>
<th>Longitude x</th>
<th>Latitude y</th>
<th>Temperatures in °C at 4 hrs interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>02:00 AM</td>
</tr>
<tr>
<td>1</td>
<td>80.22159</td>
<td>12.8744</td>
<td>30.04</td>
</tr>
<tr>
<td>2</td>
<td>80.221</td>
<td>12.87434</td>
<td>30.22</td>
</tr>
<tr>
<td>3</td>
<td>80.22076</td>
<td>12.874</td>
<td>30.10</td>
</tr>
<tr>
<td>4</td>
<td>80.2205</td>
<td>12.87363</td>
<td>29.87</td>
</tr>
<tr>
<td>5</td>
<td>80.21962</td>
<td>12.87409</td>
<td>30.12</td>
</tr>
</tbody>
</table>

### Table 2. Daily Relative Humidity at Various Locations

<table>
<thead>
<tr>
<th>Location / Logger</th>
<th>Longitude x</th>
<th>Latitude y</th>
<th>Relative Humidity in % at 4 hrs interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>02:00 AM</td>
</tr>
<tr>
<td>1</td>
<td>80.22159</td>
<td>12.8744</td>
<td>73.43</td>
</tr>
<tr>
<td>2</td>
<td>80.221</td>
<td>12.87434</td>
<td>72.95</td>
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<td>80.22076</td>
<td>12.874</td>
<td>74.51</td>
</tr>
<tr>
<td>4</td>
<td>80.2205</td>
<td>12.87363</td>
<td>75.53</td>
</tr>
<tr>
<td>5</td>
<td>80.21962</td>
<td>12.87409</td>
<td>72.99</td>
</tr>
</tbody>
</table>

Air temperatures and relative humidity recorded on a typical summer day has been mapped at 02:00 hrs, 06:00hrs, 10:00hrs, 14:00hrs, 18:00hrs & 22:00hrs with a four hour interval. The isopleths derived using ArcGIS is shown in Figure 3 which revealed a distinct temperature difference between the streets with greenery and non green spaces. The canyon geometry and the street orientation also had a significant impact on the temperatures.
At 6:00 am locations 1 & 4 experienced the lowest temperature and location 5 recorded the maximum temperature with a difference of 2.03°C. Location 5 situated in the N-S oriented street has a higher canyon geometry of 1.67, attributed to the increase in temperature. The narrow street geometry reduces the reradiation of longwave radiation back to the sky and also because of the differential heating of the surfaces. Determining the mean radiant temperature (MRT) by measuring the long wave and short wave radiation (VDI 1994, Ali-Toudert 2005) from different directions would be more effective in calculating the outdoor comfort conditions more precisely but has not been done in this study. At 10:00hrs Location 5 experienced the lowest temperature and maximum temperature was recorded at location 2 with the temperature difference of 2.8°C. The presence of vegetation at location 5 shaded the streets and also reduced the incoming solar radiation. At 2:00 PM, when the maximum temperatures are recorded, location 5 experienced the lowest temperature when compared to the other locations with a maximum heat island intensity of 4.40°C. At 6:00 PM during sunset location 2 experienced the maximum temperature of 31.8°C. The temperature isopleths at 6:00 PM shows clearly the existence of UHI around
location 2 where the E-W orientated streets, the street geometry and non greenery play a vital role. The concrete roads, the wider streets with the reflected radiation from the abutting buildings increased the air temperatures at location 2. The cool spots throughout the day is identified at location 5 followed by location 4 which is attributed to the presence of greenery. Thus the study reinforces the fact that existence of vegetation and trees reduces the ambient air temperatures significantly. During night time, the temperature remains almost the same in all locations at 10:00 PM and 2:00 AM. Thus improvement of daytime outdoor comfort is essential in hot humid climates like Chennai.

During daytime, the relative humidity varies from 61.65% to 84.63% and the maximum humidity is recorded at location 5, due to the presence of vegetation and the minimum humidity recorded at location 2. At night, maximum humidity is recorded at location 4 and minimum at location 5. During night, the ambient air temperature at location 5 is high as the trees reduce the sky view factor thereby restricting the reradiation to the sky. The elevated air temperatures at location 5 reduce the humidity during night as shown in Figure 4.

Figure 4 Relative humidity Isopleths of in the academic zone of the institutional campus at 4 hrs interval.
Analysis of Questionnaire Survey

The results of questionnaire survey in the selected locations are compared with the isopleths to comprehend the thermal sensation of the users in the academic zone. Figure 5 show the thermal perception of human with respect to the thermal sensation, feeling of comfort, satisfactory level of comfort in the place and the overall conditions of acceptance. The result on thermal sensation revealed that the respondents felt the heat and were almost tolerable at location 5 due to vegetation shading and none of the other locations were comfortable. At locations 1 & 2, the thermal perception the respondents were too warm due to the absence of shading and the reflective nature of the abutting buildings.

The users were not satisfied with the ambient air temperature in the campus. The dissatisfaction is more at locations 1 & 2 and satisfaction rates are high at locations 3 & 5 due to the presence of greenery. The overall conditions inside the campus are acceptable for the users near the locations 3 & 5 due to the N-S orientation and the presence of vegetation at location 5, thus providing a comfortable environment.

Figure 5 Bar charts showing the survey results of the respondents in the campus at various logger locations.

CONCLUSION

The study revealed that heat pocket exists in the campus at location 2 in the academic zone both during day and night. Temperature difference as high as 4.4°C exists during the peak time of 2:00 PM. The radiation of heat from the buildings and pavement and the street orientation increases the ambient air temperature at location 2. Also, the absence of vegetation at location 2 accelerates the air temperature thus attributing to the heat stress. The isopelths highlights the importance of the greenery in the built form which helps in the reduction of ambient temperatures. At locations 4 and 5, the existing greenery keeps the place comfortable when compared to other locations and the respondents expressed the feel of comfort. The subjective response of students on the comfort levels of outdoor thermal environment during daytime also revealed the heat stress at location 2. Increasing the shading through vegetation in the campus and the internal shading of buildings as in location 3 with a height to width ratio of 2 can provide better daytime comfort.
NOMENCLATURE

- UHI = Urban Heat Island
- H/W = Height to width ratio
- Street Canyon = Street Geometry
- OUT SET* = Outdoor Standard Effective Temperature in degree Celsius
- SET* = Standard Effective Temperature in degree Celsius
- MRT = Mean Radiant Temperature

REFERENCES


APPENDIX 1

**STUDY ON THERMAL COMFORT IN AN INSTITUTIONAL BUILDING**

I like your participation in answering this questionnaire based on your thermal comfort, the inputs from this survey helps us to analyze occupants comfort level in this institutional building.

<table>
<thead>
<tr>
<th>Age:</th>
<th>Sex:</th>
<th>Time:</th>
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<tbody>
<tr>
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</table>

Please Tick ( ) the suitable bubble against the various scales:

1. Orientation of the Location:

<table>
<thead>
<tr>
<th>North</th>
<th>South</th>
<th>East</th>
<th>West</th>
</tr>
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</table>

2. Vegetation Index of the Location:

<table>
<thead>
<tr>
<th>No vegetation</th>
<th>Sparse Vegetation</th>
<th>Existence of Shrubs</th>
<th>Existence of Trees</th>
</tr>
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<tbody>
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</table>

3. Thermal Sensation:

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<tr>
<th>Cold</th>
<th>Cool</th>
<th>Slightly cool</th>
<th>Neutral</th>
<th>Slightly warm</th>
<th>Warm</th>
<th>Hot</th>
</tr>
</thead>
<tbody>
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</table>

4. Feeling of Comfort:

<table>
<thead>
<tr>
<th>Too cool</th>
<th>Comfortably cool</th>
<th>Comfortable</th>
<th>Comfortably warm</th>
<th>Too warm</th>
</tr>
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<tbody>
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5. Satisfactory level of temperature in the place:

<table>
<thead>
<tr>
<th>Very satisfied</th>
<th>Satisfied</th>
<th>Dissatisfied</th>
<th>Very dissatisfied</th>
</tr>
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<tbody>
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6. Level of Air movement should be:

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<tr>
<th>Lesser</th>
<th>As it is</th>
<th>More</th>
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7. Level of Humidity should be:

<table>
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<tr>
<th>Lesser</th>
<th>As it is</th>
<th>More</th>
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8. How would you like to be:

<table>
<thead>
<tr>
<th>Cooler</th>
<th>As it is</th>
<th>Warmer</th>
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9. Are the overall conditions acceptable:

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
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Passive Cooling Techniques in an Outdoor Space and its Effects on the Indoor Climate

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ABSTRACT

Passive cooling techniques such as evapotranspiration from plants and watering are effective for ameliorating outdoor microclimates in hot summer. Natural ventilation also helps to make an indoor thermal environment more comfortable. However, in Japan’s humid and hot summer climate, there is a limited opportunity to gain a cooling effect by ventilation. Therefore, this study focuses on passive cooling techniques to improve the outdoor microclimate near the window of a residential building to achieve a cooling effect by ventilation despite the hot climate and to reduce the demand for cooling energy. Measurements were conducted two cases during one summer on a target building located in a residential area with a window which located at the floor level to help natural ventilation. The first case had no additional plants in front of the window, and the second case did. The results show that when the ground and in front of the window were kept wet by watering and shaded, the radiant temperature, measured by a thermal infrared camera, was about 1−7 °C lower than the outside air temperature at the 3p.m. Consequently, the air temperature near the window was 2−4 °C lower than the outside air temperature. However, due to watering and evapotranspirating of plants, absolute humidity increased 2 g/kg’ in the after adding plants case in front of the window. Although the indoor wind velocity came to a tenth of the roof wind speed, because of adding plants, inflow rate through the window was not changed. Therefore, the cooling potential was created at the outdoor space by applying the passive cooling techniques. When this cooling potential was used by ventilation, the sensible heat flux decreased 200–300 W through the daytime, and latent heat flux increased 100–300 W at the nighttime.

INTRODUCTION

Natural ventilation is known to be one of the most effective passive methods for creating a comfortable indoor climate and to conserve energy consumption. The outdoor microclimate, including air temperature, humidity, wind velocity, wind direction and solar radiation, has a direct impact on the effectiveness of ventilation for cooling. Fig. 1(b) shows the average, maximum, and minimum monthly temperatures from April to October in Tokyo from 2000 to 2013(Obeserved by Japan Meteorological Agency). Maximum temperatures in midsummer (July and August) are higer than 30 °C. Therefore, Tokyo’s air temperatures in July and August are too high to utilize outside air for natural ventilation. Many studies show that maximum suitable outdoor air temperature for natural ventilation is between 28 and 30 °C (Givoni, 1992; Habara et al., 2012). Therefore, not only the indoor thermal environment but also the outdoor microclimate around the house must be improved in order to utilize natural ventilation in the midsummer season.

Many passive cooling techniques and designs have been developed and studied. Solar shading (Nikoofard et al., 2011; Berry et al., 2013) by structures and trees reduces the amount of solar radiation...
in the summer season, and contributes to a decrease in a building’s surface temperature and energy demands. The transpiration of trees can prevent increases in the air temperature around trees (Umeda et al., 2006). Atmospheric radiation cooling is a phenomenon by which heat is lost by the emission of longwave radiation toward the sky at nighttime. Nocturnal ventilation cooling (Givoni, 1991) with cold storage lowers the daytime temperature and makes possible to reduce the length of the periods requiring the operation of additional cooling systems. Each of these examples is individual approaches to improve and evaluate indoor, and outdoor microclimates. However, there has been little research about evaluating the change of the indoor thermal environment utilizing multiple passive cooling systems.

This study aims to introduce the passive cooling systems at an outdoor space and to evaluate its effect on the indoor thermal climate utilizing the natural ventilation by measurement. We measured the cooling effects of plants and water retentive blocks as well as the negative influences of increased humidity and air flow decrement by analyzing the microclimatic parameters around the actual house quantitatively. Then, we focused on changing the indoor thermal climate by introducing cooled air through an open window which helps the natural ventilation located at the floor level.

Figure 1 Outlines of measurement
MEASUREMENT DETAILS FOR HORIZONTAL AND VERTICAL AIR TEMPERATURE DISTRIBUTION

In order to adequately investigate the space where cooled air is created and where the air flows into building, the spatial distribution of the microclimatic parameters must be measured minutely. In this section, we propose a method for measuring the air temperature using polyvinyl chloride (PVC) piping with fan-aspirated ventilation. We then, describe the measurement method and the improvements made to the microclimate with plants and watering.

Measurement Method

When the measurement of air temperature and humidity is conducted at the outdoor space, solar and other radiation factors in the immediate surroundings must be removed. To do so, an aspirated radiation shield is often used. However, as the aspirated radiation shield is large, it is not suitable for measuring vertical and multipoint temperature distributions. We used PVC pipes (Φ13 mm) and ventilation fans (air volume: 75 m³/h, static pressure in the pipe: 100 Pa) to measure outdoor air temperature and humidity accurately. Each of the measurement points was connected by piping. The measurement sensors were a thermo-couple (Φ0.1 mm type T thermo-couple) and a resistance change type humidity sensor (TDK, CHS-UPS), which were inserted into a pipe. When taking measurements using the PVC pipe, to prevent overestimation due to radiation from the surroundings, the pipe diameter was controlled to maintain sufficient wind speed (3 to 5m/s) at each measurement point. Ventilation fans were then connected to PVC pipes. In addition, the PVC pipes at the measurement point were screened two times with an aluminum sheet (Fig.1(c)).

The measurement results using this proposed PVC pipe method were compared with forced ventilation thermometer with aspirated radiation shield to verify accuracy. The measurement comparisons were made at intervals of 10 s for two days (September 21 and 22, 2013). Fig. 1(d) shows the differences in air temperatures between the PVC pipe method and the forced ventilation thermometer. Air temperature is almost identical at night when there is no solar radiation and a temperature error maximum of +0.9 °C exists at daytime when insolation is elevated. The results show an accuracy of +0.6 °C with a 95% confidence interval.

Measurement Conditions

| Table 1. Details of the measurements of the effect of plants and water retentive blocks |
|-----------------------------------------------|-----------------------------------------------|
| Condition | July 15(Case 1) | August 29(Case 2) |
| Trees (height 0.8 – 3 m) were 0.7 m away from the window. | Additional planting, water retentive blocks were added. |
| Watering | Automatic watering at 7a.m, 11a.m, 3p.m, and 7p.m by mist sprayer for 5 min. | Continuous watering from 7 a.m. to 7 p.m. by hosepipe. |
| Photographs | ![Photograph of measurement setup](image1.jpg) | ![Photograph of measurement setup](image2.jpg) |

Measurements of the microclimate around the building were made on July 15 and August 29, 2013. The measurement conditions are detailed in Table 1. In the July measurement, there were trees 0.7 m away from the window. There was nothing except the PVC pipe for measurement in front of the window. In the August measurement, we added additional plants and water retentive blocks as passive cooling materials in front of the window. Moreover, the watering method and times were changed to wet more
surfaces of the leaf and block. In addition, vertical measurement points were added in front of the window to measure in detail the cooling effect of the additional plants. The indoor air temperature was measured near the window (A5 in Fig. 1(a)) and in the living room (A6, A7 in Fig. 1(a)).

**EFFECTIVENESS OF EVAPORATIVE COOLING IN CASE OF UTILIZING PLANTS AND WATER RETENTIVE BLOCKS NEAR THE OPEN WINDOW**

In order to analyze the cooling effect around the house, we used the abovementioned method to measure the effects of the passive cooling system applied outside the house. This section focuses on the following factors: improvement in surface temperature, decrease in air temperature, increase in humidity, and wind velocity decrement.

**The Improvement in Surface Temperature**

Thermal infrared images of the area in front of the window were obtained using spherical thermography (Asano, 1996). Fig. 2(a) shows an image obtained at 3p.m on August 29. The surface temperature of the wall was over 40 °C due to the afternoon insolation. However, the surface temperature of leaves and blocks in front of the window (shown in the inside of white rectangle on this thermal image) was 1 °C to 7 °C lower than the air temperature. Therefore, we have confirmed the cooling potential created by additional plants, watering, and shade near the window. In particular, the surface temperature of the water retentive blocks under the window is about 8 °C lower than the air temperature. However, we must also address how to introduce this cooled air into the indoor area.

**The Decrease in Air Temperature**

Fig. 2(b) shows the vertical air temperature distribution in front of the window (A4, Fig. 1(a)). While the vertical distribution was almost similar as that before the additional planting (Case 1), a temperature discrepancy of 2 to 4 °C occurred after the additional planting (Case 2) during the daytime.

An A – A' cross-section (Fig. 1(a)) of the air temperature distribution can be seen in Fig. 2(c). At noon, the air temperature near the window (A4) was 1.5°C to 2 °C lower than the air temperature outside the target area (A1). At 3p.m, the air temperature near the window (A4) showed a decrease of about 2 °C in comparison with the A1 air temperature in the case 2 measurement, while the air temperature near the window (A4) was 1 °C higher than the A1 air temperature in the case 1 measurement. This difference occurred because the afternoon solar radiation was blocked and evapotranspiring was more conducted by the additional plants, so the A4 air temperature was lower on August 29. In addition, the indoor and outdoor air temperature difference was just 1 °C at night-time. It is clear that the decrease in the nighttime indoor air temperature was due to ventilation.

**The Increase in Humidity**

Fig. 2(d) shows the absolute humidity at each of the measurement points (A1, A4, A5, and A6 of Fig. 1(a)). Before the additional planting (left side of Fig. 2(d)), humidity decreased as the daytime air temperature increase. However, with the additional plants and watering, the humidity of the indoor space (A6) on August 29 had increased to 14 g/kg, while the outdoor (A1) humidity was about 10 g/kg. Thus, even when the initial indoor humidity was higher than the outdoor humidity, the humidity of the indoor space in the case 2 was shown to be 2 g/kg higher than the outdoor measurement.

**The Wind Velocity Decrement**

To analyze the wind flow frequency, we conducted a test on September 13(A5) using a 3D supersonic anemometer. The wind direction on the date of the main measurement and that on September 13 are shown in the left side of Fig. 2(e). The July 15 wind direction (before the additional planting) was a little different than the September measurement. However, wind direction data for the August 29 and September 13 cases, both occurring after the additional planting, are almost identical. Graph, right side
of Fig. 2(e), shows the inflow and outflow frequency at the window. In day-time, the inflow rate was recorded to be 40% on average after additional plants.

Fig. 2(f) shows the decrement of wind speed after the additional planting, both in the velocity at the roof and near the window. However, the difference of the inside velocity in the before and after the additional planting cases near the window was approximately 0.2 m/s. Although wind speed decreased, the results show that cooled air flowed to the inside area through the window. Thus, the cooled air created in front of the window did effectively replace the indoor air.

Figure 2  Spatial distributions of the microclimates
Evaluation of the Passive Cooling Effect by Heat Flux

In order to evaluate the effect of the passive cooling techniques at the outdoor space to the indoor space, we calculated the sensible and latent heat fluxes using the following equations. A comparison of these fluxes is shown in Fig. 3.

\[
q_{\text{sensible heat flux}}[W] = C_p \cdot \rho \cdot V \cdot (T_{\text{out}} - T_{\text{in}}) \cdot 1000
\]

\[
q_{\text{latent heat flux}}[W] = \gamma_f \cdot \rho \cdot V \cdot (x_{\text{out}} - x_{\text{in}}) \cdot 1000
\]

The August 29 sensible heat flux decreased maximum 200–300 W compared with that on July 15 in the daytime. Furthermore, the length of time when the sensible heat flux was above zero diminished from 9 to 4 h. In the midnight, 100 W or more of sensible heat was removed from the indoors to the outdoors through the window on August 29. Conversely, the August 29 latent heat flux at nighttime was higher by 100–300 W than that of July 15. However, although latent heat flux of August 29 was high, the indoor humidity was lower than that on July 15. It means humidity increases due to the plants and water retentive blocks, however, its effect on the thermal comfort of indoor is small because the absolute humidity is influenced by the weather conditions.

CONCLUSION

By locating plants and water retentive blocks in front of a window, we created a cooling potential at the outdoor space. We then quantitatively evaluated the influence of the cooling potential by evaporative cooling using the plants and water retentive blocks on the thermal environment of the indoor space by ventilation through the window.
1) To measure in detail the microclimate around the building, air temperature measurements were taken using a PVC piping method. The accuracy of this method verified to be +0.6 °C with a 95% confidence interval.

2) A decrease in the air temperature was observed 2 to 4 °C by passive cooling due to solar shading and evaporative cooling.

3) Although the wall surface temperature was over 40 °C at 3p.m due to the afternoon sun, the surface temperature of leaves and blocks with watering and shading in front of the window was 1 °C to 7 °C lower than the surrounding air temperature.

4) Due to the presence of additional plants near the window, the inside wind speed came to a tenth of the roof wind speed.

5) The length of time when the sensible heat flux was above zero diminished from 9 to 4 h.

The results show that application of passive cooling techniques can enhance the microclimate at the outdoor space, create a cooling potential around the building in the daytime. And there was little effect of the increase in humidity on the indoor climates by the passive cooling techniques. In the next study, we are going to measure the effect of nighttime ventilation with cold storage at floor and to evaluate how it can control the increase in the indoor daytime air temperature.

**NOMENCLATURE**

\[ Cp \] : Specific heat at constant pressure of air (=1.006[kJ/kg \cdot °C])

\[ \rho \] : Density of air (=1.2[kg/m^3])

\[ V \] : Air Volume \([\text{m}^3/\text{s}]=H0.5 \text{[m]} \times W0.7 \text{[m]} \times 2 \times \text{Wind velocity [m/s]}\]

\[ T_{\text{out}} \] : Air Temperature at A4 [°C]

\[ T_{\text{in}} \] : Air Temperature at A6 [°C]

\[ X_{\text{out}} \] : Absolute humidity at A4 [kg/kg (DA)]

\[ X_{\text{in}} \] : Absolute humidity at A6 [kg/kg (DA)]

\[ \gamma \] : Latent heat of vaporization (=2430 [kJ/kg])

Refer to Fig.3 (b) where the detail points are (A4, A6).

**REFERENCES**


Japan Meteorological Agency: http://www.jma.go.jp


Session 6C: Energy and resource mapping, management & improvements

PLEA2014: Day 2, Wednesday, December 17
14:10 - 15:50, Grace - Knowledge Consortium of Gujarat
The Effects of Energy-efficient Buildings on Facilities Management and Usability with a Focus on Passive House Schools in Norway

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ABSTRACT

The objective of this paper is to improve the understanding of energy-efficient buildings’ management and usability. The intention is to contribute to overall improvements in the energy efficiency of built environments through an integrated approach to considerations of building design, facilities management, and user perspectives. An overview of the development of highly energy-efficient buildings with a focus on passive house school buildings is presented. The passive house standard is defined considering a newly developed and recently implemented passive house standard for non-residential buildings in Norway. The effects of energy-efficient buildings on facilities management and usability are comparatively studied with a focus on Norway’s first and one of the newest passive house schools. Finally, the benefits and risks, the need to develop highly energy-efficient buildings, and the management and user interaction are discussed and summarized.

1 INTRODUCTION

Energy-efficiency of the built environment is of high importance all over Europe and on international level. Since it has become common knowledge that buildings contribute to 40% of the total energy consumption in European countries much effort has been input into improving existing building stocks and further improvements are still needed (EU, 2012). While the energy-efficiency improvement of the built environment lasts for some time, the development of management concepts and a better understanding of the buildings users’ behavior merits more attention. Such integrative understanding would help to achieve buildings’ projected performance and close the research gap recently highlighted by Bordass and Leaman (2013, p. 1): “Research into building performance continues to reveal that even the best buildings often fail to perform as anticipated.” Consideration of the effects of interaction between building design, management, and use would also contribute to a better understanding of the processes or mechanisms that occur within building stocks. Buildings themselves do not consume energy, but rather the users or mechanisms within them create the demand for energy (Sartori, Wachenfeldt, & Hestnes, 2009). The development of innovative technology and its implementation in highly energy-efficient buildings such as passive houses and nearly zero-energy buildings is driven by policy and legislation, including for example Directive 2012/27/EU on energy efficiency. This energy efficiency directive states requirements regarding the improvement of energy efficiency in the public building sector: “Member States shall encourage public bodies, including at regional and local levels, with due regard to their respective competences and administrative set-up, to follow the exemplary role of their central governments to purchase only products, services and buildings with high energy-efficiency performance” (EU, 2012, p. 15). If the implementation of Directive 2012/27/EU is accepted as performance-based norm, it might also increase the demand for facilities management competence with...
reference Joanna Eley’s vision—published before the implementation process of the EU’s Energy Performance of Buildings Directive (EPBD) had begun—that “In the fullness of time, if performance-based building and regulations are accepted as the norm, facility managers will become key players in assessment” (Eley, 2001, p. 5).

The decision to study passive house schools is based on the fact that school buildings form the largest group of public buildings and belong to one of the three largest groups of non-residential buildings in Europe. Non-residential buildings are more complex and less studied than residential buildings. The European non-residential building stock includes mainly wholesale and retail buildings (28%) a large amount of office buildings (23%), and as third largest group the educational buildings with a 17% share in terms of total floor area. The remainder of the non-residential building stock comprises the following categories: hotels and restaurants (11%), hospitals (7%), sport facilities (4%), and other buildings (11%) (Laustsen et al., 2011, p. 8). The overall building stock of all EU27 countries, Norway, and Switzerland has been assessed as having c.25 billion m² of useful floor area, of which 25% are non-residential buildings and 75% residential buildings, used by more than 500 million people (Laustsen et al., 2011). Norway, the northernmost country in Europe, currently has a population of 5 million people. The country’s existing building stock is estimated as having a gross floor area of 325 million m² divided between residential buildings (210 million m²; 64%) and non-residential buildings (115 million m²; 36%) (Haugen, 2008). Sartori et al. (2009, p. 1614) state: “Energy demand in the building stock in Norway represents about 40% of the final energy consumption, of which 22% goes to the residential sector and 18% to the non-residential sector.” Norway has traditionally used a high amount of electrical energy for heating buildings. Due to the country’s dependence on hydroelectricity, buildings in Norway have some of the lowest CO2 performances found in Europe (Laustsen et al., 2011). However, due to limited supplies of hydropower, the increasing demand for electricity causes problems, as stated by Halse (2005, p. 1) almost ten years ago: “consumption of electricity is reaching a level where additional growth will have to be covered by traditional non-renewable resources.”

2 METHODOLOGY

The research is mainly based on the conduction of case studies. Case studies are considered as a most suitable approach to develop insights in a high level of complexity in its real-life context. The passive house school examples have been selected based on a thoroughly conducted state of the art literature review. The development and implementation of passive house school design has been studied on an international level (PHI, n.d., NS3710, 2012) and the management and usability with a special focus on Norway (THOMSEN, J., BERKER, T., HAU GE, Å. L., DENIZOU, K., WÅGØ, S., & JERKØ, S., 2013). The information utilized for the first case study, Åsveien School, is based on a project which has been conducted in cooperation with a public Real Estate and Facilities Management department. In autumn 2013 a group of master students were involved in workshops, and the conduction of experts’ interviews and site visits. The information about the second passive house school case study is based on published scientific conference papers (DOKKA, T. H., & ANDERSEN, G. (2012), JERKØ, S., MYSEN, M., HOMB, A., NERSVEEN, J., NILSEN, S., BLO M, P., & CHRISTOPHERSEN, J. (2006), research reports (THUNSHELLE, K., & LAPPEGARD HAU GE, Å. (2012) and interviews and site visits conducted by the author in 2014.

3 THE STATE OF THE ART

The passive house concept has been described earlier as “buildings, for which thermal comfort (ISO7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions—without the need for additional recirculation of air” (PHI, n.d.). The basic principles of passive houses were summarized in five categories: (1) thermal insulation, (2) passive house windows, (3) ventilation with heat recovery, (4) airtightness, and (5) thermal bridge free design (Feist, 2013). This concept was mainly applied on passive houses, which were built as private homes, with the main objective of reducing the amount of energy used for heating. This was achieved through the construction of highly insulated, compact and airtight buildings with
ventilation systems with heat recovery and special passive house windows.

In Norway, the passive house concept was further developed into a passive house standard for non-residential buildings (NS3701, 2012). Lexow and Dokka (2012, p. 5) state: “Standards Norway is the first member of the European Committee for Standardization (CEN) to have a national standard with criteria for Passive Houses covering all building categories defined in the national building code.” The standard specifies requirements for different non-residential building types, according to the Norwegian climate, building construction method, and architectural context. All buildings in Norway certified as energy-efficient conforming to either passive house or low-energy standards. The certification includes the minimum requirements for heat losses, cooling demand, heating demand, energy supply, and technical infrastructure as elements of a building’s design, components, and systems, as well as air tightness of the building envelope.

A conceptual structure for the description of passive houses can be summarized as follows: (1) General information providing some general information about the building (building type, gross floor area, location, and year of construction); (2) Winter heat insulation described by the compactness of the building form and quality of the thermal insulation of the building envelope (ground floor, outer walls, and roof), regarding the passive house requirement of reduced heat losses for transmission and infiltration; (3) Summer heat protection described by the quality of summer heat protection and how zero energy supply for cooling is achieved considering the orientation of rooms, heat storage, solar shading; (4) Energy supply considering the main energy sources and the technical systems of heating, domestic hot water, ventilation, lighting, technical equipment, and cooling; and (5) Windows described as such and as building parts, and with consideration of entrance doors.

4 PASSIVE HOUSES IN NORWAY AND SELECTION OF CASE STUDIES

The passive house concept has been studied in Norway since the year 2000. In 2005, Norwegian researchers recognized a growing interest in the passive house concept in relation to low-energy housing. At that time mainly residential passive house buildings such as single-family houses were constructed. However, a growing interest in the passive house concept was identified. Halse (2005, p. 4) stated: “Passive houses and low-energy housing is on the verge of market breakthrough.” Five years later, in 2010, the first Norwegian passive house school building, Marienlyst School in Drammen, was taken into use (Dokka & Andersen, 2012; Thomsen et al., 2013; Thunshelle & Lappegard Hauge, 2012).

The number of high-energy efficient non-residential buildings is expected to increase continuously up to 2020 in Norway. (Enova, 2012, p. 15). The Norwegian Government is supporting municipalities in the development and construction of climate and environmentally friendly pilot projects under the programs “Framtidens by” (Cities of the Future) and “FutureBuilt.” As part of the program “Framtidens by”, city municipalities are encouraged to share ideas on climate-friendly city development in cooperation with the business sector, the regions, and the Government. “Framtidens by” is scheduled to run for six years (2008–2014) and the 13 largest cities in Norway involved in the program are: Bergen, Bærum, Drammen, Fredrikstad, Kristiansand, Oslo, Porsgrunn, Sandnes, Sarpsborg, Skien, Stavanger, Tromsø, and Trondheim (Government.no, 2011).

The “FutureBuilt” program is scheduled to run for ten years (2010–2020) and will support the realization of 50 projects contributing to the reduction of greenhouse gas emissions and a good city environment. Projects may also include urban areas or individual buildings. The cooperating partners in “FutureBuilt” are four municipal authorities (Oslo, Bærum, Asker, and Drammen), the Ministry of Local Government and Modernisation, the Norwegian State Housing Bank (Husbank), the Norwegian energy national fund (Enova), the national fund to reduce greenhouse gas (GHG) emissions from transport (Transnova), the National Office of Building Technology and Administration, the Green Building Alliance, and the National Association of Norwegian Architects (NAL). In 2014, the project documentation included six school projects (Table 1) within a total of 30 pilot projects: urban areas, schools, kindergartens, office buildings, cultural centers, and housing projects (futurebuilt.no, 2014).
Table 1. The development of passive house schools in Norway sorted by the year of construction (Newest, Oldest), (Source: futureb uilt.no, 2014, “Framtidens by” and/or “Future Built”)

<table>
<thead>
<tr>
<th>School building</th>
<th>School name (Norwegian name), location, year of construction</th>
<th>Energy-efficiency and FM relevant key figures</th>
<th>School type of use and user relevant key figures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Åsveien skole,*</td>
<td>Trondheim, 2013–2015</td>
<td>Gross floor area (GFA): 8836 m² Energy demand: 61 kWh/m²/year</td>
<td>Primary school with 630 students, and autism center for 20 students</td>
</tr>
<tr>
<td>Veitvet skole, Oslo, 2011–2015</td>
<td>GFA: 8789 m² Energy demand: 62 kWh/m²/year</td>
<td>Primary and lower secondary school for Class 1 to 10, class with multiple-use hall, 840 students (school and multipurpose hall)</td>
<td></td>
</tr>
<tr>
<td>Nye Gran skole, Oslo, 2010–2015</td>
<td>GFA: 6079 m² Energy demand: 61 kWh/m²/year</td>
<td>Lower secondary school, 540 students, 65 man-labor years, 80 users</td>
<td></td>
</tr>
<tr>
<td>Frydenhaug skole, Drammen, 2011–2014</td>
<td>GFA: 5795 m² Energy demand data unavailable</td>
<td>Intermunicipal primary school and resource center for students with disabilities 100 students, 110 man-labor years</td>
<td></td>
</tr>
<tr>
<td>Bjørnsletta skole, Oslo, 2010–2014</td>
<td>GFA: 9677 m² Energy demand: 64 kWh/m²/year</td>
<td>Primary and lower secondary school, 790 students, special department for 12 students with autism</td>
<td></td>
</tr>
<tr>
<td>Stasjonsfjellet skole, Oslo, 2010–2014</td>
<td>GFA: 3663 m² Energy demand: 74 kWh/m²/year</td>
<td>Lower secondary school 390 students, 35 full-time equivalent (FTE) man-labor years</td>
<td></td>
</tr>
<tr>
<td>Søreide primary school, Bergen,* 2011–2013</td>
<td>GFA: 7910 m² Energy demand: 43 kWh m²/year</td>
<td>Primary school</td>
<td></td>
</tr>
<tr>
<td>Heistad skole, Porsgrunn, 2008–2012</td>
<td>Energy demand (NS-3031): 37 kWh/m²/year</td>
<td>Primary school, special department for 14 severely disabled students</td>
<td></td>
</tr>
</tbody>
</table>
5 SIMILARITIES AND CONTRASTS BETWEEN THE OLDEST AND NEWEST PASSIVE HOUSE SCHOOLS

Åsveien School in Trondheim is the newest passive house school in Norway. The building has been under construction since July 2013 and will be finished and taken into use in 2015, five years after the completion and start of operation of Norway’s first passive house school Marienlyst School in Drammen in 2010.

5.1 Comparison of the schools’ energy performance

In Trondheim, Åsveien School, which will be a passive house primary school has been under construction since 2013 and will be finished and taken into management and use in 2015. The project, including the main building of the primary school for 630 students and a department for 20 students with autism, has a total gross floor area of 8836 m². In addition, a multipurpose hall with a gross floor area of 2336 m² is under construction on the same site (Hasenmüller, 2013).

Marienlyst School, a lower secondary school is located in the centre of Drammen, a city c.40 km west of Oslo. The school is adjacent to a sports arena (Marienlyst idrettspark) and a public swimming pool (Drammensbad). The school has a heated floor area of c.6450 m². The school has a compact building form comprising three stories. Due to natural changes in the ground level on site, the first floor is partially buried and includes a large auditorium for the whole school, as well as locker rooms, rooms for special functions, and a library. The second floor has a community area with a café, workplaces for teachers, administration offices, and rooms for special functions. The third floor consists mainly of compact student areas and group rooms. The architectural design is characterized by a clear and simple building shape with much variation in architectural expression, form, and use of materials (Dokka & Andersen, 2012, Hahn, 2013).

Table 1 shows a comparison of the simulated energy demand of both Åsveien School and Marienlyst School, built according to Norwegian standards (NS3700, NS3701, and NS3031). The measured energy consumption of Marienlyst School for the academic year 2011–2012 is also shown.

Table 2. Building Energy Performance (kWh/m²/year) of Two Passive House Schools in Norway (Dokka and Andersen, 2012, Hasenmüller, 2013)

<table>
<thead>
<tr>
<th>Energy use categories</th>
<th>Åsveien School simulated energy budget</th>
<th>Marienlyst School simulated energy budget</th>
<th>Marienlyst School measured energy consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room heating</td>
<td>9</td>
<td>12.8</td>
<td>13.7</td>
</tr>
<tr>
<td>Ventilation heating</td>
<td>4.4</td>
<td>0.6</td>
<td>4.1</td>
</tr>
<tr>
<td>Domestic hot water</td>
<td>10</td>
<td>10.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Fans and pumps</td>
<td>12.7</td>
<td>10.8</td>
<td>12.8</td>
</tr>
<tr>
<td>Lighting</td>
<td>8.3</td>
<td>15.5</td>
<td>13.3</td>
</tr>
<tr>
<td>Technical equip.</td>
<td>8.8</td>
<td>13.3</td>
<td>13.9</td>
</tr>
<tr>
<td>Cooling</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total net energy demand</td>
<td>53.9</td>
<td>62.9</td>
<td>60.9</td>
</tr>
</tbody>
</table>

5.2 Effects on facilities management

The general understanding of facilities management in Norway is that it refers to the European
standard, and it includes all traditional roles and methods related to the administration, operation, maintenance, and development of buildings, and service provision for building users. A triangular symbol is often used to visualize the interaction between the three key players, namely the building owner, building user, and building manager. However, in everyday practice many actors interact and thus there are also strategic, tactical, and operational levels in the functioning of buildings. For example, the school janitor may be described as an actor at an operational level (Haugen, 2003, p. 14). Some Norwegian public authorities are continuing with the traditional administration, operation, and maintenance (forvaltning, drift, vedlikehold (FDV)) focus, whereas others have adopted the FM approach in full. A variety of organizational models and service provision concepts exist, including the client-supplier-model, and different approaches to in-house service provision, outsourcing, or outtasking (Haugen, 2003, 2008; Junghans & Olsson, 2014; Novakovic et al., 2012).

Marienlyst School is one of 21 school buildings that together account for 300,000 m² of public buildings owned by Drammen Municipality. Drammen Eiendom KF, the real estate and FM department of Drammen Municipality, represents the owner of the school building and is responsible for the buildings’ management and operation as well as the management of facilities service provision. The general field of responsibility of the real estate and FM department includes operation, maintenance, modernization, new building development and realization, purchasing, selling, leasing, and renting.

Energy management is a subdomain of FM, and integrates all relevant facilities services to ensure that “Client demand for utilities (technical infrastructure) is satisfied by services resulting in a comfortable climate, lighting/shading, electrical power, water and gas” (EN 15221-1, 2007). The main area of responsibility is visible in the operational and utilization phase of a building. Regular monitoring of the power consumption, benchmark analyses, and identification of savings potentials and their implementation are essential working areas in energy management (Junghans, 2012).

The users of Marienlyst School experienced some problems with their school building that could be associated with the commissioning of the building and fine-tuning of automatic systems in the first year of occupation. The researchers highlighted the following issues (Thunshelle & Lappegard Hauge 2012):

1. Temperature: Cold temperatures during the first winter, in 2010, especially in the mornings, were reported in interviews. A lack of supply from the district heating network was indicated as the main reason together with the fact that the winter of 2010 was particularly cold. One year later, the problems were not mentioned, but many of the interviewed students responded that some rooms could be cold or have varying temperatures. It was also pointed out in the interviews that some rooms could be hot and airless in summer months. The latter problem was connected with the use of sunscreens (see “Solar shading” below).

2. Ventilation and air flow: The interviewees indicated that there were problems with air pressure conditions in the building. Doors were either slamming or were too heavy to open easily, or they remained open and emitted a peeping sound, probably due to the ventilation system. [Comment from the author: Probably the maintenance staff would have known why the doors made a peeping sound? Perhaps the doors were also fire doors that needed to be kept closed when not in use, and therefore emitted a warning sound if they were accidentally left open.] There were some complaints about the heavy and bad quality air in the small auditorium and small group rooms in core areas on the third floor, and thus the ventilation in these areas needed to be investigated further. The described problems indicated a need to examine the balancing and sizing of the ventilation units in the school.

3. Solar shading: The interviews and responses to the researchers’ questionnaire documented that the automatic shading and lighting did not work properly. Heat from the sun was also sometimes problematic. Teachers often wanted opportunities to override the solar shading systems in order to have more control over room temperatures. In addition, it appeared that the electric lighting that turned off automatically (controlled by light motion sensors) should have been fine-tuned so that it was more sensitive to movement than it was when the evaluation was conducted.
5.3 Effects on usability

Norwegian researchers have developed a systematic approach for the assessment of school learning environments. The main criteria evaluated are structured in the following three categories, with increasing degrees of complexity:

1. Evaluation of the Indoor climate with focus on five subcategories: thermal- (temperature quality), atmospheric- (air quality), acoustic- (sound quality), actinic- (light and radiation), and mechanical environment (vibrations)

2. Evaluation of the indoor environment, which includes: indoor climate, together with two subcategories, namely the aesthetic environment (visual impact) and the psychosocial environment (interpersonal relationships)

3. Evaluation of the physical environment, which includes the evaluation of the indoor environment (mentioned in point 2 above), together with four subcategories: the building’s suitability for the use (operations and functionality), its suitability for the users (universal design), the user density (area efficiency, m²/student, and volume/student), and usage time (duration of room usage, over time) (Jerkø et al., 2006).

Teachers, other employees, and students at Marienlyst School needed more information about how the building automation system worked and could be adjusted. Especially the solar shading, lighting, and temperature regulation needed to be better understood. Thus, there is a need for cooperation between the users and management staff of new schools when the final adjustments to all technical systems are being made according to user demand. The passive house building at Marienlyst School has improved awareness of the environmentally friendly profile of the school. Moreover, the teachers indicated that they would have liked more information about the passive house concept to communicate to their students (Thunshelle & Lappegard Hauge 2012).

6 CONCLUSION

In this paper, the complexity of energy-efficiency improvements in built environments has been studied with focus on passive house schools in Norway. The intention has been to improve the understanding of passive houses and how they are managed and used. A structure for the description of passive house examples has been developed based on the definition of the passive house concept and the Norwegian passive house standard (NS3701). Nine Norwegian passive house school projects have been identified through publically accessible sources. Marienlyst School in Drammen and Åsveien School in Trondheim, respectively the first and most recent passive house schools, were selected as study cases. The building energy performance of both schools has been compared on the basis of the simulated energy budgets, and the measured energy consumption of Marienlyst School has been reported. The definition of facilities management in Norway and an approach for usability evaluation have been shown to structure the effects of facilities management and usability. In the studied cases, the effects of FM referred to energy management and the janitor as a key actor at an operational level were indentified. The paper reveals that the main aspects of usability are related to the provision of a good indoor climate quality and communication with and feedback from the building user.

REFERENCES


ABSTRACT

City regions and metropolitan areas form the scale on which the battle for will be won or lost, and the level at which cities can become resilient and even self-sufficient. A master plan for a sustainable energy system for city regions is not a luxury anymore.

An energy master plan will be based on incremental steps of transition. The approach needs to start with the charting of energy sources, sinks and unused potentials of a studied area. Herein the method of Energy Potential Mapping can play an essential role. The next step deals with the identification of demand reduction possibilities in the existing built environment – new construction can already be zero energy. Differences in simultaneous discrepancies between supply and demand can be bridged by synergetic systems, heat exchange, cascading and intermediate storage of energy. Finally the remaining demand needs to be solved with renewable energy, inside the city as well as in its environs, which become ever more indispensable to the modern metropolis.

In the energy master plan EPM deals with the identification of supply and demand, supports the finding - in place and time - of energy potentials from sun to magma, helps the discovery of simultaneous mismatches, surpluses and shortages, and helps determine the effect on the urban climate. Mapping is done in 3D, soon to be 4D, including the time factor (diurnal differences, seasonal differences, long-term developments).

Since 2005 Energy Potential Mapping has been developed at TU Delft. It has gained international scientific standing. The advanced 3D method has been used for sustainable energy plans and currently forms the basis for making Dutch regions energy-neutral, in cooperation with local stakeholders. The full paper will describe the Energy Master Plan approach and Energy Potential Mapping method, illustrated by cases executed so far.
1. INTRODUCTION

Sustainable development will become a question of climate adaptation and mitigation (IPCC, 2014) on the one hand and the lasting availability of resources on the other (Haas, 2013). Of these resources, after the basic needs for human survival – oxygen, drinking water and food – energy is the most quintessential element for human society. Without energy no element of civilization can be continued: buildings cannot be operated anymore, drinking water cannot be pumped around or poured into bottles, food cannot be transported from farms to cities and people will be limited again by travel distances they can cover by foot, bike or horse. Energy is the fuel of modern society – the end of energy will be the end of cities as we know them.

One might argue that present-day economy has built in sufficient safety and security for the continued provision of energy and all other needs, but over the past few decades various occurrences have demonstrated that cities are very vulnerable to hampering supplies. For instance, technical failures and black-outs have rendered power plants out of operation (e.g. New York City, USA, 2006), airplane accidents have cut major high-voltage lines supplying urbanized areas (e.g. the central river region, Netherlands, 2009), natural disasters have led to the destruction of power plants (e.g. Fukushima, Japan, 2010), politically driven decisions have blocked supplies (e.g. Russia versus Ukraine, 2009 and 2014), terrorist attacks have damaged energy infrastructure (e.g. Russia, 2010), and – more ‘friendly’ as we know it – market price mechanisms have influenced supplies in various ways (e.g. the Gulf War effects, late 1990s).

In the past most city regions used to be self-supporting entities: think of the Mesopotamian cities, Greek City states, yet also European mediaeval regional centres. Resource cycles used to be closed, meaning that all food, water, energy and materials came from the direct environs and waste products were reused in that same vicinity. Where this evolved out of balance, cities collapsed – think of the ancient Egyptian centres and Mayan cities on the Yucatán peninsula in Mexico. We are now in an era where none of the world’s cities is self-sufficient. Globalisation has made cities strongly dependent on supplies from elsewhere, and wastes are also treated in places mostly not known to citizens. As described with the examples of hampering supplies of energy, this implies cities presently are very vulnerable to failures in the system.

The inevitable conclusion of the previous is that for a secure, sustainable future, cities need to become resilient. A greater extent of self-sufficiency will help to achieve this. Supported by historic examples, city regions and metropolitan areas are still the most suited level at which sources and sinks can be solved locally. Therefore these form the scale on which the battle for sustainability will be won or lost, and the level at which cities can become resilient and even self-sufficient. However, how are we going to transform existing cities or emerging and growing metropolitan areas, with their non-sustainable systems, to sustainable ones?

A master plan for a sustainable energy system for city regions is not a luxury anymore. There is not one single solution that will provide the answer; enforced by successful examples this paper discusses one approach that may help.

2. ENERGY MASTER PLAN

For the research presented the authors based themselves on existing urban regions. Handling an existing city must entail a stepped approach, since commencing with an integrated design from scratch is impossible. The proposed Energy Master Plan will therefore be based on incremental steps of transition.
A quintessential basis for an effective approach to cities is formed by proper knowledge of the city’s use patterns of energy: data are needed of energy consumption, production of energy and residual waste flows, to as much detail as possible. So the Energy Master Plan starts with the charting of energy consumption figures, sources, sinks and unused potentials of the studied area. Herein the method of Energy Potential Mapping discussed further on can play an essential role.

A first real step deals with the identification of demand reduction possibilities in the existing built environment. Every part of the energy demand you can reduce, means avoidance of required energy production; so it is a first step to self-sufficiency. New to be constructed buildings can already be net zero energy. Ambitious cities had better enforce that new development actually is energy-neutral, because all new non-sustainable developments add up to the already present problem. The greatest potential in most cities however lies in an improvement of the existing stock of real estate, so a meticulous analysis of the potential of energy saving in different districts and neighbourhoods, depending on the urban typology and architecture, will help make a leap forward.

A second step deals with the potential that lies within differences between supply and demand. In temperate climates with both heat and cold demands simultaneous discrepancies in demand and supply can be bridged by synergetic systems, heat exchange, cascading and intermediate storage of energy. Heat grids are already well-known in colder climates; these are usually based on high-caloric heat sources, often originating from fossil energy sources. There are however other options (as studied, for instance in the European FP7 projects CELSIUS and City-zen). Lower-temperature grids can also be deployed in order to optimize the exchange of heat (Dobbelsteen et al., 2012b), and cold grids can serve cities with a substantial demand for cooling. Energy can also be reaped from other resources’ wastes, such as waste water or waste material. In these cases processing is most likely to be arranged outside the city borders. So inter-exchanging with the region becomes important here.

Finally, the remaining demand needs to be fulfilled with renewable energy, to be generated inside the city but in terms of quantity most logically outside the urbanised area, which has more space to allocate conversion techniques to produce electricity or heat. We should acknowledge that with the fossil reserves depleting, the world’s energy supply needs to come from its surface ever more. This entails a
competition with other forms of land use: agriculture, nature, recreation, building sites, etc. Therefore we need to become very considerate about the use of land around cities, for which Energy Potential Mapping (EPM) is a proven means to provide insight in the energy potentials locally available inside and outside the city. Taking into account the enormous quantity of energy a modern city consumes, every acre of urbanised area needs at least an acre of energy-productive land. The city’s environs therefore become ever more indispensable to the modern metropolis.

3. ENERGY POTENTIAL MAPPING

As discussed, present-day urban energy systems largely rely on a controlled supply, capable of delivering high-exergy electricity and heat when and where required. Dimensioning of energy systems is mostly defined by peak demands. As the many renewable sources from sun to magma are fluctuating and/or take on a lower exergetic form (for example low-temperature heat), knowing both the spatial and temporal behaviour of urban energy demand and supply are paramount to shaping an Energy Master Plan.

The method of Energy Potential Mapping (Dobbelsteen et al., 2011; Broersma et al., 2013a), developed since 2005 at the chair of Climate Design & Sustainability at the Delft University of Technology and having gained international standing, aims to provide quantitative insight in the when and where of these, visualising both mismatches, surpluses and shortages. The advanced 3D method (soon to be 4D, by detailed geospatial inclusion of the time factor) has been used for sustainable energy plans and forms the basis for making Dutch regions energy-neutral, in cooperation with local stakeholders, by providing them with a palet of possibilities with which they can choose and design appropriate, robust and long term sustainable measures.

Figure 2  Graphical explanation of the Energy Potential Mapping method, with consumers at left and potentials at right (Broersma et al., 2013)

EPM takes into consideration conversion losses and various limitations on the demand side and theoretical renewable supply potentials in order to arrive at a more realistic potential for a chosen area, preferably while promoting multiple land use. An example would be the technical potential of
photovoltaic panels on existing roofs, where the amount of solar radiation arriving at a given area is reduced by suitable roof area and orientation and expected long term PV panel performance. This can further be enhanced by structural suitability, glare issues, financial models and other local limitations and results in a detailed but realistic quantitative potential for photovoltaic electricity. Common themes on the demand side are assessing actual demand (thermal comfort, tap water heating, lighting and electricity use of appliances) from known metered figures and reduction potentials.

When combined, these form a stack of maps of many different demand and supply potential categories that provide both detailed quantified insight in and a policy-maker friendly overview of the available potentials, making it possible to arrive at a robust and realistic Energy Master Plan.

**Figure 3** (Left) Detailed 3D heat map of the central district of the city of Rotterdam: hollow cores indicate heat demands, full cores and layers are heat potentials, natural and anthropogenic (Broersma et al., 2011). (Right) Combined energy potential map stack for a neighbourhood in the Dutch town of Hoogezand-Sappemeer (Broersma et al., 2010).

4. PRACTICAL APPLICATION IN CITY REGIONS

**Rotterdam region**

In the Netherlands, data are available for some 30 different housing typologies, for which average energy consumption and measures to improve energy efficiency are known. A step by step energy approach to integrate energy into spatial planning and making energy data easy accessible by EPM has proven to be a crucial part in preparing a stakeholder-based Energy Master Plan in the city.

A first step in building an Energy Master Plan was mapping the existing energy demand and reduction potentials per housing typology, which prioritised actions for policy-makers. Consequently, EPM en Heat Mapping presented the potential use of waste flows and the capacity for renewable energy generation of Rotterdam in a user-friendly format for a wide range of stakeholders as all maps were compatible to Geographical Information Systems (GIS). This meant that urban energy planning could finally be performed. Two cases will show the effect of EPM in GIS in the city. Since 2013 the Energy Atlas of Rotterdam is online. Using a 50 cm by 50 cm pixel grid, solar potentials are presented for the whole city of Rotterdam. This means that each square of 50 by 50 cm is presented with data of the
feasibility of installing PV panels. The open data set is used by 2000 citizens and companies every month. Solar data are not only linked to weather data, roof angles, shading, cloud coverage etc. to get potentials as realistic as possible, but also to ownership of buildings. This way the Energy Master Plan can be translated directly into action plans. A second case is rolling out the district heating network in the city. Combining energy demand maps, heat maps, density maps and maps of existing pipelines made it possible to work with housing associations, energy companies and investors to work on a district heating master plan for the city. With threshold values agreed on by stakeholders a future district heating map could be drawn with new areas to connect, or areas to intensify, or areas where district heating was not feasible. This was a clear map for policy-makers, now translated into action plans for each area.

Figure 4  (Left) 2D solar potential map in GIS of the Lijnbaan neighbourhood in Rotterdam, which can be combined with an ownership map as an example; yellow is low potential. (Right) 3D solar potential map for the same neighbourhood. Roof angles, orientation and shading are integrated in these maps; red is high potential (maps by Roland van der Heijden).

One more important aspect of EPM is that it constituted the input for energy scenario planning methods such as GRIP, the Greenhouse Regional Inventory Protocol (Carney et al, 2009). A stakeholder-based energy scenario was the basis of the Energy Master Plan.

The energy scenario process can be run using bottom-up or top-down data. However, the internal consistency of the developed scenario pathways and their value for stakeholders will be much higher using local data as they can be directly translated into the Energy Master Plan and local actions. In short, one can state that EPM is an enabler of urban energy planning.

Oostland region

Figure 5: Energy potential maps of heat demand of households in Oostland (left) and potentials of deep geothermal wells (right) (Broersma et al., 2013b)
A recent regional energy study, in which the method of EPM was applied, was executed for the Dutch Oostland region (Broersma et al., 2013b). This 100 km² area is dominated by horticulture, spread between several smaller towns, including Pijnacker. The energy demand maps of different functions and origins as well as the various maps of sustainable potentials of the region (e.g. wind, solar, biomass, geothermal heat, thermal and electric potentials on roofs) served as the basis to expose and quantify sustainable interventions in the built environment. Figure 5 shows two examples of energy potential maps of Oostland, one of demand (left: heat demand of households) and one of supply (deep geothermal heat).

These two maps are shown here in order to explain an example of the application of EPM to a proposal of a geothermal energy cascade in the town centre of Pijnacker. The proposal is schematically shown in figure 6. The concept of a geothermal energy cascade comprises the maximised use of a geothermal energy source. This can be achieved by re-injecting the extracted hot water with the lowest possible temperature into the injection well. Different functions within the built environment can have different temperature trajectories used for heating (differences in inlet and outlet temperatures of the heating systems). If different areas, neighbourhoods or functions with consecutive temperature trajectories will be connected in series, a thermal cascade is created. Heat networks will distribute the hot water. The different districts need to have a similar heat demand too.

The centre of Pijnacker (encircled in the potential maps) has great geothermal potential. An old quarter here has a relatively high-temperature demand (~70°C inlet temperature); a significantly lower temperature could provide the adjacent newer area (~50°C inlet temperature). Adjacent to these two residential areas, a new greenhouse area is planned. If energy-efficient greenhouses are realised, very low temperatures (~35°C) will suffice. The two dashed residential areas in figure 6 have a similar heat demand. The new greenhouse area is finally dimensioned appropriately and connected by the heat supply of the cascade.

In this proposal, the present geothermal heat, at around 2000 m depth, provides a temperature of around 70°C and is re-injected at around 25°C. In the longer run, in an ideal situation, the geothermal well would be replenished by high-temperature heat in summertime, at present perhaps coming from fossil-fueled power plants, and in the future preferably from residual solar heat, won in collectors on...
roofs and in urban surfaces.

5. CONCLUSION

This paper discussed an approach to energetically resilient city regions, based on various energy studies that gradually led to the stepped approach, coined as the Energy Master Plan. The examples used in this paper were from the Netherlands, but the authors think the generic approach may be applied in various countries and climates, only leading to different outcomes than the relatively cool temperate climate of the Netherlands. Since this paper argued the importance of becoming energetically resilient in detail, cities anywhere across the world may profit from a generic approach that helps them to become more self-sufficient whilst maintaining the quality of life, or even increase it, when speaking of emerging or rapidly growing metropolitan areas.

The first self-sufficient city still needs to be developed, or rather: redeveloped. Many cities across the world have made vows to become climate-neutral, carbon-neutral or energy-neutral by a certain year in the nearby future, but only few of them have their energy administration up-to-date. The authors think that using the science-based approach of the Energy Master Plan, including the method of Energy Potential Mapping, will help to realise their ambitions better than using a less-rationalised approach.

By testing the approach in its full potential, flaws or specified deviations will inevitably emerge, but it is the only way to get ahead in times when old solutions do not provide an answer anymore to new challenges.

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A Comparative Analysis of Household Energy Consumption in Jakarta and Bandung

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ABSTRACT

This paper aims to reveal the detailed household operational energy consumption patterns in major cities of Indonesia. A total of 297 households were surveyed in Jakarta, while 247 households were investigated in Bandung, focusing especially on unplanned landed houses. The detailed information about household appliances and gas consumption were investigated through face-to-face interviews. The households in the two cities were grouped into three clusters based on their ‘wealth’ and ‘household size’. It was seen that the average household energy consumption and their CO₂ emissions increase with the increase in the above two factors, in particular the ‘wealth’. The household energy consumption in major Indonesian cities was predicted to increase very sharply in line with the rise of middle class in the near future if proper energy-saving strategies are not implemented. We recommended the following potential energy-saving strategies for urban houses in Indonesia: (a) provision of more apartments rather than landed houses (from the viewpoint of energy), (b) natural lighting and use of LED lamps, (c) passive cooling techniques wherever possible, and (d) insulation for building envelope.

INTRODUCTION

Indonesia has been experiencing high economic growth in line with rapid urbanization and therefore sees large increase in urban energy consumption. The real GDP increased stably by approximately 6-7% over the last few decades, whereas the nationwide final energy demand rose by 14 times from 1970s to the present (Dewi et al., 2010). Energy-saving strategies are, therefore, essential to be introduced further to make the cities more sustainable. At present, Indonesia has a population of 240 million and the percentage of people living in urban areas reached approximately 50% as of 2010. It has been reported that approximately 60% of the total population are distributed in the relatively small island, Java, which accounts for only 6% of the total national land. As a consequence, major cities in the Java Island are densely populated, such as Jakarta, Bandung and Surabaya, etc.

In Indonesia, the household sector contributes to the nationwide final energy consumption by approximately 29% in 2011 (Indonesia, 2011) and the household energy consumption is expected to increase dramatically as the middle class in urban areas rises in the near future (JETRO, 2011). At present, most of the residential buildings in major cities are considered to be unplanned houses called ‘Kampungs’. These dwellings were settled in unplanned and overcrowded urban villages without being provided properly with basic urban infrastructure and services. These unplanned houses account for a large proportion in the existing housing stocks in the major cities: 74% in Jakarta, 89% in Bandung and 98% in Surabaya, etc.
The objective of this study is to reveal the detailed household operational energy consumption patterns in major cities of Indonesia. A total of 297 households were surveyed in Jakarta, while 247 households were investigated in Bandung, focusing especially on unplanned landed houses. Firstly, the samples of the two cities are classified into several groups based on household characteristics through a cluster analysis in order to analyze their household energy consumption patterns. Secondly, multiple regression analyses are carried out for respective cities to figure out the causal structures on the household energy consumption. Potential energy-saving strategies for urban houses in Indonesia are discussed based on the results of the above analyses.

METHODS

Jakarta, the capital city, has a population of 9.6 million in 2010 while that of Bandung is 3.3 million as of 2011. Both of the cities saw rapid population growth over the last few decades. The two cities are situated in the West Java and experience uniform hot-humid climates throughout the year. However, the average temperature in Bandung is not as high as other cities because of its relatively high altitude (700-800 m above the sea level). The monthly average temperature ranges from 22.9-23.9°C in Bandung, whereas that of Jakarta is 27.1-28.9°C. Due to the relatively cool climate, few houses use air-conditioning in Bandung.

As described before, the majority of urban houses are considered unplanned houses in Indonesia. The Indonesian government further classifies these unplanned houses into three categories based on construction cost and lot area, namely simple, medium and luxurious houses (Figure 1). Although the quality and size of houses differ among these three house categories, they are similarly constructed of brick-walled structure. Moreover, most of the building materials used and the construction methods of these houses are similar regardless of the house category (Surahman and Kubota, 2013).

A total of 14 typical residential neighborhoods were selected in Jakarta while six areas were chosen in Bandung for the surveys. The survey was conducted in Jakarta from September to November 2012, whereas it was carried out from September to October 2011 in Bandung. A total of 297 and 247 houses were investigated respectively (see Table 1). The detailed information about household appliances and gas consumption were obtained by means of face-to-face interviews using a questionnaire form. The content of the questionnaire covers the following items: (a) socio-economic profile, (b) building information, (c) monthly energy bills (electricity, water, gas (LPG), and kerosene), and (d) number and usage time of household appliances. Meanwhile, on-site measurements using watt meters (MWC01, OSAKI) were carried out to investigate the electric capacity of respective household appliances. Then, the monthly average household electricity consumption was estimated based on the data of (a) number of appliances, (b) usage time, and (c) measured electric capacities. These measured electricity consumption was validated by the data obtained through the electricity bills. The monthly gas (LPG) and kerosene consumption was estimated simply based on the data from their bills.

The annual average household energy consumption was then calculated in the form of secondary energy by combining electricity consumption for all the household appliances as well as gas and kerosene consumption. As explained before, the seasonal variation in climate conditions is not large in both Jakarta and Bandung. Therefore, the usage time of appliances was assumed to be constant.

Figure 1 Views of sample houses. (a) Simple house; (b) Medium house; (c) Luxurious house.
throughout the year. Nevertheless, the small seasonal changes of air temperature and humidity were considered in the estimation of energy consumption caused by air-conditioners and refrigerators, though the resulting changes were found to be negligible.

The primary energy used for generating electricity in Indonesia comprised 42% of coal, 17% of oil, 28% of natural gas, 10% of hydro and 3% of geothermal as of 2010 (Indonesia, 2010; IEA, 2012a). Finally, the electricity consumption was converted into primary energy by considering the above energy mix, electric efficiencies and transmission losses in order to estimate the household CO₂ emissions.

RESULTS AND DISCUSSION

Profile of respondents

Table 1 shows the socio-economic profile of the respondents. The percentages of simple, medium and luxurious houses are approximately 42%, 38% and 20% in Jakarta, and 48%, 40% and 12% in Bandung. These percentages were determined to represent the approximate proportions among all houses of the cities, respectively. As shown in Table 1, the average household size of the respondents was approximately 4.5-5.0 persons in both of the cities. The luxurious houses tend to have slightly larger households of about 5.5 persons. The proportions of household income strata are almost the same between the two cities, although the average income in Jakarta is slightly higher than that of Bandung. In general, household income increases with the house category from simple to luxurious houses.

Classification of households: Factor analysis and cluster analysis

In order to figure out the socio-economic and demographic characteristics that affect their household energy consumption patterns, an exploratory factor analysis with principal axis factoring and a cluster analysis were carried out for the combined whole samples of the two cities (n=544). The orthogonal varimax rotation was employed and the factors were determined based on the eigenvalues (>1). As shown in Table 2, three factors were extracted from the combined samples. The variables with rotated factor loads of more than 0.4 were grouped into the same groups. These three factors were named as follows: ‘Factor 1: Wealth’, ‘Factor 2: Building age’, and ‘Factor 3: Household size’.

It was found that both Factors 1 (wealth) and 3 (household size) have significant relationships with household energy consumption respectively. Then, cluster analyses were conducted by using factor scores of the selected two factors (i.e. ‘wealth’ and ‘household size’) for the combined samples (Figure 2). Since sample sizes were relatively large, the K-means nonhierarchical clustering technique was adopted. By considering the resulting average household energy consumption values, three clusters were determined for the combined samples (Figure 2). In both cities, the factor score of Factor 1 (wealth) consisting of total floor area, house category, household income, lot area, and educational attainment, increases from Cluster 1 to 3. However, the wealth levels are almost the same between Cluster 1 and 2 in both cities. Instead, the households in Cluster 2 have larger household size than those of Cluster 1 as shown in Figure 2.

Household energy consumption by clusters

Figure 3 presents the ownership levels of major household electric appliances in respective case

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Table 1. Socio-economic profile of respondents

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<thead>
<tr>
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<th>Jakarta</th>
<th>Bandung</th>
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<tbody>
<tr>
<td>Sample size</td>
<td>297</td>
<td>247</td>
</tr>
<tr>
<td>House category (%)</td>
<td></td>
<td></td>
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<tr>
<td>Simple</td>
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<tr>
<td>Medium</td>
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<td>11.3</td>
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<tr>
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<td>Male</td>
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<td>60.7</td>
</tr>
<tr>
<td>Age (%)</td>
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<tr>
<td>&gt; 60</td>
<td>12.1</td>
<td>23.1</td>
</tr>
<tr>
<td>Household size (persons)</td>
<td>4.5</td>
<td>4.8</td>
</tr>
<tr>
<td>Monthly household income (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 90 (US$)</td>
<td>3.0</td>
<td>4.5</td>
</tr>
<tr>
<td>90-450</td>
<td>58.9</td>
<td>61.5</td>
</tr>
<tr>
<td>450-900</td>
<td>26.6</td>
<td>28.7</td>
</tr>
<tr>
<td>&gt; 900</td>
<td>11.5</td>
<td>5.3</td>
</tr>
<tr>
<td>Total floor area (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 50 (m²)</td>
<td>33.7</td>
<td>25.9</td>
</tr>
<tr>
<td>50-99</td>
<td>28.3</td>
<td>32.4</td>
</tr>
<tr>
<td>100-300</td>
<td>34.0</td>
<td>37.7</td>
</tr>
<tr>
<td>&gt; 300</td>
<td>4.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>
studies. As shown, lighting bulb (100%), television (95-100%) and refrigerator (79-100%) recorded high ownership levels similarly in the two cities among three clusters. In the case of Jakarta (Figure 3a), the stand fan also recorded high ownership levels of 78-84%, reflecting its severe hot climatic conditions. In general, the ownership levels of other appliances increase from Cluster 1 to 3 respectively, except for a few appliances such as water pump in Bandung. The ownership levels of air-conditioners significantly differ between the two cities: they are 16-79% in Jakarta and 0-17% in Bandung.

In both cities, compact fluorescent lamps are well penetrated among households regardless of the clusters (Figure 4). It has been reported that the Indonesian government highly promoted fluorescent lamps for replacing incandescent lamps from 2007 (BUMN, 2007). The national power company (i.e. Perusahaan Listrik Negara) exchanged one incandescent bulb by three compact fluorescent bulbs for free for their customers all over Indonesia with the aim of reducing the nationwide electricity consumption and the government’s subsidies for electricity tariffs.

Figures 5 and 6 show the annual household energy consumption (secondary energy) averaged in respective clusters. Figures 5a and 6a indicate the energy consumption by different energy sources and Figures 5b and 6b show those by different end-use categories. Overall, the average annual energy consumption in Jakarta is approximately 5,726 kWh, which is 1,402 kWh larger than that of Bandung. The difference is mainly attributed to the use of air-conditioning between the two cities. As shown in Figure 5b, the energy consumption for cooling accounts for 22% in Jakarta on average, whereas the corresponding percentage is only 1.3% in Bandung. Hence, in the case of Jakarta, basically, the average household energy consumption of clusters increases with the increase in ownership and use of air-conditioning (Figures 3a and 5b). In the case of Bandung, the energy consumption for cooking, lighting, entertainment and power, etc. largely influence the increase in the overall energy consumption (Figure 5b). As described before, Clusters 1 and 2 have similar wealth levels on average, while Cluster 2 has larger household size than Cluster 1 in both of the cities (see Figure 2). As shown in Figure 5b, the
The difference of household size between Cluster 1 and 2 cause a significant difference in energy consumption for cooking in the case of Bandung. In both of the cities, electricity consumption is larger than that of LPG and kerosene except for Clusters 1 and 2 of Bandung, even when they are assessed based on secondary energy: 62-73% in Jakarta and 43-58% in Bandung (Figure 5a).

Figure 6 shows the corresponding annual energy consumption per square meter. Interestingly, the averaged energy consumption decreases from Cluster 1 to 3, except for Clusters 1 and 2 of Bandung. This is mainly because the occupant density declines from Cluster 1 to 3 accordingly. In particular, the average total floor area of houses in Cluster 1 of Jakarta is so small (64 m²) that the corresponding energy consumption per square meter is larger than the others.

The annual household CO₂ emissions were estimated through multiplying the energy consumption by the CO₂ emission factors. Table 3 lists the CO₂ emission factors for different energy sources.

Figure 7 Annual household CO₂ emissions by clusters (Primary energy). (a) by energy source; (b) by end-use.

Table 3. CO₂ emission factors

<table>
<thead>
<tr>
<th>Energy source</th>
<th>CO₂ emission factor (kg CO₂-eq/GJ)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>196.9</td>
<td>IEA, 2012b</td>
</tr>
<tr>
<td>LPG</td>
<td>66.7</td>
<td>Kurdi, 2006</td>
</tr>
<tr>
<td>Kerosene</td>
<td>72.5</td>
<td>Kurdi, 2006</td>
</tr>
</tbody>
</table>

30th INTERNATIONAL PLEA CONFERENCE
16-18 December 2014, CEPT University, Ahmedabad
(primary energy) for each fuel type by its corresponding CO₂ emission factor (Nansai et al., 2002; Surahman and Kubota, 2013). Table 3 presents the CO₂ emission factors used for this analysis. As indicated in Figure 7, the average annual CO₂ emission in Jakarta is estimated at 7.8 ton CO₂-equivalent, while that of Bandung is 4.8 ton CO₂-equivalent. The major contributors in Jakarta are cooling (2.4 ton (31%)), cooking (1.6 ton (20%)) and refrigerator (1.3 ton (17%)), while those in Bandung are cooking (1.2 ton (26%)), refrigerator (1.1 ton (23%)) and lighting (1.0 ton (21%)). If the amount of CO₂ emissions caused by cooling are excluded, then the difference of total CO₂ emissions between the two cities would be insignificant (5.4 ton in Jakarta and 4.7 ton in Bandung). This clearly indicates that the increase in use of air-conditioning in the future would dramatically increase the household energy consumption and therefore their CO₂ emissions.

### Causal structures on household energy consumption: Multiple regression analyses

Multiple regression analyses were carried out to further analyze the causal structure on household energy consumption in the two cities (Table 4). Since electricity and LPG were found to account for almost all the energy consumption in the two cities (see Figure 5a), firstly, we examined the major factors explaining consumption of these two energy sources (Table 4ab). In this analysis, the new
variables (electricity consumption caused by respective appliances) were created for each of the household electric appliances by multiplying its electric capacity by the number of the appliance and its usage time. Secondly, further determinants for respective electric appliances were analyzed in the two cities respectively (Table 4c).

As shown in Table 4a, the major appliances contributing the electricity consumption largely differ between the two cities. In the case of Jakarta, air-conditioner ($\beta=0.71$) is found to be the major determinant for the electricity consumption in this model, followed by television (0.21), stand fan (0.20), ceiling fan (0.16), and refrigerator (0.14), etc. As seen in Figures 5b, 6b and 7b, this result confirms that energy consumption for cooling appliances, in particular air-conditioners, is significant and large in the case of hot-humid climate of Jakarta. In contrast, in the case of Bandung, water pump ($\beta=0.35$) is found to be the most influential contributor for the electricity consumption in this model, followed by television (0.29), lighting bulb (0.26), and refrigerator (0.24), etc. Both of the regression models obtain high $R^2$-values of 0.93 and 0.87, respectively. The determinants for LPG consumption are similar in the two models for respective cities, although both of the $R^2$-values record low values of 0.08 and 0.13 respectively (Table 4b). In the two cities, both household size and building size may be able to explain weakly the LPG consumption.

As shown in Table 4c, in Jakarta, the energy consumption caused by air-conditioning, which is the main contributor to the electricity consumption, can be explained by the total floor area, the household income and the age of husband with a coefficient of determinant of 0.47. Other major appliances (i.e. television and stand fan) are weakly explained by the total floor area and the number of children, respectively. On the other hand, in Bandung, water pump is weakly explained by the household income. Other major appliances (i.e. television and lighting bulb) can be determined by the lot area and the household income, and total floor area, respectively.

It is seen that overall, the increase in household income and building size, such as total floor area and lot area, increase the electricity consumption caused by the major appliances. In both of the cities, it was found that the increase in household income increase their building size such as the total floor area ($r = 0.38^{**}$ in Jakarta and $r = 0.72^{**}$ in Bandung) and the lot area ($r = 0.39^{**}$ in Jakarta and $r = 0.60^{**}$ in Bandung). Hence, it is anticipated that the further increase in household income would increase the building size, thus the energy consumption caused by major household appliances. As a consequence, the increase in household income would increase the total household energy consumption significantly in the near future in Indonesian cities. It has been reported that the household income in Indonesia is predicted to rise dramatically in the near future in line with the rise of middle class as described before (JETRO, 2011). The household energy consumption in major Indonesian cities is predicted to increase very sharply if proper energy-saving strategies are not implemented.

It is important to avoid the tendency that building size increases straightforwardly with the increase in household income. From the viewpoint of energy, one of the possible solutions is to recommend more apartments rather than landed houses that generally increase total floor area. It should be noted that most of the incandescent bulbs were already replaced by compact fluorescent bulbs in Indonesian cities. This means that further energy-saving should be made for lighting by utilizing more natural lighting or using LED lamps. The increase in air-conditioning would be a major concern in terms of the energy-saving strategies in Indonesia (the relatively cool climate of Bandung is not typical of other major cities). Even in Jakarta, the ownership level of air-conditioner was only 32% on average at the moment in this survey. It is important to reduce the use of air-conditioning in the future despite the expected increase in household income. Passive cooling techniques should be adopted wherever possible. Insulation for building envelope should also be considered.

On the other hand, the current energy efficiency in electricity generation in Indonesia is not as good as other developed nations. The total loss due to electric efficiency and transmission losses results in the increase in primary energy consumption by approximately 2.7 times than the end-use electricity consumption. This exceeds the scope of this paper but this should also be considered in the future energy-saving strategies in Indonesia.
CONCLUSIONS

Key findings are summarized as follows:

1. The households in Jakarta and Bandung can be grouped into three clusters based on their ‘wealth’ and ‘household size’. It was seen that the average household energy consumption and CO₂ emissions increase with the increase in the above two factors, in particular the ‘wealth’. Overall, the average annual energy consumption in Jakarta was approximately 5,726 kWh, which was 1,402 kWh larger than that of Bandung. Accordingly, the average annual CO₂ emission in Jakarta was estimated at 7.8 ton CO₂-equivalent, while that of Bandung was 4.8 ton CO₂-equivalent.

2. The difference of household energy consumption and CO₂ emission between the two cities was mainly attributed to the use of air-conditioning. The ownership levels of air-conditioners significantly differed between the two cities: they are 16-79% in Jakarta and 0-17% in Bandung. It was predicted that the increase in use of air-conditioning in the future would dramatically increase the household energy consumption and therefore their CO₂ emissions.

3. It was anticipated that the further increase in household income would increase the building size, thus the energy consumption caused by major household appliances. As a consequence, the increase in household income would increase the total household energy consumption significantly in line with the rise of middle class in the near future in Indonesian cities if proper energy-saving strategies are not implemented.

4. It is important to avoid the tendency that building size increases straightforwardly with the increase in household income. We recommended the following potential energy-saving strategies for urban houses in Indonesia: (a) provision of more apartments rather than landed houses (from the viewpoint of energy), (b) natural lighting and use of LED lamps, (c) passive cooling techniques wherever possible, and (d) insulation for building envelope.

ACKNOWLEDGMENTS

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ABSTRACT

The city of São Paulo is the richest city in Brazil, accounting for more than 12% of the national GDP, offering employment opportunities for the countries’ middle class as well as for the poor (IBGE, 2012). As a result, approximate 2 million people live in slums with deficient urban infrastructure (FRANÇA, COSTA, 2012). In the last decade, the increase buying power of the low income families in the big cities of the country has caused a dramatic raise on electricity demand due to the acquisition of domestic appliances, which have proved to become comparable to those of middle class, based on the data gathering in the fieldwork research presented in this paper. Hence, the growth of urban slums in Sao Paulo is associated with the increase of its population density accompanied by an increase of electricity demand, adding pressure on the precarious infrastructure and impoverishing even more the living conditions, due to the accumulation of heat gains in compact irregular and overcrowded housing, agglomerated in informal settlements of poor quality open spaces. In this context, this work examines the environmental challenges of slums in the city of São Paulo, the so called “favelas”, drawing from two cases: “favela Morro da USP”, covering 18,500m² and housing 515 families, and “favela Paraisopolis”, the second biggest in São Paulo, with almost 60,000 inhabitants living over 100 hectares. Field work has shown energy consumption of the slums’ households of around 220kwh/month, the equivalent to the typical figures from the local middle class homes. In addition, the environmental research has identified the potential of improving internal conditions with bigger openings to higher ventilation rates and shading of roof components.

INTRODUCTION

Being the 10th richest city in the world, São Paulo entered the new century accounting for 12.26% of the national GDP and 36% of the total output of goods and services of the State of São Paulo (IBGE, 2012). Associated with its economic development, the city of São Paulo is seen as a place of employment opportunities, availability of infrastructure and access to education, health, leisure and culture in the country. On the other hand, economic and urban growth has also reflected in a series of socio-economic, urban and environmental negative impacts, compromising the quality of life of various neighbourhoods in the city, formal and informal. In this context, the housing deficit is one of the most critical issues in the city. According to the census of 2010 (IBGE, 2010), 1.16 million people were counted.

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in the slums, 1.8 million inhabitants in irregular settlements, and about 9,000 homeless in the city of São Paulo. The phenomena of the favelas in São Paulo, which started in the 70s, became visible and distinguished in the urban fabric of the city (figure 1).

Covering an area of almost 2 hectares (18,500m²) and housing 515 families, Favela Morro da USP is a small informal settlement where 50% of residents live in units smaller than 30m² (Pizarro, 2014). On the other end, Favela Paraisopolis is the second biggest slum in São Paulo, with almost 60,000 inhabitants living over 100 hectares (França, Costa, 2012). Whilst the first case has the population and a total area equivalent to a couple of typical urban blocks, Paraisopolis covers a territory of a medium size city in the country. Despite these differences, both case studies have similar social and physical structure, typical of the consolidated urban slums in the city. The consolidated slum in São Paulo has a basic infrastructure in place (roads, water, sewage and energy utilities), the permanent character of the buildings and the identification of a coherent social organization. Problems for the quality of life are found in the lack of open spaces and in the environmental conditions of the residences.

![Figure 1](image1.png)

**Figure 1** Overview of Paraisopolis, the 2nd biggest slum of Sao Paulo, in cityscape of the city. Photo: Eduardo Pizarro.

**CLIMATE**

The city of São Paulo is located in the latitude 23°24’south, with a tropical climate subjected to the effects of altitude (approximately 800 metres above sea level) where thermal comfort is likely to be achieved for approximately 70% of the year (ASHRAE, 2009). The climate offers sunny winter days, when direct solar radiation is a key factor for thermal comfort, especially in outdoor spaces, and partially cloudy days in summer, when the main strategy for thermal comfort is solar protection combined with natural ventilation. The mean air temperature in the summer months stays around 23°C, whilst humidity can easily reach 80 per cent (figure 2). However, it is worth highlighting that in the hot periods of the year, thermal comfort indoors and outdoors is highly dependent on shading strategies and proper ventilation rates. Winters are mild, with mean air temperatures between 16°C and 18°C, though even in winter relative humidity stays high. Heating demand is identified for short periods of the year, being easily solved passively with solar gains and internal gains from dense occupation patterns.

![Figure 2](image2.png)

**Figure 2** Monthly average temperatures of the climate of Sao Paulo with incident radiation. Source: Pizarro, 2014.
In addition to the characteristics of the natural climate, the city presents a huge variety of urban microclimates, influenced by the multiple aspects of the urban form and human activities and characterized by problems with air quality, urban heat islands, poor urban ventilation, urban noise, among others, which affect the quality of both open spaces and buildings, typical in the slums (CETESB, 1990, Silva, Ribeiro, 2006). Moreover, it is important to consider that, in the residential units, high occupation density coupled with insufficient air changes (due to small windows), compromise the internal environmental conditions in the warm days of the year, as shown below.

THE BUILT ENVIRONMENT OF SLUMS

Urban fabric

Originally, the urban fabric of both case studies (as in the majority of slums in Sao Paulo) developed on top of a formal parceling of the territory (figures 3 and 4). As a consequence, main roads were kept within their original size (10 meters long), whilst a complex grid of alleys grew within the urban blocks to give access by foot to the internal and smaller residential units (figures 5 to 8). As a result, the built environment is characterized by a diversity of circulation spaces with contrasting environmental conditions in need of improvement. The compactness of the urban blocks leads to lack of vegetation and space to the accommodation of urban and living activities, which are either castigated by solar radiation or deprived of daylight and air flow between buildings due to the rather narrow canyons (figures 5 and 6).

Figures 3 and 4 On the left, the urban fabric of Favela Paraisopolis, over 100 hectares. On the right, the site planning of Favela Morro da USP, covering the small area of 2 hectares. Despite the difference in size, both cases have a similar pattern of urban fabric. Source: Pizarro, 2014.

Figures 5 and 6 The urban environment in Favela Paraisopolis. On the left, the canyon and socioeconomic activities on the pavement of the main street. On the right, the appropriation of open space of the alley. Photo: Eduardo Pizarro.
The building

The buildings in the slums of Sao Paulo vary from one to four storeys, supported by concrete columns and beams and brick walls. The area of the residential unit (one per floor), vary from 30 to 50m², for an average family size of four people. Typically, each residence has one façade to the exterior. As identified in Samora and Vosgueritchian (2006), the limited exposure to the outside combined with the compactness of the urban fabric incurs to internal spaces characterized by lack of solar access, daylight and ventilation. On the other hand, the thermal capacity of the buildings, in addition to the self shading of the urban fabric and external shading strategies, protects internal and external spaces from the harsh impact of solar radiation.

ENVIRONMENTAL CONDITIONS AND CHALLENGES

Outdoor environment: walking through the streets of Paraisopolis

Measurements of environmental variables in the streets of Paraisopolis included air temperatures, surface temperatures, relative humidity and air movement. Comparing the results found in the streets with those from the alleys, the fieldwork showed the significant positive impact of the shading and
shaded mass in reducing surface and air temperatures in hot days. The unshaded street presented surface temperatures as high as 50°C and air temperature around 36°C (figure 11). In contrast to that, within a short period of time, the protected space of alley had higher air temperatures around 36 °C but significantly lower surface temperatures, showing figures around 28 °C, which have a major favourable impact on pedestrians’ comfort and on the thermal conditions within the rooms facing the alleys (figure 12). Air movement also varied from higher than 2 m/s in the main street to around 1.5 m/s in the alley, in the best scenario. Nevertheless, insufficient daylighting in the alleys is obvious.

**Figure 11** Synthesis of thermal conditions in one of the main streets of Paraisopolis, showing air temperature, surface temperature, relative humidity and air movement taken on a hot day at 4 pm. Source: Pizarro, 2014.

**Figure 12** Synthesis of external thermal conditions in one alley, showing air temperature, surface temperature, relative humidity and air movement on a hot summer day at 4:15 pm. Source: Pizarro, 2014.

**Thermal environment in internal spaces**

Measurements of thermal conditions of an internal space were taken in one of the houses facing a main street. The exposure to solar radiation coupled with the concentration of internal gains and insufficient ventilation rates resulted in air temperatures as high as 40°C in the living space (bringing together living and kitchen in one area) at 4 pm of a week day, when outdoor temperatures oscilated around 33 °C (figure 13). The way windows are design, protection against solar gains would inevitably block the
already limited air ventilation rates, so as a common practice, windows are kept open by the occupants during the day in order to provide some air movement, however, inefficient to control the rise of internal temperatures. At night, internal temperatures drop up to 10 °C. It is known that windows are kept open during the night allowing for night time cooling of the internal spaces and the building fabric of brick walls and concrete block ceilings. However, during the internal temperatures quickly go up to 35°C and than 40°C degrees during the 1st half of the day. In principle, solar protection and higher ventilation rates would improve such conditions.

Figure 13 Measurements of air temperature in a residential unit with a multistory building, facing a main street in Paraisopolis. Source: Pizarro, 2014.

ENERGY DEMAND: THE CASE STUDY OF FAVELA MORRO DA USP

The main type of energy consumed in the building sector in Brazil is electrical. The electricity consumption in the Brazilian residential sector represented 20% of the total in 1991, whilst in 2000 it grew to 27% (CCPE, 2004). In the group of cities of the South-East region of the country, where São Paulo is located, the main energy consumer is the fridge with approximately 30%, followed by the electric shower with approximately 26% and the artificial lighting with approximately 10% (Guisi et al., 2007). Looking at the electricity consumption in a typical middle class residence in São Paulo, this trend results in an average of 117Kwh/ m² month, in a residence of around 70m² (BESP, 2009). Compared with data from the National Energy Balance (BEN, 2010), the numbers relating to residential energy consumption in São Paulo are very close to the national average, being 113kWh/m². It is worth noticing that almost 40% of the residential energy consumption range from 100 to 160kWh/m², with an average of 3.2 people per family (BEN, 2010).

Looking at the case of Favela Morro da USP, although almost 70% of its population have an monthly income below five minimum wages (between US$545,00 and US$1,818,00), proving the hypothesis that the consumption of electricity in consolidated favelas has a similar pattern to that from the local middle class homes in Brazil (Pizarro, 2014). This is due to the increasing access to affordable appliances. As the energy demand grows in consolidated slums, as in Morro da USP, the provision of electricity becomes problematic for two reasons: the difficult access to the residential units, due to the informal use of land and compact nature of the built environment, and the dynamic changes of the slums’ social and physical structures. The precarious nature of living combined with great expansion of self-
built units and subdivisions of one residence in multiple ones (figures 14 e 15), imposes a fundamental challenge to the task of checking and monitoring the consumption of the different buildings and families.

In Favela Morro da USP it is common to observe a single residential unit housing two or more families, which would demand different electricity meters. In a number of cases, the informal sharing of the spaces and domestic appliances between families makes the division in electricity consumption of different families not clearly distinguishable and difficult to be priced.

*Figures 14 e 15* On the left, the precarious electricity grid running in front of windows in favela Morro da USP. On the right, the multiple electricity meters installed in one residential building.

In this context, the total monthly energy consumption by household cannot be translated into kWh/m², once the area occupied by each household is a constant changing factor and cannot be simply identified by the plot ratio of the building. In order to present a clear energy consumption profile, the figures chosen to illustrate the electricity consumption in the case study of Favela Morro de São Paulo refer to only one month, corresponding to the biggest number of households being registered in the year of the fieldwork, May 2013 (Pizarro, 2014). The fieldwork showed that for 82% of households the threshold of electricity consumption is 200kwh per month, thus achieving the Social Discount Rate Low Income, created by the Federal Government in January 2010 (figure 16 e 17). The new social tariff of electricity consumption promoted discounts for social housing, varying between 10% a 65% in cases which the monthly family income per capita is equal or less than half of the national minimum wage. The degree of discount is associated with the household consumption, varying from the minimum of 30kWh per month for the maximum discount of 65%, to 202kWh per month for the minimum discount of 10%.

*Figures 16 e 17* Energy consumption in the residential buildings of Favela Morro da USP in May 2013. On the left, the percentage of households below 50kWh and above, including demands over 151kWh. On the right, a detail assessment of consumption above 1501kWh, with 82% up to 220kWh, the threshold of the Social Discount Rate Low Income, and percentage of units above.

With respects to life-style, it is important to note that the population of consolidated favelas such as Morro de São Paulo, where addresses have been established based on to energy and sewage bills, has led residents to have access to bank credit and, therefore, to domestic appliances existing in a typical middle-class residence in Brazil (TV, microwaves, stereos, computers, irons, electric shower, washing machine, etc.). The gradual increase in the buying power of the low income sector in Brazil, which is visible and practiced in the city of Sao Paulo is among the factors that justify the levels of energy consumption shown in figures 16 and 17. In order words, the oficialization of energy consumption has become an efficient way of socioeconomic inclusion. Nevertheless, the challenges to access all residential units, provide electricity with a safe grid and measure the consumption of individual households remain. Furthermore, the compact urban fabric of the favela results in a highly-concentrated
energy demand. In this scenario, to avoid risks of power supply for electricity, implementation of conventional infrastructure facilities could be planned with the introduction of the so called alternative or ”green” technologies, such as solar collectors for water heating and photovoltaic cells for electricity.

FINAL CONSIDERATIONS

Access to electricity became an effective means of social inclusion. In that sense, since the energy bill is associated with a formal address, within an informal urban settlement, the households have the minimum requirements to take part in the formalized market of goods and appliances, including the access to financial credits. In addition to that, contrary to the misconception that low income families inherit inefficient domestic appliances (or have none at all), the reality in consolidated favelas is that there is a trend of energy consumption similar to those of the overall residential sector in the region. On the other hand, different from the formal part of the residential sector, the energy supply in favelas faces the challenges brought by the constant growth and changing of the physical environment, including the horizontal and vertical expansion and multiple subdivisions of one building in several households.

From the point of view of broader environmental issues, whilst energy consumption shows the increasing buying power of low income families living in favelas in São Paulo, the comfort of the inhabitants inside the buildings and the environmental conditions of open public spaces do not offer good quality. In this respect, the performance of the local built environment of the favela with the principles of environmental design for the specific climate of São Paulo needs to be further improved both for indoor and outdoor spaces, if quality of life is to be provided beyond access to energy.

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Sustainable water management in buildings, an affordable approach. Case Study: Terra Bio-Hotel Project, Medellín, Colombia

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ABSTRACT

Water management model in cities is based upon large-scale systems which take water form external watersheds located dozens to hundred kilometers to the municipalities they supply. Water is treated to drinking standards despite the intended use, leading to wastewater which is discharged back to the environment through sewer systems, often without previous treatment, being an important source of environmental pollution and public health hazards. Meanwhile rainwater is considered a problem, being collected from roofs and streets to be also disposed in sewers as other kind of wastewater. Although water technologies have evolved, this model has virtually remained the same since the ancient Rome, twenty centuries ago. A paradigm shift is urgently required and buildings must be in the center of this transformation. Terra Bio-hotel, a 41 room hotel located in Medellín is a project designed and being built with sustainable water systems, integrating low consumption devices, rainwater harvesting, greywater recycling and groundwater catchment. Although the building is connected to the municipal service, altogether these strategies allow the project to function as net-zero as far water is concerned. As expected, the water management scheme of this project is considerably more expensive than a conventional one. Nevertheless, when operation costs are compared to conventional water fares, it appears that investment costs are returned in five years, demonstrating eco-efficiency to be an economically sustainable choice at this scale.

INTRODUCTION

As world urbanization increases so does the pressure upon water resources. This is particularly true for Latin America and the Caribbean, where 80% of population lives in cities which are dependent on external water sources to supply, where wastewater treatment is low and vulnerability to urban floods from storm water is high (Howe, Butterworth, Smouth, Duffy, & Vairavamoorthy, 2012; World Bank, 2013)

This unsustainable condition is related to sectorial water frameworks where local governments, environmental agencies and water companies work for contrasting agendas and measure their challenges and achievements by divergent indicators, whereas citizens, private sector and public institutions remain as passive users, with no say on water governance (Domenech, 2011; Bedoya, 2011)

Since urban water is mainly used and polluted through building operations; water-efficient buildings are a reasonable starting point to give users a more meaningful role on water governance. This paper...
describes and discusses the water management model implemented on Terra Bio-Hotel Building in Medellin – Colombia, as a study case, whose comprehensive adoption on other building projects in Latin America and other regions may make a significant contribution for cities to become less dependent, more efficient, healthier, less contaminant, more resilient and more sustainable with regards to water (Howe, Butterworth, Smouth, Duffy, & Vairavamoorthy, 2012).

OBJECTIVE

The aim of this applied research was to conceptualize, develop and implement a model for water efficiency on a real scale building in Medellin – Colombia and to forecast the expected environmental and financial cost-benefit ratio in order to provide governs, planners, designers and constructors a framework to make informed decisions on sustainable water management schemes.

PROCESS APPROACH

Case study

Terra Bio-Hotel is a medium size hotel building with 41 rooms and 2400 m² built area, looking to be distinguished for its environmental standards at both construction and operation phases, giving host a differential factor concerning architecture and technical facilities. The project is set in Medellin, biggest of ten municipalities assembling a metropolitan area called the Aburrá Valley, inhabited by 3.5 million people.

Water management data for Aburrá Valley

Information concerning water management for Abarra Valley was collected and analyzed from local land and water plans, publications by local environmental authorities and local Water Service Company, as well as from technical relevant literature.

Water management systems for the case of study

Prior to hydraulic design, two water system schemes were pre-designed, analyzed and compared. System 1 is conventional, whereas System 2 is an alternative system proposed to lower the environmental impacts related to water demand and wastewater disposal along operation phase of the building (see figure 1).

![Figure 1. Water treatment systems installed at Terra Bio Hotel](image-url)
Water treatment plants for System 2

In order to fulfill the principles for System 2, two treatment plants are required: one plant to treat grey water to be reused on activities that do not require drinking-quality water, such as toilet flushing, general maintenance and irrigation of green areas; the other plant is to treat rain water and groundwater up to drinking-quality standards, to be used for showers and faucets. Both rainwater and groundwater were previously sampled and tested for compliance to water quality regulations set for water sources intended for domestic supply (data not shown).

Cost-benefit analysis

Financial investment costs for pre-designs of each hydraulic system scheme were calculated. Water demand is estimated as established for hosting facilities by Colombian regulations.

Environmental costs-benefit analysis is based on the following indicators:

- Total water consumption (m³/year)
- Dependency on water sources external to the watershed (m³/year)
- Wastewater discharge (m³/year)
- Storm water discharge (m³/year)

RESULTS

Water in the local context: Water management model in the Aburrá Valley

Table 1 provides main data concerning water management in the Aburrá Valley, which is highly dependent on external water sources despite of its high water yield. Most urban population has access to water supply, but unaccounted for water is high. Most population also has access to basic sanitation trough connection to a sewer network, although the level of wastewater treatment remains low. New wastewater treatment facilities are under construction and will be fully operating by 2015 though. Due to such investments, sanitation is charged higher than supply. Groundwater is an abundant source and it is used, mainly by industry, but total withdraw is unknown. For building sector, such abundance becomes a problem since parking lots and basements get below the water table, thus water has to be pumped out and discharged into the sewer system which is charged at sanitation fares, this would also be the case for Terra Bio Hotel project (see table 1) (Municipio de Medellín, 2014; URBAM, Área Metropolitana del Valle de Aburrá, & Municipio de Medellín, 2011)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water cycle balance</strong></td>
<td></td>
</tr>
<tr>
<td>Valley Area (km)</td>
<td>1250</td>
</tr>
<tr>
<td>Average precipitation (mm/year)</td>
<td>1672</td>
</tr>
<tr>
<td>Average evaporation (mm/year)</td>
<td>1172</td>
</tr>
<tr>
<td>Water yield (mm/year)</td>
<td>500</td>
</tr>
<tr>
<td>Water yield (million m³/year)</td>
<td>625</td>
</tr>
<tr>
<td><strong>Water supply</strong></td>
<td></td>
</tr>
<tr>
<td>Total water consumption from water supply (million m³/year)</td>
<td>192</td>
</tr>
<tr>
<td>Dependency on external water sources – watersheds located outside Aburrá Valley (%)</td>
<td>90</td>
</tr>
<tr>
<td>Unaccounted for water (%)</td>
<td>40</td>
</tr>
<tr>
<td>Volume extracted from external sources, considering unaccounted for water (million m³/year)</td>
<td>288</td>
</tr>
<tr>
<td>Population served (% of total urban population)</td>
<td>99</td>
</tr>
</tbody>
</table>
Environmental costs comparison

Figures 2 and 3 show a water balance conceptual model for System 1 and 2.

System 1 consists of:

- 100% of water needs supplied by the local water company
- drinking-quality water is used for all purposes
- no reuse is considered
- rainwater is directed to sewer without use
- since parking lot base is below water table, groundwater is pumped in order to prevent floods and discharged into sewer with no prior use

Principles for System 2 are:

- water needs supplied from diverse sources
- water source defined according to required quality by use
- reuse is considered
- rainwater as well as groundwater are caught, treated and used

As shown in figures, System 1 produces more environmental impacts than System 2. Water demand for the two systems is the same, but system 1 requires 40% more water, since it fully depends on external sources (table 1). System 1 also produces more pollution since groundwater and rainwater are not harvested but just discharged on sewers and grey water is not reused.

![Figure 2. Water balance conceptual model for conventional water management system, System 1. Numbers are expected volumes expressed as m³/year. Frame fill colors are related to water quality: white = high quality, black = low quality.](image-url)
Due to the use of groundwater and rain water as well as the reuse of grey water, implementation of System 2 not just significantly reduces pollutant discharges from the project but also would eventually allow it to be fully independent from external water sources (see figure 2), in fact, volume balances for System 2 shows that the project may produce more water than it actually needs (see table 3).

Cost-benefit analysis

Investment cost

Table 2 lists the investments required for hydraulic installations under Systems 1 and 2 schemes. Implementation of the efficient water management option costs as much as 38% more than implementation of the conventional system.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost for System 1</th>
<th>Cost for System 2</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water pumps</td>
<td>$ 28.947</td>
<td>$ 32.632</td>
<td>On System 2 an additional pumping system for grey water supply is required, but the pumping capacity required for drinking water supply gets reduced</td>
</tr>
<tr>
<td>Storage tanks</td>
<td>$ 10.526</td>
<td>$ 12.632</td>
<td>On System 2 an additional storage tank is required for grey water supply, but the storage capacity for drinking water supply tank gets reduced</td>
</tr>
<tr>
<td>Drinking water network</td>
<td>$ 9.944</td>
<td>$ 5.966</td>
<td>Drinking water supply network gets shorten on System 2, since part of it is replaced by the grey water supply network</td>
</tr>
<tr>
<td>Grey water supply network</td>
<td>$ -</td>
<td>$ 6.526</td>
<td>It only applies for System 2</td>
</tr>
<tr>
<td>Wastewater network</td>
<td>$ 13.158</td>
<td>$ 11.053</td>
<td>It gets reduced on System 2 since part of it becomes greywater supply network</td>
</tr>
<tr>
<td>Rainwater network</td>
<td>$ 6.642</td>
<td>$ 8.105</td>
<td>Rainwater network becomes longer on System 2 in order to reach treatment system</td>
</tr>
<tr>
<td>Treatment systems</td>
<td>$ -</td>
<td>$ 18.421</td>
<td>Only applies to System 2</td>
</tr>
</tbody>
</table>
### Operational costs

Table 3 compares both financial and environmental operation costs for the two systems, water treatment per cubic meter under System 2 costs just 10% of the fare charged on water supply and 6% of the fare charged on sanitation. Hence the cost of using rainwater is 10% of conventional supply. Groundwater use and grey water reuse have a further benefit since these volumes do not get charged for sanitation. Altogether operational cost for System 2 is 40% of operational cost for System 1, allowing full return of the additional investment costs by year 3 of operation. On a 30 year lifecycle basis System 2 leaves the project a US $ 261000 net benefit over System 1 (see figure 4).

**Table 3. Operation cost comparison between System 1 and System 2**

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of romos</td>
<td>R</td>
<td></td>
<td>41</td>
</tr>
<tr>
<td>Water demand (m3/room/day)</td>
<td>wd</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>According to Colombian regulation</td>
<td>oi</td>
<td></td>
<td>75%</td>
</tr>
<tr>
<td>Occupation index for hotels in Medellin (%)</td>
<td>dd</td>
<td>r<em>wd</em>oi</td>
<td>15.4</td>
</tr>
<tr>
<td>Daily water demand (m3/day)</td>
<td></td>
<td></td>
<td>5611.9</td>
</tr>
<tr>
<td>Total water demand (m3/year)</td>
<td>WD</td>
<td>dd*365</td>
<td>534.4</td>
</tr>
<tr>
<td>Total rainwater (m3/year)</td>
<td>RW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total groundwater withdraw (m3/year)</td>
<td>GW</td>
<td></td>
<td>3650.0</td>
</tr>
<tr>
<td>Grey water reuse (m3/year)</td>
<td>GyW</td>
<td></td>
<td>1571.3</td>
</tr>
<tr>
<td>Dependency on water sources external to the watershed (m3/year)</td>
<td>DEW</td>
<td>System 1 = WD/(1-Unaccounted for water from table 1)</td>
<td>9353.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>System 2 = WD - GW - RW - GyW</td>
<td>-143.8</td>
</tr>
<tr>
<td>Total wastewater discharge (m3/year)</td>
<td>WW</td>
<td>System 1 = WD + GW</td>
<td>9261.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>System 2 = WD - GyW</td>
<td>4040.6</td>
</tr>
<tr>
<td>Supply water costs (US $/m3)</td>
<td>wc</td>
<td></td>
<td>0.86</td>
</tr>
<tr>
<td>Supply annual costs (US $/year)</td>
<td>SWC</td>
<td>WD*wc</td>
<td>4.826</td>
</tr>
<tr>
<td>Sanitation charge (US $/m3)</td>
<td>sch</td>
<td></td>
<td>1.3</td>
</tr>
<tr>
<td>Sanitation annual costs (US $/year)</td>
<td>SnWC</td>
<td>(WD+GW)*sch</td>
<td>12.040</td>
</tr>
<tr>
<td>Total water system operation costs (US $/year)</td>
<td>WOC</td>
<td>SWC + SnWC</td>
<td>16.867</td>
</tr>
<tr>
<td>Difference</td>
<td></td>
<td></td>
<td>(11.171)</td>
</tr>
</tbody>
</table>
In spite of requiring higher investment costs, an alternative ecoefficient water management system shows to be the best choice in order to reduce both economic and environmental costs for this case of study. Dependency on external water sources and storm water discharge might get down to zero, as total water demand and wastewater discharge might reduce down to 45% at a financial present net cost of 53% as compared to a conventional water management system.

DISCUSSION

Aburrá Valley urban water management is characterized by a high dependency on external water sources, a high unaccounted for water index, a non-regulated groundwater withdraw, a low level of wastewater treatment and no policies on storm water discharges, leading to a vulnerable, inefficient, pollutant system. Most Colombian and Latin-American cities might be described likewise (Howe, Butterworth, Smouth, Duffy, & Vairavamoorthy, 2012; Domenech, 2011)

These concerns are being addressed from centralized approaches such as upgrading supply systems and building new wastewater treatment facilities, but the role of end users is not yet being considered a key issue. This paper shows that buildings, as end water users, would significantly improve the whole system performance by reducing dependency, inefficiency and pollution, while significantly reducing operational costs, leaving in fact economic benefits on a lifecycle basis (Penagos, 2007; Bedoya, 2011)

The model described here may be adopted by building projects along the Aburrá Valley, similar approaches might be analyzed, developed and implemented in other Colombian and Latin-American Cities, which will continue expanding in coming years under uncertain scenarios concerning incidence of climate change on water availability, which is already a critical threat to human development in the region. This study would be also a useful base for governments in order to promote policies and regulations encouraging sustainable water management for healthier cities (Howe, Butterworth, Smouth, Duffy, & Vairavamoorthy, 2012; Penagos, 2010)

REFERENCES


Session 6D : Tools and methods/ framework

PLEA2014: Day 2, Wednesday, December 17
14:10 - 15:50, Trust - Knowledge Consortium of Gujarat
Energy certification process in Chile: steps to dynamic simulation of buildings’ energy performance.

Massimo Palme, PhD
Catholic University of the North
Email mpalme@ucn.cl

ABSTRACT
This paper presents comparative studies among dynamic simulation and steady-state evaluation (degrees – day) for residential building certification in Chile. Energy certification is still young in the country, but its impact in reduction of thermal demand could be very high. The main problem seems to be the use of simplified methods, which have not been tested for all the country’s climates. Chile has a lot of very different scenarios, from the Atacama Desert to the extreme south Patagonia, which are not always well represented by daily average temperatures. The Chilean National Energy Certification System started in 2013 to qualify residential buildings, most of them by using steady-state evaluation. However, in the northern deserts of the country, dynamic simulation is needed to permit a quality work of certification. This paper presents 21 dwellings located in the city of Antofagasta, simulated by using normative software CCTE and also evaluated by using the simplified normative method developed by the Government. Results shows important differences in the final results, both in terms of estimated thermal demand and final etiquette obtained. Steady-state evaluation definitively seems to be not very useful for the desert climate, even in the coast region, were thermal oscillation is relatively low because of the Ocean’s effect.

INTRODUCTION

In 2013, The Chilean Government introduced the National Energy Certification System for Dwellings. The system is voluntary but the Ministry of Housing has the intention to make it mandatory by 2015. The system assigns two different energy classes: one relates to architectural parameters (envelope, form, orientation) and the other relates to systems efficiency (heating system, solar energy use for hot water, and photovoltaic panels for electric generation to be used in electricity). The first group of accredited evaluators started to certify social and private projects in order to test the results of system implementation. Two options are managed to estimate heating energy demand: simplified steady state option that uses degree-day concept and fully dynamic simulation by using CCTE software (MINVU, 2012).

Chile is a country that extends from a latitude of 18 South (Arica) to 56 South (extreme south Patagonia). For this reason, in Chile all kind of climates can be detected, from arid to cold, from mountain to tropical. However, the national certification system only considers heating needs of the central and southern zones. The climate classification developed to use the degree-day concept divides the country in seven zones, plus two sub-zones (extreme south and north), not considering day-night thermal oscillations to distinguish locations with the same average temperature but very different maximum and minimum temperatures (MINVU, 2008b).
Thermal zones defined by Ministry of Housing are different with respect to climate zones defined by norm NCh 1079 (2008) that consider longitude and altitude as well as latitude defining Chile’s climates. This contradiction has been mentioned in the country as one of the most important limitations of the National Energy Certification System; see for example Bustamante (2009).

In northern regions of the Country, the system does not appear to be completely useful, because of a lack of consideration in regards to cooling demand and because of the simplified options, which don’t consider thermal inertia of construction. To reach a good energy class (starting from “D”), in the north zones dwellings have to have less than 75% of the thermal demand and less than 80% of total energy consumption in respect to the reference building. The reference building has the same size and form of the analyzed building, but mandatory compliance in materials and average orientation.

In addition, low heating demand in the North leads to poor energy labeling, because of the limitation in reference building demand (if reference building has an estimated heating demand lower than 30 kWh/m2, thermal performance is not calculated and only hot water and electricity are considered to assign the energy class). To investigate discrepancies between the simplified method and dynamic full simulation, a social dwelling project was selected as a case study.

**METHODOLOGY**

In this research, 21 dwellings are evaluated by using steady-state method and also simulated by using dynamical software CCTE. Then, a comparison of results is done, searching for differences in heating demand and in the final energy class assigned to each dwelling.

**Case study “Tres Marías”**

Dwellings located in the city of Antofagasta, 23° south and 70° west, at Sea level. Figure 1 shows project emplacement and dwelling orientation (courtesy of SERVIU). Site has a little slope, resulting in shadows on the east side and solar access on the west. Moreover, on the east the first line of mountains protects houses from solar access in the morning. On the south and north other buildings generate shadows at specific hours of the day in summer and winter, respectively.

![Figure 1](image1)

Figure 1 House’s emplacement and orientation

Figure 2 shows architectural distribution on two floors. Houses have a floor surface of 45 m² (22 m² on each floor). Figure 3 shows the facade.
Materials and equipment

Construction uses two kind of vertical walls: block walls and external board walls. Block walls are composed by 150 mm of concrete plus 20 mm of insulation (polystyrene) and 10 mm of ceramic finishes. Thermal transmittance is 1.32 W/m²K. External board walls are composed by OSB (11 mm) plus 40 mm of insulation (rock wool) between steel profiles, plus another 20 mm of insulation (polystyrene) and 10 mm of ceramic finishes. Thermal transmittance is 0.88 W/m²K. Roof is made of block work (130 mm) plus 100 mm of insulation (rock wool). Thermal transmittance is 0.38 W/m²K. Floor is composed by blockwork. Door is made of pressed wood, thermal transmittance 3.7 W/m²K. Windows are single glazed, with thermal transmittance of 5.3 W/m²K and solar factor 0.87. Table 1 resumes transmittance values of construction elements. Transmittances have been calculated as indicated in Chilean norm NCh 851 (2008), NCh 853 (2008) and Thermal Norm of MINVU (2008a).
Table 1. Walls and windows properties

<table>
<thead>
<tr>
<th>Wall</th>
<th>Transmittance (W/m²K)</th>
<th>Thickness (mm)</th>
<th>Solar factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blockwork wall</td>
<td>1.32</td>
<td>180</td>
<td>0</td>
</tr>
<tr>
<td>Board wall</td>
<td>0.88</td>
<td>81</td>
<td>0</td>
</tr>
<tr>
<td>Roof</td>
<td>0.38</td>
<td>230</td>
<td>0</td>
</tr>
<tr>
<td>Floor</td>
<td>3</td>
<td>230</td>
<td>0</td>
</tr>
<tr>
<td>Door</td>
<td>3.7</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>Window</td>
<td>5.3</td>
<td>6</td>
<td>87</td>
</tr>
</tbody>
</table>

Dwellings do not have heating systems. Hot water system is electric boiler with 150 dm³ deposit. No solar panels are considered for hot water or electricity production. Electricity is considered in certification as standard system. No other appliances are considered.

RESULTS AND DISCUSSION

Steady state evaluation

21 dwellings were evaluated, first by steady state method. The system considers a reference building that has the same form of the project, compliance materials and average orientation. Reference building has in most cases a heating demand of less than 30 kWh/m² year. As a result, most dwellings facing south or north are not evaluated in terms of heating demand. Only the dwelling numbers 1, 7, 12 and 17 are evaluated. East and west dwellings are also evaluated, because of the higher exposed surface. All dwellings are evaluated in terms of hot water production (electric system).

In the Chilean system, the architectural energy class assigned to a dwelling depends on the thermal zone where the dwelling is placed. In northern deserts, to attain an “E” label, the dwelling must have a thermal demand between 75 and 110% of the reference dwelling. Reference dwelling has the same form, average orientation and minimum standard compliance for materials. To reach a “D” class, the dwelling must have a thermal demand between 55 and 75% of the reference. To obtain a “C”, thermal demand has to be between 40 and 55%; to obtain a “B”, between 30 and 40% and to earn an “A”, between 0 and 30%.

System energy class depends on the primary energy consumption; therefore electrical systems for hot water are normally evaluated as “G”. To obtain an “E” label, primary energy consumption has to be between 80 and 110% of the reference; to obtain a “D” has to be between 60 and 80%; to obtain a “C” 45 to 60%; “B” 30 to 45% and “A” less than 30%. This indicator is not dependent on the thermal zone as the heating demand. Table 2 resumes the label correspondence for thermal zone 1 (northern coast deserts of Chile).

Table 2. Energy percentage respect to reference building

<table>
<thead>
<tr>
<th>Label</th>
<th>Demand</th>
<th>Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Label A</td>
<td>0-30</td>
<td>0-30</td>
</tr>
<tr>
<td>Label B</td>
<td>30-40</td>
<td>30-45</td>
</tr>
<tr>
<td>Label C</td>
<td>40-55</td>
<td>45-60</td>
</tr>
<tr>
<td>Label D</td>
<td>55-75</td>
<td>60-80</td>
</tr>
<tr>
<td>Label E</td>
<td>75-110</td>
<td>80-110</td>
</tr>
</tbody>
</table>

Results are resumed in table 3: most of the dwellings have class energy “G” or “F”. The main reason of this result is the impossibility of evaluating dwellings if reference has less than 30 kWh/m² year heating demand. However, the result is illogical, because the dwelling has better values of transmittances than reference building, then a better class is expected (if dwelling has the same demand of the reference, class “E” is assigned).
Table 3. Steady state evaluation results

<table>
<thead>
<tr>
<th>Dwelling</th>
<th>Orientation</th>
<th>Architecture</th>
<th>Systems</th>
<th>Heating demand (kWh/m² year)</th>
<th>Heating reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N</td>
<td>D</td>
<td>E</td>
<td>22.0</td>
<td>42</td>
</tr>
<tr>
<td>2</td>
<td>N</td>
<td>/</td>
<td>G</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>3</td>
<td>N</td>
<td>/</td>
<td>G</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>4</td>
<td>N</td>
<td>/</td>
<td>G</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>5</td>
<td>N</td>
<td>/</td>
<td>G</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>6</td>
<td>N</td>
<td>/</td>
<td>G</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>7</td>
<td>N</td>
<td>D</td>
<td>E</td>
<td>22.2</td>
<td>40</td>
</tr>
<tr>
<td>8</td>
<td>W</td>
<td>E</td>
<td>F</td>
<td>39.4</td>
<td>15</td>
</tr>
<tr>
<td>9</td>
<td>W</td>
<td>E</td>
<td>F</td>
<td>40.2</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>W</td>
<td>E</td>
<td>F</td>
<td>38.2</td>
<td>19</td>
</tr>
<tr>
<td>11</td>
<td>W</td>
<td>E</td>
<td>F</td>
<td>41.1</td>
<td>10</td>
</tr>
<tr>
<td>12</td>
<td>S</td>
<td>E</td>
<td>F</td>
<td>41.7</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>S</td>
<td>/</td>
<td>G</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>14</td>
<td>S</td>
<td>/</td>
<td>G</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>15</td>
<td>S</td>
<td>/</td>
<td>G</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>16</td>
<td>S</td>
<td>/</td>
<td>G</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>17</td>
<td>S</td>
<td>E</td>
<td>F</td>
<td>39.7</td>
<td>5</td>
</tr>
<tr>
<td>18</td>
<td>E</td>
<td>E</td>
<td>F</td>
<td>40.1</td>
<td>8</td>
</tr>
<tr>
<td>19</td>
<td>E</td>
<td>E</td>
<td>F</td>
<td>36.4</td>
<td>17</td>
</tr>
<tr>
<td>20</td>
<td>E</td>
<td>E</td>
<td>F</td>
<td>30.1</td>
<td>21</td>
</tr>
<tr>
<td>21</td>
<td>E</td>
<td>E</td>
<td>F</td>
<td>32.6</td>
<td>19</td>
</tr>
</tbody>
</table>

CCTE simulation

CCTE evaluation uses dynamical simulation of the real and the reference buildings. Because in this case the reference building has the same orientation of the analyzed one, four simulations have been done and reference building results are the average of the four orientations considered (N, S, E and W). Figure 4 shows the CCTE model of East/West dwellings.

All dwellings are analyzed because in this case the reference building has a heating demand higher than 30 kWh/m² per year. In general, analyzed dwellings are better than the reference in terms of heating demand (between 20% and 30%) and very close to the reference in terms of energy consumption, because of the low efficiency of the electric boiler.

Figure 4  CCTE model used in simulations
Results in this case are more consistent, because all dwellings have a better or at least the same energy class of the reference building. The reason is that dynamic simulation leads to more than 30 kWh/m² year of heating demand, which permits the obtainment of the architecture class. Table 4 summarizes the results.

<table>
<thead>
<tr>
<th>Dwelling</th>
<th>Orientation</th>
<th>Architecture</th>
<th>Systems</th>
<th>Heating demand (kWh/m² year)</th>
<th>Heating reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>D</td>
<td>E</td>
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<td>D</td>
<td>E</td>
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<td>E</td>
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<td>E</td>
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<tr>
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<td>E</td>
<td>E</td>
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<td>E</td>
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<td>9</td>
<td>W</td>
<td>E</td>
<td>E</td>
<td>36.1</td>
<td>24</td>
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<tr>
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<td>E</td>
<td>E</td>
<td>34.9</td>
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</tr>
<tr>
<td>11</td>
<td>W</td>
<td>E</td>
<td>E</td>
<td>34.2</td>
<td>27</td>
</tr>
<tr>
<td>12</td>
<td>S</td>
<td>E</td>
<td>E</td>
<td>35.9</td>
<td>19</td>
</tr>
<tr>
<td>13</td>
<td>S</td>
<td>E</td>
<td>E</td>
<td>27.9</td>
<td>19</td>
</tr>
<tr>
<td>14</td>
<td>S</td>
<td>D</td>
<td>E</td>
<td>26.3</td>
<td>28</td>
</tr>
<tr>
<td>15</td>
<td>E</td>
<td>D</td>
<td>E</td>
<td>26.3</td>
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<tr>
<td>16</td>
<td>S</td>
<td>E</td>
<td>E</td>
<td>31.9</td>
<td>23</td>
</tr>
<tr>
<td>17</td>
<td>S</td>
<td>E</td>
<td>E</td>
<td>40.1</td>
<td>26</td>
</tr>
<tr>
<td>18</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>32.2</td>
<td>34</td>
</tr>
<tr>
<td>19</td>
<td>E</td>
<td>D</td>
<td>E</td>
<td>30.1</td>
<td>32</td>
</tr>
<tr>
<td>20</td>
<td>E</td>
<td>D</td>
<td>E</td>
<td>35.5</td>
<td>26</td>
</tr>
</tbody>
</table>

North-facing dwellings have “D” class assigned (most of them), because of better solar access in winter. Some south-facing dwellings also have “D” class because they reach 25% of demand reduction.

Steady-state evaluation leads to unreliable results in most considered cases; because of low heating demand of the climate zone, architecture is not evaluated and only electrical system for hot water production is considered. Dwellings that have better performance than the reference building (between 20% and 30% considering heating demand) are classified as “G” or “F” because of the low efficiency of electric boilers for hot water production. Only two of the north-oriented dwellings are evaluated and classified as “D” in architecture and “E” in energy consumption. On the other hand, CCTE dynamic simulation lead to more realistic results and all the 21 dwellings are evaluated, obtaining architectural class “D” or “E” (depending on energy saving: to obtain “D” class energy saving has to be more than 30%). In this case, all consumption classes are “E”.

CONCLUSION

The energy certification process in Chile is focused on heating demand reduction, the most important problem in southern regions of the country. Northern regions are considered to be temperate, and building overheating is nowadays resolved by natural ventilation. However, some considerations have to be made. First, the energy certification system has two options, simplified evaluation and dynamic simulation. In the South of Chile, both methods lead to the same energy class in most cases, but in the North many cases have different classes, as discussed in this paper. Thermal mass effect and especially 30 kWh/m² limitations in reference building to evaluate architecture thermal demand are problems in the current system.
Second, natural ventilation is supposed to be sufficient to cool buildings, but in the future some urban climate changes could modify this situation. Global warming in northern Chile will probably be very high (up to 5 degree increase of temperature in the middle of the century), heat island effect will be present in cities of middle size, tall buildings construction in the first coast line will act as a blockage to sea wind. All these factors are clearly indicated as a danger for overheating in built environment; see works of Chilean Government (2013), Palme (2014), Valenzuela (2013).

Finally, economic development of the country, especially of the northern mining zones, will have the consequence that people will search for better comfort standards, and install air conditioners to avoid overheating in residences. This could be very dangerous, because it will add to an increase in global warming. In this conclusion, it appears very important to recommend the introduction of a dynamic system of energy certification, taking into account heating and cooling demand, as well as the removal of the 30 kWh/m$^2$ limitation in reference building heating demand.

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Effects of Aggressive Energy Efficiency Regulations on an Unprepared Building Sector using Uncertainty Analysis

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ABSTRACT

Building Assessment Tools (BATs) are widely used to estimate the performance of building and to assist designers in making decisions. As building codes and rating systems move from prescriptive to performance-based metrics, BATs are increasingly used to show compliance. BATs use computational methods and the results are mostly in a single annualised metric. However, the scientific community has shown that aleatory factors such as occupant behaviour and weather make the potential energy use of a building far from being a single deterministic value. Also, it is known that there is a significant deviation between predicted (at design stage) and actual energy use in buildings. These variations reduce the credibility of the predictions, questioning the acceptance of BATs results without considering underlying errors. This problem is amplified in developing nations because of under-policed construction sector. To address this, our work analyses uncertainty in a typical air-conditioned multi-storey residential building’s performance in Delhi and shows implications of variable inputs in the results.

The paper first reviews the use of BATs and existing studies on simulation uncertainty. Then uncertainty is evaluated in energy simulation of a sample building, including effects of inconsistent and construction practices. EnergyPlus is then fed values sampled (by Monte-Carlo method) from probability distribution functions of inputs (building fabric and operational parameters). Further sensitivity and uncertainty analysis of the results is performed. From the 3500 simulations, the most sensitive inputs found were internal gains; cooling setpoints and infiltration. The variation in cooling demand and discomfort hours is more than double between the best and worst case.

INTRODUCTION

Anthropogenic activities in the last decades have altered climatic stability, water cycles and natural habitats. At the time of writing, atmospheric CO\textsubscript{2} concentration is 399 ppm (Tans & Keeling, 2014) (Mauna Loa Observatory); 37% more than the highest concentrations in 8,00,000 years (EPICA DATA) (Lüthi, D., et al., 2008). The annual mean surface temperatures are rising due to greenhouse gasses
(GHG) concentration increase. It is estimated to rise by 0.3 to 4.8 in next 100 years (IPCC, 2013).

Governments around the world are evaluating the impacts of climate change on their economies. The Indian economy could be considered as climate sensitive as many sectors are wholly or partially dependent on seasonal weather cycles. Indian meteorological data shows a 0.4°C increase in the mean annual air temperature in the past 50 years (INCCA, 2010). Also, intensity and frequency of extreme weathers like heat waves, dry spells and heavy rainfall have increased (INCCA, 2010). Data assessments indicate warmer climates in India, with temperatures rising by 2-4°C by 2050 (INCCA, 2010).

Buildings have a significant impact on the environment. Infrastructural development of cities leads to rapid growths in construction, causing 25% of India’s current carbon emissions (Parikha, et al., 2009). Buildings are responsible for 40% of energy use and 33% of GHG emissions globally (UNEP, 2009). The energy use in buildings includes operational and embodied energy and 80% of building’s life cycle energy is by the former (Gregory A. Keoleian, 2008) (Chris Scheuer, 2003). Also, the building sector has the highest and most cost-effective potential for providing long-term, energy and GHG emission savings globally (IPCC, 2014). This has also been observed at a national level in India (PC : IEP, 2006).

Buildings assessment tools (BATs) are widely used for detail assessment of energy use in buildings. Buildings are complex systems and their energy use assessments dependent on many parameters. However, in most cases, these parameters are variable and not certain (Pettersen, 1994). These uncertainties arise due to lack of knowledge in simulation inputs, improper construction methods, approximate weather data and unpredictable occupant behaviour. Statistical analysis of energy simulations has been seen as a powerful tool in predicting this variability (MacDonald, et al., 1999) (Blight & Coley, 2013). In this paper, we assess the effect in outputs by the variation of some building design input parameters, which are regulated by energy saving related polices.

This paper begins with a background section reviewing: (1) the use of BATs for design decision making; and (2) existing studies that analyse uncertainty in simulation results. This is followed by assessing variations in input parameters in energy simulations of a residential building in Delhi, including the effects of construction processes used. The paper focuses on uncertainties in the fabric (i.e. thermal properties) and operational parameters. It concludes by performing uncertainty and sensitivity analysis of the input variables for the output of cooling and heating energy use and discomfort hours.

BACKGROUND

Use of Building Assessment Tools (BATs) for code compliance to reduce energy use in buildings

BATs are widely used to estimate energy performance of building designs. These tools assist designers in the decision making process by providing comparative and detailed assessments of building performance under various design conditions and strategies. Due to their capabilities to model building systems and physical phenomena in detail, they are used make predictions about the performance of a building under a wide range of scenarios. But, in most cases, these tools rely on input parameters that are either assumed or averaged to provide deterministic outputs, i.e. predict future scenarios that are known to be uncertain (Haldia & Robinson, 2011) (de Wilde & Tian, 2009) (Blight & Coley, 2013) (Ramallo-González, et al., 2013). This results in simulations that are fundamentally unrealistic and have shown to have errors exceeding 100% (Brohus, et al., 2009) (Demanuele, et al., 2010).

Apart from the issues of uncertain results due to deterministic nature BATs’ results, construction techniques that are widely used in India might result in underperforming fabrics even when conforming to ECBC specifications. Uncertainty analysis (with the inclusion of construction process deficiencies) could provide a contextual picture, with a more robust understanding of the likely outcomes of measures in the ECBC.

**Uncertainty and applicability of BATs**

Most BATs use deterministic algorithms to predict a single value for the building performance. Actual prediction is more complex. Uncertainty in building simulations arise due simplifications in computation process and building complexity to reduce computing time; or because of unknown and erroneous input parameters (Clarke, 2001). Simplification generally occurs in inputs like weather data, material properties (like U-values), geometry etc. There, only the mean or most probabilistic values are used. This provides an unrealistic picture as value of each input can vary within a range of data. This theoretical simplification gives a range for the value calculated but not a credible result (especially when results depend on many such inputs). Adapted from Ramallo-González’s PhD thesis (Ramallo-González, 2013) and other similar works, we classify the types of uncertainty into three groups:

1. Environmental: Uncertainty in weather data because of use of nearest weather station’s synthetic weather file and uncertainty in prediction of changing climate.
2. Workmanship and quality of building elements: Differences amid the design and the real building: Conductivity of insulation and thermal bridges, infiltration amount or U-values of walls and windows.

Additionally there is divergence in computation i.e. the approximation and uncertainty in computational formulas in the simulation tools. Above groups, describe the broad areas of uncertainty. Based on the reasons of existence they can also be divided in two types, aleatory and epistemic. Aleatory uncertainties represent the randomness nature of some variables. Epistemic uncertainties are due to lack of knowledge (Sandia Lab, n.d.). Uncertainties make it impossible to find, for some inputs, a value that is actually true; observed by Newton when building energy simulations were in their infancy (Newton, et al., 1988):

“…the choices of climatological data and occupancy patterns are not easy and, in many cases, there is no single correct value.”

Assessment of uncertainties at all levels is required to get results with confidence intervals. It is the only way to have realistic assessments and a better understanding of energy simulation results. In this study, aleatory and epistemic uncertainties in groups 2 and 3 would only be considered.

Areas where consideration of uncertainty can play a major role are in energy-savings performance contracts and in certification and code compliance for green and ultra-energy efficient buildings (e.g. LEED Ratings, or codes like EPBD in Europe or ECBC in India.). Since BATs are used to inform and evaluate designs, there is a significant risk (could be financial or of occupant comfort) if the real and predicted performance vary. Additional information about the uncertainty (like confidence intervals) would facilitate a more informed decision by the designer. Therefore, the argument of this paper is to prove how BATs should not be relied upon in a deterministic manner but in a probabilistic way, to provide the designers with stochastic indicators of the future performance or demand of the building. In this paper, we have used these indicators to verify the impact of uncertainties in workmanship and operations in the final energy performance of buildings.

Most of the studies discussed in the next section take the variation in input parameters as a normal distribution. These variations when seen practically do not necessary apply. E.g. actual measurements of accumulated electricity use in the UK (Carbon Trust, 2011) show a non-normal distribution. For that reason, in this paper, probability distributions that are more representative have been used. They
Existing studies on uncertainty in building energy design

There have been many studies in the last two decades vis-à-vis uncertainties influencing the results of BATs. However, the studies are mainly theoretical and have not been applied in real world problems. Pettersen’s work is one of the first studies that looked at the effects of climate variability, building characteristics and occupants (Pettersen, 1994). Using a statistical simulation method based on Monte Carlo Analysis (MCA), Pettersen studies the variation of energy use in dwellings, which was about 15%.

There is little literature showing the impact of uncertainties in specific inputs. De Wit studies the effect of uncertainty as well as relative importance of non-linear effects and parameter interactions on thermal comfort, using factorial sampling (de Wit, 1997) (de Wit & Augenbroe, 2002). He also explores effect of assumptions in measurement and simplification in calculations. Domínguez-Munoz studies the impact of uncertainties on the peak-cooling loads using MCA with a global sensitivity analysis to identify the most important uncertainties (Domínguez-Munoz, et al., 2010).

Hopfe et al. have also worked on uncertainty and sensitivity analysis for thermal comfort prediction to help in design decision making and optimisation (Hopfe, et al., 2007). Another paper written by Hopfe and Hensen (Hopfe & Hensen, 2011), covers the implication of uncertainties on energy consumption and thermal comfort using a theoretical case study and studying various building performance parameters using as inputs physical, design based, and scenario variables with their standard deviation.

Several works of MacDonald have focused on quantifications and application of uncertainty on the predictions of demand using building simulation software (MacDonald, et al., 1999), (Macdonald & Strachan, 2001), (MacDonald, 2002). His thesis (MacDonald, 2002) shows two ways of achieving this: The first way altered the input variables, requiring multiple simulations of systematically altered models and the subsequent analysis of the changes, with differential, factorial and Monte Carlo sampling. The second way altered the algorithm of BAT to include uncertainty at all computational stages. Applying these changes, the predicted uncertainty in thermo-physical properties, casual heat gains and infiltration rates was quantified and was compared with MCA and differential analysis. Further, the issue of non-convergence building simulations was discussed (MacDonald & Clarke, 2007). The non-convergence was caused by introduction of new uncertainty terms that were uncorrelated to existing terms.

In other recent works, Wang examines uncertainties in energy consumption due to annual weather variation and building operations using MCA (Wang, et al., 2012). Eisenhower enlarged uncertainty and sensitivity analysis to take into account the influence of 1000+ parameters (Eisenhower, et al., n.d.).

Uncertainties in India Context

The uncertainties in building input parameters are particularly relevant in the Indian context because of the techniques of construction used. Indian standards, codes and practices for construction allow significant tolerances and deviations in the fabric (IS: 2212: 2005 (BIS, 1991)), (IS4021: 1995 (BIS, 1995)), (IS: 4913-1968 (BIS, 2001)), (IS: 1948: 1961 (BIS, 2006)). General construction practice shows that most of the construction procedures are not consistent. From mixing of concrete by rough estimation to fabrication of wood framed doors and windows, all the work is done on-site. The quality is mainly dependent on the skills of the professionals. The doors and windows, constructed on site have gaps created at the time of installation which are filled with plaster (IS: 4913-1968 (BIS, 2001))(IS: 3935: 1966 (BIS, 1986)). This technique compromises the U-value of the construction and airtightness and it might lead to thermal bridging because of the improper sealing and frame effects.

The bricks used for construction also have variation in their properties due to the variation in the composition of clay used and non-consistency of the firing process (Sarangapani, Reddy, & Jagadish, 2002). Small ducts for building services (plumbing pipes and electric conduits) are also embedded in the walls (SP20 (BIS, 1991)), (IS: 2212: 2005 (BIS, 1991)). This reduces the wall’s thermal effective thickness, affecting the overall U-value. These inconsistencies in the fabric can create variation in the actual energy use. We show here a method to quantify this effect. We think it is a powerful tool for...
policymakers, as it will enable them to understand the fruitless and somewhat detrimental impact of stringent energy policies on an un-prepared industry. In other words the building sector, at present, is not prepared for incorporating energy policies unless the functioning of the whole sector is modified. The building components used should be quality controlled, ensuring consistency in performance then only the energy polices can be implemented. Such recommendations are incorporated in ECBC, e.g. supply-chain improvements to ensure availability of certified products, but are not exercised in practice.

![Figure 1 Uncertainty Parameters included in existing studies](image)

In order to estimate the overall effect, uncertainties due to variation in inputs, discussed earlier, have to be combined with the impact of construction procedures in India on the building fabric. Studies exploring the latter issue were not found. Based on past studies (Heo, et al., 2012), (de Wilde & Tian, 2009), (Hopfe, et al., 2007), (MacDonald, 2002), (Wang, et al., 2012), (Pettersen, 1994) on uncertainty (Figure 1) and assuming the uncertainties because of local factors, uncertainties in various parameters are estimated. A more accurate finding of the distributions is suggested for further work. For this paper, we have used generic distributions that could be changed for each region to obtain more accurate results.

In this paper, a methodology for uncertainties related to thermal properties, temperature set points, internal loads and ventilation is presented. Weather, system efficiencies and other operation parameters have not been considered in this study, but the method can be extrapolated to include these too.

METHODOLOGY

Uncertainty propagation, sensitivity analysis (SA) and uncertainty analysis (UA) has been carried out in this paper in the following manner (It has been assumed in this study that the input variables are not dependent):

1. A baseline building with fabric based on ECBC specifications was created as reference point.
2. Based on existing studies, six major uncertainty factors were selected and the calculations of their variability with probabilistic distributions defined.\(^1\)
3. The deviation in conditioning loads and occupant comfort in relation to the input variables was explored. Random MCA sampling is used for input variables based on their determined probability distributions. Those samples are used for multiple EnergyPlus runs for Propogation of uncertainty.
4. Multiple Linear Regression (MLR) is done to assess the sensitivity of variables - sensitivity analysis (SA).
5. A mean and peak variation for each output is calculated to assess the uncertainty - uncertainty analysis (UA).

\(^1\) It has to be calculated as there was no data found that could provide with the variations of these factors.
SIMULATION

Building Plan

The reference building is a three story residential building in New Delhi based on normal practice. The floor area is 75 m$^2$ (total built up area of 225 m$^2$). The floor-to-floor height is 3 meters. The building has longer axis along E-W direction. The Living (4.275m*4.8m – with toilet)/Dining (2.915m*2.8m) room is in North and the bedrooms are located on in SE (3.915m*4.21m) and SW (3.235m*4.21m – with toilet) corner; the kitchen faces West (2.8m*1.885m). Each room is taken as a separate zone.

Construction and operation

The building has a mixed mode running system with natural ventilation happening between heating and cooling setpoints. Table 1 below shows the input parameters for the initial base case.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Remarks</th>
<th>Room type</th>
<th>Occupancy schedule</th>
<th>Internal gains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>RCC and brick infill panel walls</td>
<td>Bedroom</td>
<td>Weekdays</td>
<td>2200-0600</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Weekends</td>
<td>2200-0600;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1400-1600</td>
</tr>
<tr>
<td></td>
<td>Walls</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.44 W/m2K ; Insulated brick cavity walls</td>
<td>Kitchen</td>
<td>Daily</td>
<td>0600-0800;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1200-1400;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1900-2100</td>
</tr>
<tr>
<td></td>
<td>Windows</td>
<td>Living/dining</td>
<td>Weekdays</td>
<td>0600-1000</td>
</tr>
<tr>
<td></td>
<td>3.3 W/m2K; Openable, and air filled clear double glazed (6-12-6)</td>
<td></td>
<td>Weekends</td>
<td>0600-0200;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1600-2200</td>
</tr>
<tr>
<td></td>
<td>Roofs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.40 W/m2K; Insulation covered RCC slabs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Setpoints</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heating -19°C; Cooling - 24°C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Two outputs were obtained from the simulations: (1) the total heating and cooling energy use; and (2) the number of non-comfortable hours of the occupied spaces. The standard ASHRAE 55-2004 Predicted Mean Vote (PMV) was used to define non-comfortable hours (integrated in EnergyPlus).

Variable inputs and their distributions

As described earlier, based on existing research, the uncertain factors taken are fabric thermal properties, temperature set points, and ventilation. The section below describes the input variables and Table 2 shows the base case, upper and lower values distributions selected and their variation graphs.

**Internal loads**

Internal loads are one of the most significant aspects governing the building performance. Internal loads cannot be negative, thus, a normal distribution is not ideal to represent the variation in internal loads. In previous studies (Schnieders & Hermelink, 2006) internal loads have been assumed to vary in a symmetric distribution. However, in actual measurements done on accumulated electricity use in the UK (Carbon Trust, 2011) it has been seen that the electricity use has been an asymmetric distribution.

**Infiltration rate**

Infiltration is primarily due to construction defects, gaps and cracks. Onsite fabrication of windows and high tolerances in construction of fenestration increase infiltration drastically.

**Temperature set points**

Set points depend on personal preferences. Variation in heating and cooling set points is assumed to follow a normal distribution as these variables are far from zero, therefore could be assume symmetric. During sampling, if the heating set point is less than 2 degrees below the cooling set point, the sample is rejected and another one calculated as this is considered the width of comfort (ASHRAE, 2009).
Wall U-value

Wall U-Value has a large impact on energy calculations. Standard deviation in U-values because of measurement techniques is 5% (MacDonald, 2002). Moreover, due to construction techniques, detailing and material manufacturing processes, the variation is more. It is more likely that errors in manufacturing processes and workmanship lead to a larger U-Value (lower quality).

Window U-value

The in-situ construction of windows will affect the overall U-Values. The variation in the overall U-Values is mimicked by changing in thickness of the cavity as we consider it is the parameter of the window more likely to vary in a production process with poor quality control.

Table 2 Uncertain parameters chosen and their distributions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Element changed</th>
<th>Units</th>
<th>Base</th>
<th>LB</th>
<th>UB</th>
<th>Distribution Name</th>
<th>Distribution details</th>
<th>Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Loads</td>
<td>Equipment Loads</td>
<td>W/m²</td>
<td>20</td>
<td>10</td>
<td>50</td>
<td>Scaled inverse chi-squared</td>
<td>μ = 20 ; ν² = 2</td>
<td></td>
</tr>
<tr>
<td>Infiltration Rate</td>
<td>Space Infiltration Design Flow Rate</td>
<td>Ach/h</td>
<td>0.75</td>
<td>0.25</td>
<td>2</td>
<td>Log Normal Distribution</td>
<td>σ = 0.45 ; μ=0</td>
<td></td>
</tr>
<tr>
<td>Cooling Set points</td>
<td>Thermostat</td>
<td>°C</td>
<td>24</td>
<td>22</td>
<td>26</td>
<td>normal</td>
<td>μ = 24 ; σ²=1</td>
<td></td>
</tr>
<tr>
<td>Heating Set points</td>
<td>Thermostat</td>
<td>°C</td>
<td>19</td>
<td>17</td>
<td>21</td>
<td>normal</td>
<td>μ = 19 ; σ²=1</td>
<td></td>
</tr>
<tr>
<td>Wall U-Value</td>
<td>Insulation Cond.</td>
<td>W/mK</td>
<td>0.03</td>
<td>0.02</td>
<td>0.11</td>
<td>inverse gaussian</td>
<td>μ = 0.5 ; λ = 4</td>
<td></td>
</tr>
<tr>
<td>Window U-Value</td>
<td>Air Gap</td>
<td>mm</td>
<td>0.013</td>
<td>0.010</td>
<td>0.016</td>
<td>normal</td>
<td>λ = 0.013 ; σ²=0.0015</td>
<td></td>
</tr>
</tbody>
</table>

LB=lower boundary; UB=upper boundary; μ=mean, σ²=standard deviation; λ=shape parameter; ν =degrees of freedom and τ²=scale parameter

SIMULATION RESULTS ANALYSIS

Based on the values ranges and the PDFs, values between the upper and lower bounds are selected by random monte-carlo sampling for multiple simulation runs. Results of all 3427-simulation runs are analysed to propagate the uncertainty and to perform a SA and UA.

Uncertainty propagation

The histograms in Figure 2 show variation in heating and cooling energy use and non-comfortable hours (minimum, average and maximum of all zones). Being a cooling dominated climate the cooling energy use is in GJ and heating energy use is in MJ. The cooling energy use in the building varies between 150 GJ and 385 GJ with the peak frequency at 225 GJ. Heating energy use shows a very large variation with values ranging from zero to 17GJ. The peak frequency is at 100 MJ of energy with the average use of 446 MJ. The graph is presented in logarithmic scale. For the non-comfortable hours the values vary from 0 to 2180, 0 to 3110 and 0 to 4960 for minimum, average and maximum for all the rooms respectively.
Sensitivity Analysis (SA)

Sensitivity of each input, for the outputs is gauged through regression. The analysis is similar to one in (Blight & Coley, 2013). Table 3 shows adjusted R Square value and Significance F for regression.

<table>
<thead>
<tr>
<th>Output Variable</th>
<th>adjusted R square</th>
<th>Significance F</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Energy Use</td>
<td>0.9869</td>
<td>0</td>
<td>Regression model fits the outputs very well.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Coefficient values are significant.</td>
</tr>
<tr>
<td>Heating Energy Use</td>
<td>0.5460</td>
<td>0</td>
<td>There are more factors which affect the output. Coefficient values are significant</td>
</tr>
<tr>
<td>Non Comfortable Hours Min</td>
<td>0.8635</td>
<td>0</td>
<td>Regression model fits the outputs very well.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Coefficient values are significant.</td>
</tr>
<tr>
<td>Non Comfortable Hours Avg</td>
<td>0.8183</td>
<td>0</td>
<td>Regression model fits the outputs very well.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Coefficient values are significant.</td>
</tr>
<tr>
<td>Non Comfortable Hours Max</td>
<td>0.7213</td>
<td>0</td>
<td>There are some factors more affecting the output. Coefficient values are significant</td>
</tr>
</tbody>
</table>

It can be seen that adjusted R square values are high (except heating energy use) showing high accuracy of the data. Significance F value is 0. This shows that the variables are still important and relevant enough and that the results are not by chance. The regression analysis is done at 95% confidence interval and P-value <0.05 in Table 4 shows that those input variables are significant for the output. Green means significant and red means insignificant.

<table>
<thead>
<tr>
<th>Insulation Conductivity</th>
<th>Window Air Gap</th>
<th>Internal Loads</th>
<th>Cooling Set points</th>
<th>Heating Set points</th>
<th>Infiltration Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Energy</td>
<td>0</td>
<td>0.79</td>
<td>0</td>
<td>0.13</td>
<td>0</td>
</tr>
<tr>
<td>Heating Energy</td>
<td>0.00003</td>
<td>0.48</td>
<td>0.000001</td>
<td>0.0001</td>
<td>0</td>
</tr>
<tr>
<td>NCH Min</td>
<td>0.0003</td>
<td>0.59</td>
<td>0</td>
<td>0.34</td>
<td>0</td>
</tr>
<tr>
<td>NCH Avg</td>
<td>0.023</td>
<td>0.29</td>
<td>0</td>
<td>0.29</td>
<td>0</td>
</tr>
<tr>
<td>NCH Max</td>
<td>0.23</td>
<td>0.21</td>
<td>0</td>
<td>0.33</td>
<td>0</td>
</tr>
</tbody>
</table>

Residuals for each output also show randomness and equal distribution about the x-axis thus showing homogeneity and linearity and verifying the credibility of the regression.

The standardised coefficients are found by dividing the ‘distance from the mean’ by the standard deviation of each variable, and can be used to directly compare the relative contributions from...
independent factors. The taller the bar, more influential is the input on the output. Positive means a direct relation between the change and vice-versa.

The most influential variables for cooling energy use are internal loads and cooling set points with infiltration and wall U-value next. Window air gap does not have any big impact on the output but does change a little. Similarly, for heating energy use infiltration and heating set points are factors that are more dominant. For the NCH hours Infiltration, internal loads and cooling set point affect the outputs the most.

It can be seen that occupant behaviour is the most important aspect as in most cases; they determine the internal loads and cooling set points. A conservative approach in estimating the internal loads can be quite detrimental when calculating building’s cooling energy needs and comfort. Infiltration and U-value of the fabric also show that construction and proper airtightness is required.

![Figure 3 Standardized regression coefficient comparing the relative influence of the explanatory variables on the dependent variables](image)

### Uncertainty Analysis

The values in all outputs show substantial variation. Table 5 below shows the upper value, lower value, mean value, and standard deviation of the various outputs.

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Maximum Value</th>
<th>Minimum Value</th>
<th>Mean</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Energy (GJ)</td>
<td>384.97</td>
<td>152.36</td>
<td>234.94</td>
<td>31.76 (13%)</td>
</tr>
<tr>
<td>Heating Energy (MJ)</td>
<td>17305.56</td>
<td>0.00</td>
<td>441.30</td>
<td>1150.85 (260%)</td>
</tr>
<tr>
<td>NCH Min (hrs.)</td>
<td>2177.75</td>
<td>0.00</td>
<td>495.17</td>
<td>411.92 (83%)</td>
</tr>
<tr>
<td>NCH Avg (hrs.)</td>
<td>3107.14</td>
<td>0.00</td>
<td>711.02</td>
<td>454.58 (63%)</td>
</tr>
<tr>
<td>NCH Max (hrs.)</td>
<td>4955.50</td>
<td>0.00</td>
<td>1108.89</td>
<td>888.76 (80%)</td>
</tr>
</tbody>
</table>

It can be seen from the results that the variation is very big and outputs have very high percentage of uncertainty. Through the results, it can be seen that occupant behaviour is the most important aspect as in most cases; the occupants determine the internal loads and cooling set points. A conservative approach in estimating the internal loads can be quite detrimental in assuming building’s cooling energy needs. Infiltration and U-value of the fabric also show that construction and proper airtightness is also required.

### CONCLUSION

Through this study, it has been shown that there could be a significant variation in the simulation result output because of the variation in the inputs. Cooling energy use because of occupant usage and construction quality alone could produce variations over the mean of about 13% with the variation in maximum and minimum values of more than 150%. Similarly, non-comfortable hours in the year could have a variation of whole year comfortable to more than half a year uncomfortable. While, the sensitivity
It is seen that the most influential variables in regard to the increase in cooling loads and decrease in comfort are internal gains and cooling set points, both factors primarily governed by occupants. Infiltration and U-value of the walls are similar in importance, both being primarily governed by quality of construction. Therefore, owing to these persistent uncertainties, simulation results should be taken in a more probabilistic manner to ensure that the risk associated with the uncertainties in the inputs is also calculated when making the assessment.

Another important issue that needs to be addressed when performing uncertainty analysis is that the type probability distribution of input variables should be based on realistic factors and measured data. The use of normal distributions might not represent the actual variation in some cases as has been shown here. Fail to use the right distribution could render the methodology misleading.

It is of prime importance that the uncertainty on input variables is considered when performing energy assessment. Obtaining stochastic results encourages constructors and designers to take the adequate measurements to minimise this variation when it has a large impact in the final energy use of the building. This has even more importance in buildings in which low-demands are the aim.

REFERENCES


Blight, T., & Coley, D. (2013). THE IMPACT OF OCCUPANT BEHAVIOUR ON THE ENERGY CONSUMPTION OF LOW ENERGY DEWELLINGS.


Developing Free-running Prototypes for different Climates of Chile

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ABSTRACT
This paper presents results from thermal simulations conducted for a terrace house in Santiago (33°S). Previous findings from field studies concluded that despite the use of polluting space heaters social housing households were unable to heat their homes to an adequate level of warmth, being exposed to noxious pollutant gases and also forced to live in fuel poverty. The studies presented here investigate whether adequate thermal comfort conditions can be provided in free-running buildings, i.e. neither heated nor cooled mechanically, within the economic limitations posed by social housing standards. Results from thermal simulations have evidenced that, through passive heating and cooling design techniques, thermal comfort can be achieved at low costs without any additional energy inputs all year-round. These results will be further used to develop a modular housing prototype for the varied climates of Chile.

INTRODUCTION
Over the last five decades, the development of social housing policies has led most Chilean cities to a scenario of social and environmental exclusion. Driven by a large housing shortage the proliferation of hundreds of thousands of apartment blocks spread around suburban areas created high poverty ghettos, characterised by low quality housing, raised levels of air pollution and degraded thermal environments. The combination of thermally inefficient housing stock and the use of fossil-fuels for space-heating have long been threatening public health and well-being in poor suburban areas. Although studies have revealed high levels of indoor air pollution attributed to the use of unvented space heaters low-income households have been unable to heat their homes to an adequate level of warmth (CENMA, 2011; Ruiz et al., 2010). Moreover, high fuel costs exacerbate vulnerability and forces inhabitants to live in fuel poverty.

With a deepening energy crisis and the prospect of fuel price increases looming large on the horizon, fuel poverty has become a progressively more urgent social issue in Chile. Although the negative impacts of thermally inefficient housing have been largely acknowledged, as well as their adverse effect on poverty, the supply of polluting fuels for residential space heating has remained unquestioned politically. This highlights the question as to whether polluting fossil-fuels are necessary to provide affordable warmth. Previous studies have proved that more thermally efficient housing could reduce space-heating demand without incurring significant extra capital costs (Bustamante et al., 2006; Méndez, 2008), but is it possible to do so under free-running conditions?

THERMAL SIMULATION STUDIES
In order to test whether thermal comfort can be provided without additional energy inputs, parametric simulations were carried out using as a case study a building in Santiago. The aims of this research is to investigate the thermal performance of housing and develop passive heating and cooling design techniques for different climates of Chile. The study here outlines a criteria to evaluate thermal comfort in residential buildings, as well as present results from a series of thermal simulation tests.
conducted to find the appropriate combination of passive designs to achieve thermal comfort at low costs. The results from this will be used to inform the design of a prefab modular prototype, Prototype Zero, proposed to test the research objectives through further thermal simulations for the cities of Antofagasta (23˚S) and Puerto Montt (41˚S). The final outcome of the project will be the design proposal of a net-zero apartment district located in inner-city Santiago.

The building case study was selected from a sample of buildings studied under the present research framework. This provides a reliable base case supported by monitored temperature results and field study observations. The selected scheme corresponds to a three storey intermediate terraced house with a total habitable floor area of 55m², taken from Olga Leiva social housing development. As shown in Figure 1, since the house has a low level of exposure and the insulation of its exterior walls are below minimum standards, this is a U-value of 1.9 W/m²K, the overall heat loss coefficient results to be significantly below an average detached house for the same location.

In order to evaluate the thermal performance of the house in relation to occupants’ preferences, a thermal comfort index is proposed. This provides a weighted indicator of the effective thermal comfort contribution made by each design strategy as well as allowing comparisons to be drawn against final construction costs. As shown in Equation 1, the thermal comfort index expressed here as $\Delta T_c$ sums the hourly difference between resultant operative temperatures and monthly comfort temperatures estimated from an adaptive model of thermal comfort. In order to simplify results, the index is assumed to equal zero when temperatures are outside thermal comfort thresholds.

$$\Delta T_c = |T_{op} - T_c|$$  \hspace{1cm} (1)

Where:
- $T_{op}$ = Operative temperature
- $T_c$ = Monthly comfort temperature

To keep track of the impact of each design parameter over final construction costs, a marginal cost index $\Delta MC$ was proposed. As shown in Equation 2, the index, which is the simple difference between initial construction costs and final construction costs of a given building when incurring any design modification, allowed thermal performance to be optimized against construction costs allocated by current housing programs. This was accomplished through a series of simulation tests conducted after the completion of the parametric studies, by further testing the sensitivity of the building to the combination of the lowest resulting comfort indexes. In order to find the appropriate combination of passive design techniques, the simulation results were computed using an analysis matrix, containing both, comfort and marginal costs indexes for each variant tested.
The criteria adopted for the cost-benefit analysis is based on subsidy schemes granted by social housing programs. According to government sources (MINVU, 2013), the total construction costs granted for the poorest income quintiles, corresponding to the first title of the Integrated Housing Subsidy System, varies from nearly 22,700 to 52,000 USD. Although for the purpose of this research it was decided to adopt the minimum cost, in order to allow further improvements to the performance of buildings, the budget scheme adopted considered the addition of a thermal conditioning subsidy which in total reaches up a budget of 27,000 USD.

$$\Delta MC = C_f - C_i$$  \hspace{1cm} (2)

Where :

- $C_f$ = Final construction cost
- $C_i$ = Initial construction cost

**ADAPTIVE THERMAL COMFORT**

The criteria by which thermal performance was evaluated was based on the assumption that thermal comfort is not a commodity, but an imperative constituent of an individual’s right to overcome poverty. Therefore is crucial to distinguish first the subtle threshold between the notion of thermal comfort and health, the former being a condition of mind associated with an individual’s perception, and the latter being a basic biological need for human survival. Under these terms, thermal comfort is stated here as an adaptable necessity subject to buildings’ inherent capacity to provide shelter from outdoors, whereas looking beyond human thermal regulation capacity, an adequate level of warmth or coolness is a minimum condition required for the maintenance of health. The assumption that space heating is required if any of these limits are exceeded has undermined the responsibility of housing authorities to provide adequate thermal environments, creating a burden for the income of poor households.

Field studies conducted under this research study, during the winter of 2011 in Santiago, evidenced that none of the above definitions were actually met in social housing. Findings drawn from interviews conducted in Olga Leiva and El Estanque housing developments, unveiled the paradox of the ‘cure being worse than the disease’ as occupants claimed that, despite raised levels of air pollution and space heating fuel costs during winter, estimated at an average around 40USD for a monthly heating load of 100kWh, above the 10% of the poorest quintile income average, the level of heat provided by common kerosene and gas space heaters was not sufficient to cover their thermal needs, where surprisingly in order to ensure health and safety many interviewees stated that they operated their houses under free-running conditions. So why are space heating fuels used at all?

The above observations were consistent with monitoring data and comfort survey results. Whereas building monitoring showed that indoor daily temperature averages around 14˚C, the outcomes of a survey conducted on a sample of 100 households showed that indoor temperature patterns tended to follow outdoor patterns, exhibiting mean comfort votes of 15.9˚C and 17.3˚C, in Olga Leiva and El Estanque, respectively (Felmer, 2014). The evidence suggests that a more open connection to the outdoors widens the scope of temperature ranges into which occupants express thermal satisfaction. Providing that people’s health is ensured through limiting building temperature extremes, an adaptive approach to thermal comfort is advocated here through the integration of adaptive thermal controls aimed at reducing space-heating, and to providing thermal comfort all year-round.

$$T_n = 17.8 + 0.31 T_m; \hspace{0.5cm} T_c = T_n \pm 3.0$$  \hspace{1cm} (3)

Where :

- $T_n$ = Neutral temperature
- $T_m$ = Mean monthly temperature
- $T_c$ = Comfort temperature

In order to widen the study across other seasons and climates, comfort temperature ranges were estimated from a database of field studies by de Dear & Brager (2001). The model adopted was developed over a linear regression obtained from the revision of 22,000 sets of raw data compiled around different climates world-wide. As can be observed in Equation 3, thermal comfort limits were taken as ± 3K from thermal neutralities estimated for each month. In order to parallel with studies in social housing, the algorithm was estimated for the same period (August; $T_m = 9.8$ ℃), resulting in a lower limit of 17.8˚C, higher than the comfort votes showed above, the equivalent of a monthly heating load of 500kWh. Although this is low, fuel expenses are unaffordable for low income households.
OCCUPANCY HEAT GAINS

Heat gains from occupants and appliances were estimated from field study observations in Olga Leiva. Although there is no empirical research on the matter previous assumptions estimated an average daily heat load for standard residential buildings of around 5.0 W/m² (Hatt et al., 2012; Müller, 2003). Whereas, the average daily heat load adopted for the studies presented here was estimated at 7.0 W/m², by considering that 4.0 W/m² comes from occupants; 2.0 W/m² from appliances and 1.0 W/m² from lighting. This results in a total daily heat load of 9 kWh, resulting at a similar rate to previous studies conducted for social housing (Bustamante, 2009). The house was assumed to be occupied by four occupants, two adults and two children, considering continuous occupation by one member of the household, while one working adult and the children out for most of the day. In order to cover energy end-uses other than space heating, only electric efficient equipment was considered, obtaining lower energy consumption rates than an average household in Santiago.

INfiltration AND VENTilation

Air infiltration rates were taken from recent empirical studies conducted to set a baseline for residential buildings. Previous simulation studies by Bustamante (2009) assumed a value of 1.0 ach as the maximum acceptable limit for thermal efficiency in social housing. However, recent evidence gathered from studies around different climates has proven that higher air tightness can be achieved with simple economic measures (Cortes & Ridley, 2012). Results from pressurization tests conducted to set a baseline standard by Figueroa et al. (2013), exhibited values ranging from 0.12 to 2.5 ach under normal pressure conditions, for both brick and timber constructions. The air change rate adopted here was then 1.2 ach, corresponding to the average value of the sample. Minimum fresh air supply rates were taken as 7.5 l/s per person for each room, when occupants were in at any given time (ASHRAE 62, 2005).

THERMAL PERFORMANCE

As can be observed in Table 1, preliminary simulation results showed that indoor temperatures were below thermal comfort limits during most of the heating season. This means the conjecture that current standards do not aim to target thermal comfort is borne out, as temperatures can drop significantly below mean comfort votes, or even further below recommended limits for healthy thermal environments. Results plotted for a typical winter’s day, as shown in Figure 2a, were consistent with space heaters patterns of use, which was around an average of four hours a day between 6.00-10.00pm, and occasionally for a few hours during the morning. Thermal comfort conditions are only achieved during the hours around midday, and from there on temperatures steadily decrease reaching below 15°C and reducing further to 10°C during early mornings. On the other hand, results from a typical day in summer in Figure 2b showed that thermal comfort was only achieved in the living area, whereas in the bedroom resultant temperatures exceed the upper limit during most occupancy hours in the evening.

Figure 2. (a) Case study performance on a typical day in winter and (b) on a typical summer’s day.
PARAMETRIC SIMULATION STUDIES

Since thermal comfort was not achieved, parametric simulations were carried out to test the influence of different design techniques. The aim was to select the parameters to be tested in further studies with a free-running prototype around the country’s varied climates. Based on a review of previous studies by Bustamante (2009) and Müller (2003), the parametric variants proposed were based on four distinctive design principles: heat loss control, passive solar design, thermal mass and natural ventilation. These were considered as a conceptual basis to move from one climate to another. However the design approach adopted for each location might be subjected to the nature of each climatic problem, rooted in the interaction between occupants’ thermal needs and outdoors. As the predominant problem found in Santiago was underheating and, as the sole choice, the use of polluting space heaters, the analyses were structured to provide thermal comfort during the heating season as a primary concern. The final result of each parametric variation can be consulted in Table 2, a brief description of the studies is given here below:

A. Airtightness: Following pressurization tests by Figueroa et al. (2013) infiltration rates of 0.12 and 2.5 ach were further tested, corresponding to the minimum and maximums values of the sample. Results from the case study evidenced a great sensitivity to slight variations in air change rates, improving significantly performance from the highest to the lowest values tested, reaching up to 5K during occupancy hours, and nearly to 2.5K average across the whole period assessed. The airtightness standard of the building proved to be crucial to allow sensitivity to any other design parameter, thus further analysis was carried out under 0.12 ach, advocated as an acceptable limit for thermal efficiency.

B. Insulation of External Walls: As previously discussed in relation to the low exposure levels of the house, the addition of insulation on external opaque elements exhibited no significant influence. Different insulation thicknesses were added on exterior walls, including further testing of alternatives, at 75mm (U=0.5 W/m²K), and 100 mm (U=0.4 W/m²K). Results exhibited no meaningful differences in both seasonal periods, suggesting that even lower resistances can be specified.

C. Interior Shutters: Despite reduced windows areas, this parameter showed to be decisive for providing thermal comfort during winter evenings. This can be explained by the ratio of glazing surfaces when compared with all exposed elements, and by the low resistances allowed for windows in current regulations. Two different alternatives were tested, one by replacing single glazed windows with double glazing (U=2.9 W/m²K), and other by the incorporation of interior night shutters (U=0.7 W/m²K), operated between 8.00pm-8.00am. The use of the shutters exhibited great efficiency, increasing temperatures by nearly 2K during evening hours, while being considerably cheaper than the double glazing alternative.

D. Window Size: In order to assess passive solar heating potential, different window sizes were performed. The windows of the case study were decreased to meet the minimum allowable size set by social housing standards, a corresponding net glazing area of 1.0 m², and increased up to 2.0m². The results showed that by simply facing windows towards the equator, incoming solar radiation can provide sufficient amounts of heat to increase indoor temperatures above thermal comfort limits, although higher levels of thermal mass would be required to stabilize indoor temperature fluctuations.

E. Thermal Mass of External Walls: Thermal mass was examined through different brick masonry constructions used in social housing. The exterior walls, built on lightweight timber construction, were performed with two different brick constructions, a ceramic perforated brick, and a clay solid brick, using the same insulation thickness. Results evidenced that thermal mass had a great potential to reduce high daily temperature fluctuations, contributing to stabilizing indoor temperatures during both seasons. The solid brick solution proved to be remarkably cost efficient, since being more economic than its alternative, exhibited a more robust performance, reducing peak indoor temperatures
by nearly 5K, and even further up, to 10K on some unfavourable winter days.

In order to conduct the cost benefit analysis, each design variant tested was compared against final construction costs. In order to reduce the data inputted in the analysis matrix, comfort indices were estimated only from bedroom performance results over a sample week selected in winter. As shown in Table 2, the matrix allowed a first improved house, based on the combination of best results obtained across the studies to be set. Since this did not necessarily represent optimum performance, either in terms of thermal comfort or costs, further tests were carried out to investigate the influence of each variant under the combined effect of the different design parameters. The results from the second improved house initially proved that thermal comfort can be achieved within reasonable costs. However a final simulation was required to test whether acceptable thermal conditions can be provided during critical occupancy hours.

### Table 2. Parametric Studies Results for a Winter Week

<table>
<thead>
<tr>
<th>Building Case study</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>∑ΔTc (Degree hours)</th>
<th>ΔMC (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B B2= 75mm insulation</td>
<td>B2</td>
<td>C1</td>
<td>D1</td>
<td>E1</td>
<td>488</td>
<td>529</td>
</tr>
<tr>
<td>B3= 100mm insulation</td>
<td>B3</td>
<td>C1</td>
<td>D1</td>
<td>E1</td>
<td>462</td>
<td>849</td>
</tr>
<tr>
<td>C C2= Double glazing</td>
<td>B1</td>
<td>C2</td>
<td>D1</td>
<td>E1</td>
<td>437</td>
<td>959</td>
</tr>
<tr>
<td>C3= Interior shutter</td>
<td>B1</td>
<td>C3</td>
<td>D1</td>
<td>E1</td>
<td>380</td>
<td>363</td>
</tr>
<tr>
<td>D D2= Net glazing area of 1.0 m²</td>
<td>B1</td>
<td>C1</td>
<td>D2</td>
<td>E1</td>
<td>508</td>
<td>-84</td>
</tr>
<tr>
<td>D3= Net glazing area of 2.0 m²</td>
<td>B1</td>
<td>C1</td>
<td>D3</td>
<td>E1</td>
<td>532</td>
<td>1,080</td>
</tr>
<tr>
<td>E E2= Ceramic perforated brick</td>
<td>B1</td>
<td>C1</td>
<td>D1</td>
<td>E2</td>
<td>401</td>
<td>2,102</td>
</tr>
<tr>
<td>E3= Clay solid brick</td>
<td>B1</td>
<td>C1</td>
<td>D1</td>
<td>E3</td>
<td>318</td>
<td>1,786</td>
</tr>
<tr>
<td>Improved House 1</td>
<td>B3</td>
<td>C3</td>
<td>D2</td>
<td>E3</td>
<td>100</td>
<td>2,914</td>
</tr>
<tr>
<td>B B1= 50mm insulation</td>
<td>B1</td>
<td>C3</td>
<td>D2</td>
<td>E3</td>
<td>190</td>
<td>2,065</td>
</tr>
<tr>
<td>C C1= Single glazing</td>
<td>B3</td>
<td>C1</td>
<td>D2</td>
<td>E3</td>
<td>234</td>
<td>2,551</td>
</tr>
<tr>
<td>D D3= Net glazing area of 2.0 m²</td>
<td>B3</td>
<td>C3</td>
<td>D3</td>
<td>E3</td>
<td>40</td>
<td>4,078</td>
</tr>
<tr>
<td>E E1= Lightweight timber construction</td>
<td>B3</td>
<td>C3</td>
<td>D2</td>
<td>E1</td>
<td>397</td>
<td>1,128</td>
</tr>
<tr>
<td>Improved House 2</td>
<td>B1</td>
<td>C3</td>
<td>D3</td>
<td>E3</td>
<td>53</td>
<td>3,229</td>
</tr>
</tbody>
</table>

**IMPROVED THERMAL PERFORMANCE**

Results from parametric studies were used to develop a final design proposal. A last simulation was performed to adjust the thermal environment of each room to the hours of occupancy when the main problems were identified to occur. As shown in Figure 3a, based on the optimized case study obtained from the matrix, resultant indoor temperatures were found to be above thermal comfort almost all day round, ensuring occupants had the minimum conditions required to perform their daily activities and safeguard the maintenance of health. Moreover, the sensitivity of the house in relation to solar radiation

![Figure 3 (a) Optimized building performance on a typical winter day and (b) on a typical summer day.](image-url)
Table 3. Comfort Indices of the Improved House

<table>
<thead>
<tr>
<th>Season</th>
<th>Room</th>
<th>$\Delta T_c$ (Degree-hours)</th>
<th>$\Delta T_c$ (%)</th>
<th>To min (˚C)</th>
<th>To avg. (˚C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>Bedroom</td>
<td>205</td>
<td>8.1</td>
<td>14.8</td>
<td>21.0</td>
</tr>
<tr>
<td></td>
<td>Living room</td>
<td>144</td>
<td>7.8</td>
<td>15.7</td>
<td>20.5</td>
</tr>
<tr>
<td>Summer</td>
<td>Bedroom</td>
<td>70</td>
<td>6.9</td>
<td>28.6</td>
<td>23.2</td>
</tr>
<tr>
<td></td>
<td>Living room</td>
<td>64</td>
<td>5.2</td>
<td>28.7</td>
<td>22.3</td>
</tr>
</tbody>
</table>

offered the choice of achieving additional levels of warmth, providing appropriate thermal conditions to dispense with polluting space heaters.

Results from a typical day in summer proved that thermal comfort can be achieved through simple design techniques. The final building performed considered the addition of ventilation, either through windows opening or the operation of a fan, increasing air change rates by 12 ach and 15 ach during occupancy hours in the bedroom and living area, respectively. The use of exterior shutters was also considered, covering 25% of window areas. As shown in Figure 3b, the controls provided allowed indoor temperatures to achieve below thermal comfort limits for most part of the day, offering occupants the choice of adapting to changes in their thermal environment. Although in terms of fuel consumption this might not be relevant, overheating may lead to thermal stress and seriously affect the daily performance of different activities within the home.

Results from cost benefit analysis allowed to draw a final estimation of the construction costs required to meet the expected results. As can be observed on Figure 4, which comprised the replacement of standard aluminium windows with PVC; the incorporation of trickle vents; and the addition of 10mm of insulation on external walls ($U=0.53 \text{ W/m}^2\text{K}$). As shown in Table 3, while resultant comfort indices where significantly reduced, the additional cost investment required was fully covered by the thermal conditioning subsidy reaching approximately 4,000 USD, the equivalent of 18% investment over the minimum construction costs allocated by the government.

CONCLUSIONS

The performance of the optimized house proved that adequate thermal comfort conditions can be provided in free-running buildings in the climate of Santiago. The findings from field studies were crucial to understand occupants’ preferences and space heating consumption behaviours, which turned to be in some extent over estimated since both thermal expectations and consumption levels were remarkably low. The underlying problem was then, thermal comfort itself, followed by occupants’ limited choice to afford clean and safe energy sources. Results from parametric simulations demonstrated that through simple passive heating and cooling design techniques thermal comfort could

Figure 4. Optimized case study, plans and construction specifications.
be provided within minimum budget allocations, questioning the role of government authorities to ensure adequate housing conditions. The potential to reduce space heating down to nearly zero and provide thermal comfort all year-round could represent a significant contribution to improve indoor environmental performance and the quality of life of the urban poor, as well as open the debate towards energy autonomy by replacing combustion fuels with clean energy powered by solar energy technologies.

ACKNOWLEDGMENTS

This study was carried out as part of a PhD thesis at the Architectural Association School of Architecture in London, UK. The author would like to thank to Prof. Simos Yannas and Prof. Paula Cadima for their supervision, support and fruitful advice. This research was supported by the National Commission for Scientific and Technological Research (CONICYT).

REFERENCES

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14:10 - 15:50, Faith - Knowledge Consortium of Gujarat
Carbon dioxide emissions of green roofing – case study in southern Brazil

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ABSTRACT

Nowadays there are several efforts in define carbon dioxide emissions of buildings components and materials. This data shall be in accordance with local building technology or methods of construction. Therefore studies of local alternatives are important. This work presents results of carbon dioxide emissions for two solutions of usual green roofing in southern Brazil. The method considers production of main inputs, road transport from point of sale to the site of construction, workmanship transport. The two green roofs are compared with ceramic and asbestos-cement tiles solution. The data were obtained by surveys, interviews with owners and scientific literature. The building materials, distances of transport were quantified. The results demonstrate that the carbon dioxide emissions are larger than the emissions of the conventional roofing and the main contribution is due to the road transport of components and materials from the point of sale to the site of construction. However, we must consider that the green roofing has a high potential for the carbon sequestration, promotes thermal resistance, humidify and filter the air, reduce the urban surface temperatures.

INTRODUCTION

Civil construction is responsible for 40% of energy demand and 38% of air emissions that contribute for global warming. However there is 30% to 50% of potential for reduction of energy consumption and 35% for reduction of air emissions [1]. In Brazil the civil construction has substantial participation on greenhouse gases. Excluding the carbon dioxide (CO$_2$) emitted by burnoffs, the building construction represents a quarter of significant air emissions, either by chemical reactions of industrial processes of materials or by the energy sources involved in these industrial processes [2]. Further, the materials transportation, mainly by roads with fossil fuel, contributes significantly for CO$_2$ emissions [3].

Table 1 illustrates the CO$_2$ emissions coefficient (Kg CO$_2$/eq) for the mainly fuels used in Brazil [2].

<table>
<thead>
<tr>
<th>fuel source</th>
<th>emissões de CO2 (kg CO$_2$/GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>diesel oil</td>
<td>79,8</td>
</tr>
<tr>
<td>natural gas</td>
<td>50,6</td>
</tr>
<tr>
<td>petroleum coke</td>
<td>72,6</td>
</tr>
<tr>
<td>other sources derived of petroleum</td>
<td>0,0</td>
</tr>
<tr>
<td>electrical energy</td>
<td>18,1</td>
</tr>
<tr>
<td>fuel wood</td>
<td>81,6</td>
</tr>
</tbody>
</table>

Table 2 illustrates the embodied energy in some construction materials expressed in percentage according to [2]. The use of energy in industrial processes also significantly contributes for CO$_2$ emissions.
emissions; therefore the consideration of production emissions is important in the life cycle of construction materials.

Table 2. Percentage of embodied energy due to source for some materials construction

<table>
<thead>
<tr>
<th>material/source</th>
<th>diesel oil</th>
<th>natural gas</th>
<th>coke</th>
<th>other sources</th>
<th>electrical energy</th>
<th>wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand</td>
<td>99</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mortar</td>
<td>86</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ceramic</td>
<td>4</td>
<td>2</td>
<td></td>
<td>85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cement</td>
<td>3</td>
<td>61</td>
<td></td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>asbestos</td>
<td>84</td>
<td></td>
<td></td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>waterproofing substances</td>
<td>10</td>
<td>30</td>
<td>34</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>polymer</td>
<td>10</td>
<td>30</td>
<td>34</td>
<td>26</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The choice of the best environmentally sound building technologies promotes the environmental impacts reduction, such as energy consumption and toxical gases emissions [4]. Technologies must be in accordance with local and regional traditional technology and disponibility of natural resources and industrialized local materials. Therefore the study of local solutions is important to achieve the building environmental performance.

In this study green roofs are understood as vegetal layer intentionally incorporate on top of buildings. They have been pointed as alternatives more sustainable if compared with conventional roofs, such as tile and asbestos-cement roofs. There are many vantages associated to green roofing, such as natural top ground, life cycle extended, better thermal performance and consequently building occupants comfort more acceptable, reduction of urban heat-island effect, carbon sequestration, among others [5]; [6].

A negative factor associated to green roofs regards to the water comsuption. This aspect is not studied in this research, but some authors pointed that there are benefits to manage stormwater in order to restore the capacity of water retention lost by excessive paving of soil in cities [7]. It is possible to reduce about 60% of runoff for rain water captation. Further, the use os plant species that require little irrigation can be reduce the water conspumption, one of negative factors associated to green roofing [7].

In Brazil some studies about green roofing has been already enhanced. Through computational simulation [8] and prototypes submitted to measurement [9] the potential of green roofs for water catchment and retention was verified. Also was verified the viability of green roofs for low-cost housing [10]. A research concerning to occupants’ satisfaction indicated that the need for constant maintenance was one of the problems more mentioned [11]. However there are a few studies about the environmental impacts of green roofs mainly referring to CO₂ emissions.

This study aims to contribute to this issue through the quantification of carbon dioxide emissions of four roofs commonly built in Brazil, two green roofs built in two different regions, provincial medium town and industrial city, and two conventional ceramic and asbestos-cement roofing in order to compare their environmental performance due to carbon dioxide emissions. Additionally the carbon sequestration potential was quantified in order to verify this important contribution of green roofs for sound environments.

METHOD

Selected green roofs

The green roofs are approximately 200km away each other (with different proximities of industries that produce the building materials involved), they are selected in accordance with the occupants permission to access the necessary data for the life cycle inventory, the construction system involves little labour and artisanal method. The ceramic tiles and asbestos-cement roof do not have the same thermal insulation, since the owners have chosen the green roofs for aesthetic and environmental sustainability, without refering their thermal performance. The Figure 1 ilustrates the green roofs studied.
The data for the inventory were obtained from interviews with the owners of analysed houses, invoices, private diaries and reports elaborated by owners, regular direct observations, in situ measurements during building production process. Layers constituting the roofs, quantitative of materials, products’ points of sale, places of production of listed materials, distances of production, sale and jobsite area, materials modal transportation were collected. The demand of labour and the distances between jobsite, workers housing, means of transport also were measured from interviews and data registered by owners. The distances were obtained from virtual maps.

Quantification of carbon dioxide emissions

Contribution of different energy inputs was defined for constituting layers and materials. For each material, the total embodied energy $CE$ was computed, the percentage of each significant source present in material production was also computed, obtained from [2], and is represented by $P\%$. The individual contribution of each source was obtained by the product of total embodied energy and the individual carbon dioxide source contribution named $coef_{CO2source}$ obtained from [2]. The somatory of individual contributions is the total carbon dioxide emissions $E_{CO2}$ represented by Equation 1.

$$E_{CO2} = \sum \left[ CE \times \frac{P\%}{100} \times coef_{CO2source} \right] \quad (1)$$

where

- $E_{CO2}$ is the carbon dioxide emission, kg CO$_2$;
- $CE$ is the contribution of different energy inputs, MJ;
- $P\%$ is the percentage of a kind energy in production process, \%;
- $coef_{CO2source}$ is an index representative of CO$_2$ emission of energy source, kg CO$_2$/MJ.

Since it was not possible to determine the characteristics of vehicle used as mean of transport and the kind of fuel, the indices established by [3], which studied carbon dioxide emissions for Brazilian road transport, were considered as reference. The mentioned author considers that it is possible to determine the CO$_2$ emissions with an admissible error considering the distances and a medium factor according to type of transport. The carbon dioxide emission index for transportation from place of production to place of sale, with heavy road transport, was considered equal to 0.895 kg CO$_2$ / km [3] since that is the conventional transport for construction materials in Brazil; for transportation from place of sale to jobplace (conventionaly transport of light load in Brazil) was considered equal to 0.106 kg CO$_2$ / km [3] by the same previus reason. The carbon dioxide emission related to mean transport for each material was calculated using the Equation 2.

$$total\ emission\ material\ transport = \text{emission}_{CO2/km} \times distane_{prod\rightarrow sale} + \text{emission}_{CO2/km} \times \text{distance}_{sale\rightarrow jobplace} \quad (2)$$
The Equation 3 was used for calculating the emissions due to transport of workers. The dioxide carbon emission index per day for mean transport was considered equal to 0.106 kg CO$_2$ / km.day, embodied energy was considered equal to 0.0015 MJ / kg and the weight for worker is equal to 70kg.

\[ WT_{CO2} = EE \times total \ weight \times distance_{home\rightarrow workjob} \times worked \ days \times emission_{CO2/km} \]

where
- \(WT_{CO2}\) is the total emission worker transport, kg CO$_2$;
- \(EE\) is the embodied energy, MJ/kg;
- \(distance_{home\rightarrow workjob}\) is the distance between the home and the workplace, km;
- \(total \ weight\) is the transported weight, kg;
- \(emission_{CO2/km}\) is the carbon dioxide emissions per kilometer due to worker transport, CO$_2$/km.

**Carbon sequestration**

Additionally the potential for carbon sequestration was calculated in order to verify one of main environmental contribution of green roofing. The larger carbon sequestration for grass with 20cm of substrate for plant growth is considered equal to 0.945 kgCO$_2$ / (m$^2$.year) [12]. The mentioned value was multiplied for the area of each green roof. Total calculated carbon dioxide emission for each green roof was divided for the index in order to obtain the number of years necessary to sequester.

**RESULTS**

Table 3 presents the carbon dioxide emissions due to materials production and Table 4 emissions due to transport for the green roof located at the big city (green roof 1) with 28.41m$^2$ of surface.

<table>
<thead>
<tr>
<th>layer</th>
<th>area or volume</th>
<th>density (kg/m$^3$)</th>
<th>mass (kg)</th>
<th>relative embodied energy (MJ/kg)</th>
<th>total embodied energy (MJ)</th>
<th>CO$_2$ emissions (kgCO$_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>asphalt fabric</td>
<td>28.41m$^2$</td>
<td>1.125</td>
<td>127.84</td>
<td>51.00</td>
<td>6,519.84</td>
<td>342.62</td>
</tr>
<tr>
<td>crushed rock</td>
<td>0.28m$^3$</td>
<td>1.400</td>
<td>397.74</td>
<td>0.15</td>
<td>59.66</td>
<td>4.21</td>
</tr>
<tr>
<td>sand</td>
<td>0.57m$^3$</td>
<td>1.470</td>
<td>835.25</td>
<td>0.05</td>
<td>41.76</td>
<td>3.31</td>
</tr>
<tr>
<td>organic soil</td>
<td>0.075m$^3$</td>
<td>1.600</td>
<td>120.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>soil</td>
<td>0.075m$^3$</td>
<td>1.400</td>
<td>105.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>garden grass</td>
<td>16.93m$^2$</td>
<td>1.500</td>
<td>1,523.70</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>(60%) garden</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>grass 2</td>
<td>11.48m$^2$</td>
<td>1.500</td>
<td>1,033.20</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>(40%) garden</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>-</td>
<td>-</td>
<td>4,142.73</td>
<td>-</td>
<td>6,621.26</td>
<td>350.14</td>
</tr>
<tr>
<td>total per m$^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>233.06MJ/m$^2$</td>
<td>12.32kgCO$_2$/m$^2$</td>
</tr>
</tbody>
</table>
in situ 0  0.00  in situ 0.00  0  0.00  

grass garden grass (60%) road 68  60.86  car 10.90  1.16  62.02  
garden grass (40%) in situ 0  0.00  car 13.40  1.42  1.42  

- - 1,434.2  1,283.61  - -  57.58  1,289.66  

Total per m²  45.39 kgCO₂/m²

The major emissions are due to asphalt fabric that is the component with industrial process more complex among the green roof layers; involves large energy inputs; with centralized production. Therefore replacement of that layer is a possibility in reducing de CO₂ impact.

Table 5 presents the carbon dioxide emissions due to worker transport for the green roof 1.

Table 5. Carbon dioxide emissions due to workers transport for green roof 1.

<table>
<thead>
<tr>
<th>layer</th>
<th>weight of transported workers (kg)</th>
<th>distance home → work/job mode (km)</th>
<th>worked days</th>
<th>transport mode</th>
<th>embodied energy (MJ)</th>
<th>CO₂ emission (kg CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>owner</td>
<td>140 Kg</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>worker</td>
<td>140 Kg</td>
<td>15</td>
<td>1</td>
<td>car</td>
<td>10.815</td>
<td>1.59</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.815</td>
<td>1.59</td>
</tr>
</tbody>
</table>

For the ceramic tile roof built in the big city, the main contributions are due to production of ceramic tiles (481.17 kgCO₂) and due to transport of truss materials (peroba wood) (1,100.22 kgCO₂). In this case, the use of wood which production is strongly centralized (with environmental license) contributes significantly to carbon dioxide emissions.

For the asbestos-cement roof built in the same place, the main contributions are due to transport of truss materials (1,100,22 kgCO₂), since there are local industries that produce fibercement tiles.

Table 6 presents the carbon dioxide emissions due to materials production and Table 7 emissions due to transport for the green roof located at the medium town (green roof 2).

Table 6. Carbon dioxide emissions due to material production for green roof 2.

<table>
<thead>
<tr>
<th>layer</th>
<th>area or volume</th>
<th>density (kg/m³)</th>
<th>mass (kg)</th>
<th>relative embodied energy (MJ/kg)</th>
<th>total embodied energy (MJ)</th>
<th>CO₂ emission (kg CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>waterproofing</td>
<td>45.28 litres</td>
<td>1.3 (kg/l)</td>
<td>58.86</td>
<td>65.00</td>
<td>3,826.16</td>
<td>201.06</td>
</tr>
<tr>
<td>pebble crushing</td>
<td>2.3 m³</td>
<td>1000</td>
<td>2,300.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>waterproofing coating</td>
<td>56.6 m²</td>
<td>0.12</td>
<td>6.79</td>
<td>51.00</td>
<td>346.29</td>
<td>25.50</td>
</tr>
<tr>
<td>soil</td>
<td>3.4 m³</td>
<td>1,400</td>
<td>4,760.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>garden grass</td>
<td>56.6 m²</td>
<td>1,500</td>
<td>5,114.44</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>-</td>
<td></td>
<td></td>
<td>4,172.45</td>
<td>226.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>total per m²</td>
<td></td>
<td></td>
<td>73.72MJ/m²</td>
<td>4.00kgCO₂/m²</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the same way of the precedent green roof 1, the major emissions are due to more industrialised component that is the waterproofing layers. The use of two waterproofing layers is critical for the poor performance of this roof.

For the ceramic tile roof built in the medium town, such as for the big city, the main contributions are due to production of ceramic tiles (958.12 kgCO$_2$) and due to transport of truss materials (peroba wood) (1,178.00 kgCO$_2$). In this case, the use of wood which production is strongly centralized (with environmental license) contributes significantly to carbon dioxide emissions.

For the asbestos-cement roof built in the medium town, the main contributions are due to transport of truss materials (1,178.00 kgCO$_2$). The incorporated cement in the asbestos tiles is responsible for 486.40 kgCO$_2$ emissions.

The Figure 3 illustrates the total emissions per square metres due to the six roofs, green, asbestos-cement, ceramic. In relation to transport materials both green roofs present lower performance than ceramic and cement-asbestos conventional roofs. This result is due to presence of layers based on fossil source (asphalt fabric and water proofing layer) with centralized production. In relation to carbon dioxide emissions produced from manufacturing the green roof 1 is more unsustainable due to asphalt fabric, presenting best performance only compared with the ceramic tile roof. Production of ceramic tiles envolves large energy for burning and transport due to their weight since this type of roofing has large embodied energy and carbon dioxide emissions. The cement-asbestos tile results in the best performance for the case study in the big town because there are local industries for this material. The three roofs type 2 located in the town far of production regions present the lower contribution in CO$_2$ emissions what is an unexpected result since is further away from production centers. This result demonstrates the importance of contextualized solutions. Green roof 2 is technically simpler; a despite of using a water proofing layer with large embodied energy and carbon dioxide emissions, it requires less amount of material to fulfil the same function comparatively with roof 1. The emissions associated to worker transport are insignificant compared to production and transport materials due to artisanal and auto-construction process, reinforcing the use local workforce and techniques.
Considering the three contributions analyzed, transport materials, production, and transport workers, there is little difference between the three roofing in the medium town, which is does not do in the case of roofing in the big city where the cement-asbestos is the best solution.

It takes the green roof 1 about 61 years for carbon sequestration due to production and transport of materials and workers. For the green roof 2, it takes about 50 years. These results demonstrate that the main benefit of green roof is obtained in very long time-lag, which counters to principal benefit associated to green roofs.

CONCLUSION

Through results the green roofs present large CO₂ emissions due to use of layers based on polymers or fossil source materials which production involves large embodied energy and several emissions that contributes for greenhouse. It pointed to need to replace the waterproofing layer based on fossil source for another one more environmentally sound. For the case studies illustrated material transport is responsible for the largest emissions for six simulated roofing. Results reinforce the importance of choosing local and regional technologies, materials, and workforce. The cement-asbestos roof has the best performance relative to carbon dioxide emissions; it flies in the face of common sense in considering the green roof necessarily an environmentally good solution. Furthermore, one of benefits associated to green roofs, the carbon sequestration, is reached in a long time opposing to general idea of sustainability.

Green roofing has been considered as a building system with low environmental impacts. The analyses of carbon dioxide emissions demonstrated that it has lower performance than the conventional solutions even if were regarded the potential for carbon sequestration. However the easiest solution adopted for the conventional roofing, without a thermal insulation, collaborate for the results achieved.

REFERENCES


Design and Testing out of an Insulating Floor Element, Composed of Recycled Rubber and Inert Demolition Waste

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ABSTRACT

Even if initially dominated by cost concerns, energy-awareness is today maturing towards a vision aimed at curtailing energy consumption and reducing carbon emissions.

In consideration of today’s large amount of tyres being used and disposed of, the purpose of this research was to investigate options for utilising recycled rubber as a building material (in combination with inert demolition waste), namely as insulation in flooring elements such as tiles, such a mix could replace new underlay insulating materials typically having a higher embodied energy content. This paper evaluates the potential of recycling used tyres in specially fabricated floor tiles for different design mixes and evaluates the success/failure of such a building element as a floor finish.

The study also looks into the best combination of materials to form a durable, non-abrasive robust tile, yet also acting as a thermal and moisture barrier. An added value of the proposed tile is its acoustic property, where the shredded rubber makes it also resilient to impact and airborne noise. Its light colour also proves ideal for solar-exposed flat roofs, where, it is also aesthetically pleasing for the outdoor evening lifestyle in a Mediterranean climate.

INTRODUCTION

Since prehistoric times human beings have always searched for ways to protect themselves against the elements, first through the use of naturally formed shelters such as caves and then evolving into proper building-shaped constructed dwellings made using either naturally occurring materials extracted from the earth or man-made artificial materials. Through time, with the introduction of energy-intensive heating and cooling systems, energy consumption in buildings has however increased. This is requiring that new methods for making a building more energy efficient be researched and studied.

In this context, particular attention is being given by researchers not only to provide building elements with good thermal properties, e.g. low thermal transmittance which prevents high rates of heat transfer, but also to the fact that these building elements are made from materials, possibly recycled ones, having a low embodied energy. One such material is recycled rubber from end-of-life automotive tyres. Due to the heavy metals they contain, rubber tyres are a very problematic waste source. If disposed incorrectly, the chemicals they contain can contaminate ground water sources. Also, other problems arise from their size which makes it very hard and expensive to dispose of. To minimise volume burning them is an option, however today this is practically forbidden due to the toxic gases discharged into the atmosphere (typically carbon monoxide and sulphuric acid). This problem is aggravated by the fact that each year millions of tyres are consumed to meet vehicle road standards. If properly recycled, this rubber however, can be made...
to good use given its inherent thermal properties, which give it a low thermal conductivity value, ideal for use in building components.

**Recycled Rubber Embodied energy**

Material selection and technologies used in building construction should aim to achieve the building occupants expected performance as well as aiming to minimise the environmental impact as much as possible, not only in the context of reducing energy consumption during its lifetime, but throughout its lifecycle, starting off from its production to the time when it is disposed off. In this context, Table 1 shows the specific total embodied energy per kilogram of tyre material produced. The rubber used for the production of tyres has a very high embodied energy and therefore finding alternative uses, especially at the end of lifecycle, can be beneficial to the environment.

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy (MJ/kg)</th>
<th>Greenhouse (kgCO₂/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Rubber</td>
<td>8</td>
<td>0.4</td>
</tr>
<tr>
<td>Synthetic Rubber</td>
<td>110</td>
<td>5.0</td>
</tr>
<tr>
<td>Carbon Black</td>
<td>125</td>
<td>5.7</td>
</tr>
<tr>
<td>All other additives</td>
<td>100</td>
<td>8.2</td>
</tr>
<tr>
<td>Fabric</td>
<td>45</td>
<td>2.1</td>
</tr>
<tr>
<td>Steel Tyre Cord</td>
<td>36</td>
<td>3.2</td>
</tr>
<tr>
<td>Manufacture per kg</td>
<td>11.7</td>
<td>1.86</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>435.7</strong></td>
<td><strong>26.46</strong></td>
</tr>
</tbody>
</table>

**Recycled Rubber as a Building Material**

The use of recycled rubber as a building material is not something completely new and various attempts have been made to make use of this resource to improve the properties of a building element.

**Recycled Rubber as Asphalt** A study made by the University of Toronto (Way et al., 2011) was carried out to investigate the use of recycled shredded rubber in normal road asphalt. Metro Toronto Roads and Traffic Department resurfaced five main roads using this new mix and no serious difficulties were encountered. In actual fact it was noticed that the new roads offered a greater durability with a lower requirement for maintenance and a subsequent higher expected lifetime, and a better overall performance with respect to road safety due to a higher frictional response (Piggott and Woodhams, 1979).

**Recycled Rubber Floorings** Rubber floorings is another use for recycled tyre rubber. Floor tiles made using recycled rubber are relatively soft, despite them being used for commercial grade durability standards. Such properties in fact render these floor tiles a particular viable option for flooring systems in retail outlets were people walk for long periods of time and in playrooms and public spaces where the impact absorption properties of such floor tiles, adds an element of safety for children playing in these spaces. Gyms also often use this product as it absorbs sound made from falling weights and the continuous uses of cardio machines. Finally, rubber floorings can also be used in bedrooms and other living spaces as an alternative to fitted carpets (Ecosurface, 2014).

**THE NEW BUILDING ELEMENT PROPOSED**

The aim of this research was to create a new type of roof tile using recycled material generated from vehicle worn out tyres and inert demolition waste, originally both intended to be disposed of, and both requiring large volumes at waste disposal facilities. In warm climates where flat roofs are the norm, solar ingress through the roof is a main source for heat gains inside buildings, since these receive the beating of a persistent scorching sun in summer, unlike walls that could be typically shaded. Therefore the provision of thermally isolating materials as part of roofing elements is of primary importance for reducing such
solar gains. This is particularly important in a hot Mediterranean Island such as Malta.

**Element Composition**

Aerated concrete was used as the base material with shredded rubber from recycled tyres added in varying percentages, namely 20%, 30% and 60% to constitute different tile mixes. Aerated concrete, classified as a lightweight concrete, is made up by mixing concrete with an aerating agent which causes the creation of a number of air voids inside the mix. The main advantage of this type of concrete is its lightweight composition and the high degree of thermal resistance which reduces the need of adding extra insulation to improve the thermal performance of a building element. The tile, having dimensions of 300mm by 300mm, was finished with a thin layer of a glass fibre coating. Polyester resin fibreglass is an impermeable material, thus adding this element would benefit the tile from making it water proof. Another added benefit of the fibreglass finish is in terms of its strength. Since the fiberglass contains and supports the aerated concrete which is considered to be weak, due to the presence of a large amount of air cavities, the tile performs better with regards to flexural strength, as the fibreglass encloses the tile creating a more compact system of materials.

**SPECIMEN BUILDING AND TESTING**

This section focuses on the procedure adopted in building and testing the proposed tile using a parametric methodology, whereby a number of design mixes were produced to analyse the effect of a selection of parameters on the thermal performance of the tile.

**Test Specimen Preparation and Construction**

Preparing the specimen involved using a mixture of recycled rubber granules, sand, cement and water to create the base constituents for the recycled rubber-infused aerated concrete mix. For the aeration process aluminium powder and sodium hydroxide were then added. In order to allow enough time for the aeration process a popular retarder was added to the mixture, to slow down the cement hardening reaction process. Once the mixture was prepared and the aeration process started, the tiles were left for two days to set within a specially designed mould. Once ready the moulds were dismantled revealing the tile. A fibreglass coating of around 4mm thickness was applied at the end of the process to give the tile a smooth clean dust-free, cream-white finish. Figure 1 shows a schematic of the different layers of the tile (inverted).

![Figure 1 Schematic of proposed tile (inverted as cast)](image)

**Testing the different design variables**

As part of the testing procedure various design mixes were produced with the intent of testing the variability in thermal performance of the different proposed design variables. The main variable parameters tested were the rubber percentage and the tile thickness, with each variable being tested for
three possible permutations for a total of nine combinations. The rubber percentage was varied between 20%, 30% and 60% of the design mix. For each rubber percentage three tile thicknesses were moulded, namely 45mm, 70mm and 90mm thickness. Table 2 summaries the different combinations created.

<table>
<thead>
<tr>
<th>Rubber Percentage (%</th>
<th>Thickness (mm)</th>
<th>Sand (g)</th>
<th>Cement (g)</th>
<th>Water (g)</th>
<th>Rubber (g)</th>
<th>Aluminium (g)</th>
<th>Sodium Hydroxide (g)</th>
<th>Retarder (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>45</td>
<td>2</td>
<td>900</td>
<td>54</td>
<td>460</td>
<td>22</td>
<td>22</td>
<td>15</td>
</tr>
<tr>
<td>30</td>
<td>45</td>
<td>2</td>
<td>820</td>
<td>49</td>
<td>690</td>
<td>20</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>60</td>
<td>45</td>
<td>1</td>
<td>615</td>
<td>37</td>
<td>960</td>
<td>17</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>70</td>
<td>3</td>
<td>1200</td>
<td>72</td>
<td>640</td>
<td>32</td>
<td>24</td>
<td>17</td>
</tr>
<tr>
<td>30</td>
<td>70</td>
<td>3</td>
<td>1150</td>
<td>69</td>
<td>900</td>
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<tr>
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<td>4</td>
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<td>4</td>
<td>1650</td>
<td>99</td>
<td>1290</td>
<td>44</td>
<td>32</td>
<td>20</td>
</tr>
<tr>
<td>60</td>
<td>90</td>
<td>3</td>
<td>1300</td>
<td>78</td>
<td>2016</td>
<td>34</td>
<td>25</td>
<td>18</td>
</tr>
</tbody>
</table>

Testing inside the Hot Box

The testing of the tiles was carried out using an established insulated Hot Box previously used and tested in the Environmental Lab. This was originally built according to BS EN 8990:1996 (BSI, 1996). The Hot Box was constructed using concrete block work, filled with C30 concrete with all joints sealed to reduce any heat losses. In order to measure the overall heat transmittance (U-Value) of horizontal building elements the Hot Box is divided into two chambers, a controlled artificially heated ‘hot’ chamber and an underlying ‘cold’ chamber, separated by a typical Maltese roof construction, as shown in Figure 2.

![Figure 2 Sectional Elevation of the Hot Box](image)

The top-most warm side of the Hot Box was set up with four heaters, grid-lined, each having a power of 700 Watts suspended from a steel square mesh connected to the top part of the Hot Box, as the grid-
matrix. Four fans were also connected to the mesh to create a continuous air flow thus creating an evenly distributed temperature profile throughout the interior warm side of the Hot Box.

Each combination of designed tile mix was tested inside the Hot Box, by laying the tiles on top of the ‘hot’ chamber floor, as shown in Figure 3, and measuring the temperature difference between the two chambers once steady-state is obtained.

In order to measure the temperature difference across the two chambers a total of 18 thermocouples were used. In the top ‘hot’ chamber, eight thermocouples were fixed on top of the tile surface while a ninth thermocouple was suspended in mid-air to measure the air temperature inside the chamber. The setup was mirrored in the ‘cold’ chamber. Each thermocouple was connected to a central data logger which recorded the readings from each individual thermocouple. The ambient room temperature was also monitored.

Surface temperature readings were recorded at 15-minute intervals until the hot box reached steady state i.e. the temperature gradient between both chambers remains at a constant rate. Once the hot box reached this thermal status, the steady state the temperature difference was calculated.

The composite tiles laid and tested into nine different categories. Each category had sixteen similar tiles, (4x4 no. x 300mm each tile), fitted in the calibrated hot box. Each category has a variation in either thickness or rubber content as indicated in subsequent output results, Figure 4.

RESULTS

Figure 4 shows how the overall heat transmittance, the building’s element U-value, as it varies with respect to changes in the recycled rubber content and the tile thickness. It can be observed that the major governing factor in decreasing the U-value of the proposed tile is by varying the thickness. As the thickness increases the lower is the U-value obtained. Increasing the rubber content also decreased the U-value but to a lower extent.

The main advantage of this design mix is that the rubber can be used to increase the volume of the tile, replacing quarried limestone sand, thus saving embodied energy, with the added benefit of making the tile more thermally resistive. With an increase in rubber content from 20% to 30%, the U-value dropped by -0.05, -0.06 and -0.13 W/m²K for the 45, 70, 90mm tiles respectively. With an increase from 30% to 60% further drops of -0.07, -0.02 and -0.03 W/m²K were noted for the 45, 70, 90mm tiles respectively, as can be seen in the summarised values in Table 3.
This further indicates that with a change of mass the drop in U-value is more pronounced than with the increase in rubber percentage. Moreover, an increase in rubber content with an increase in thickness sees the U-value drop by -0.13 W/m$^2$K. Although no further increases in %rubber or thickness was made, by extrapolation results indicate that the U-value would decrease further. An increase in mass would evidently increase its embodied energy and its cost given the greater mass per unit volume ratio. Such results can only be obtained through further studies or prediction modelling.

CONCLUSION

Currently Maltese building construction norms are slow to adhere to building regulations, technical guidance document part F, even though it has become national law. Most of the traditional Maltese roof constructions never had insulation since their thermal mass, composed of composite limestone strata in different forms, did the job reasonably well. Admittedly comfort standards were also less stringent than today, with older folk and farmers leading an outdoor life more than ever.

In warm climates where solar gains through flat roofs is a predominant heat source, roof insulation is a necessary requirement to reduce heat absorption into the building. This should reduce cooling loads particularly given the increase use of fossil-energy based HVAC systems. Based on this premise the use of the novel recycled rubber tiles reduces the overall U-value of the roofing element. Moreover, the benefit of using a material such as recycled rubber and inert waste, both with a high embodied energy content, means that there is also a lower demand for quarried limestone sand as a raw land-based resource. This is certainly an added value of using such tiles as insulation or as a complement to it to say the least. Waste rubber tyres are also shredded for re-use rather than dumped, taking precious voluminous space. So this is already a win-win scenario from a waste management perspective.

The objective of this paper was to create a new, thermally insulating roof tile made from recycled rubber as a replacement or complement to any insulating material. It can be laid on roofs and open terraces over habitable spaces, thus increasing the energy performance rating of buildings, particularly dwellings.
SCOPE FOR FURTHER RESEARCH

Parametric tests were performed to test the best percentage ratios in the mix design composition of the tile. From results obtained the newly designed tiles generally increase the thermal efficiency of the building. By increasing the thickness and also the rubber content of the tiles, the average range of U-values obtained scaled from 1.85 to 1.22 W/m²K. This is still higher then the minimum requirement for thermal transmittance allowed off roof structures in Malta, that is, 0.59 W/m²K (Technical Guidance Document, Part F, of the Building Regulations of Malta).

Although results are already promising, unless a very thick tile is used one would not achieve sufficient reductions in thermal transmittance therefore testing the tile further is recommended with the addition of complementary insulation. More work also needs to be done on varying the basic parameters, namely the design mix of rubber to sand ratio, beyond 60%, as well as the thickness of a tile over 90mm. Another area to be delved into is the aerated concrete itself, where a greater porosity brings with it a greater insulating property; hence modifications to the design mix can be tested. Different types of rubber as well as its granulated size (larger granules to pulverised) is also worth investigating. Moreover, the tile’s abrasive resistance, inherent durability, and its resistance to moisture are among a few other areas within the scope for further research.

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Design Interventions to Encourage Pro-Environmental Behavior:
An Action Research Study on Waste Diversion in a University Residence Hall

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ABSTRACT
This action research study examined the effectiveness of four design interventions, which aimed to encourage students to recycle and compost in a university residence hall. The study took place at a major university in the United States, where recent efforts have been made toward a “zero waste campus”. Zero waste is defined as diverting more than 90% of waste from landfill. In 2011, The Ohio State University successfully implemented a zero waste program in their football stadium and now plans to convert the entire campus to zero waste by 2030. Implementing zero waste across campus, however, proves challenging—especially in residence halls as they require a more complex logistical infrastructure and rely heavily on students’ knowledge, attitudes, and practices. Using approaches from social practice design and anthropology, this study examined practical and scalable interventions with the ultimate goal of assisting in the future transition to zero waste. On a larger scale, these results may provide new knowledge in comprehensive waste management and methods of social practice design that encourage pro-environmental behavior change.

INTRODUCTION
Comprehensive solid waste management is a major challenge to sustainability. The practice of recycling diverts materials from landfill, reduces pollution, saves raw materials and conserves energy. Still, inconveniences of recycling and engrained social practices lead to minimal participation in recycling and composting programs—only 34 percent of America’s waste was recovered in 2012 [1]. Academic institutions have begun to realize their environmental obligations to promote sustainable behavior among students, faculty, and staff [2, 3]. Zero waste is an emerging goal of sustainable materials management, where 90% or more of solid waste is diverted from landfills. To assist in recent efforts towards a “zero waste campus,” this action research study explored the decision-making process associated with recycling on campus and examined the effectiveness of four design interventions encouraging students to recycle and compost in a university residence hall.

CONTEXT
The study took place at a major university in the United States, where recent efforts have been made toward a “zero waste campus”. Achieving zero waste requires a shift from a waste management mindset to a resource management mindset where technical and biological nutrients are treated separately and have productive destinations [4, 5]. Zero waste plans are comprehensive and require diversion and aversion efforts including: material capturing, waste stream modification, and waste...
prevention. While waste stream modification and waste prevention are ongoing, material capturing can be improved through proper sorting practices.

In recent years, The Ohio State University (Ohio State) has made great strides in zero waste. In 2011, the Office of Sustainability started a zero waste program in their football stadium—one of the largest in the country. The stadium frequently holds over 105,000 fans and on average accumulates 8-10 tons of waste per game [6]. By 2013, the program was successful in diverting over 98% of waste—an average of 8 tons per game! Control over the material stream, cooperation from fans, and the ability to sort on the back end were critical components to the project’s success [7].

After achieving zero waste in the football stadium, Ohio State set an ambitious goal to transition their entire campus to zero waste by 2030. This goal was articulated in 2008, and in 2013—five years later—the campus was still only capturing 31% of their waste (Fig.1)[8]. To determine how much of their waste had the potential to be captured, Ohio State completed a comprehensive waste audit in 2013. The audit found that 89.1% had the potential of being recycled or composted (Fig. 1). In other words, Ohio State has the ability to increase their current diversion rate of 31% to their potential diversion rate of 89% by improving sorting practices. This shift to zero waste not only involves structural changes in how waste is collected and processed, but also behavioral changes for members of the institution [9].

![Image: Current Diversion Rate (31%) compared to Potential Diversion Rate (89%), 2013](image)

**Figure 1: Current Diversion Rate (31%) compared to Potential Diversion Rate (89%), 2013**

**APPROACH**

Interventions that promote recycling are not new, but these strategies typically address recycling as planned behavior that is guided by a rational decision-making process. Many decisions made throughout the day, however, are not rational. In terms of decision-making, people are governed by two systems of thinking: the automatic system guided by intuition, and the reflective system controlled by rational thought [10]. With a limited capacity for rational thought, many decisions turn to the automatic system where the least amount of thinking occurs. Months of observations across campus suggest that recycling is often one of these automatic decisions. As a result, the way recycling choices are presented can greatly influence the choice that is made [10]. On campus, throwing waste in the trash currently requires the least amount of thinking, in other words trash is automatic and as a result many people do not recycle.

The intervention strategies in this study targeted the automatic system and the reflective system to determine what factors most influenced students’ recycling practices. All interventions targeted the automatic system by sharing a new infrastructure where recycling and compost became automatic. Incrementally higher-level interventions targeted the reflective system by introducing education, eco-feedback, and social influence. This study used approaches from social practice design and anthropology and was completed in four iterative phases: ethnography, intervention design, intervention experiment, and analysis.
Ethnography

The research team used a grounded theory approach to observe recycling behavior and ask students why they recycle or not. The goal was to identify students’ knowledge, attitudes, and practices in regards to recycling in order to develop a theory of student decision-making. Observations and interviews took place in the participating residence hall and the main dining facility.

Students admit that they typically choose the easiest way to dispose of their waste. Many students even throw things “away” subconsciously. They often choose the nearest bin out of convenience and rarely go out of their way to recycle. Some students will recycle more obvious items such as bottles and cans, but many students throw everything in the trash because they do not have to think about what can be recycled. Some students fail to recycle because they feel their individual behavior does not make a significant environmental impact. And while there is some social pressure to keep an environment clean by not littering, students feel little social pressure to recycle. These findings became the theoretical framework that guided the strategy and development of the design interventions.

![Emerging theory of students’ decision-making process in regards to recycling](image)

**Figure 2: Emerging theory of students’ decision-making process in regards to recycling**

**Intervention Design**

Prior to the intervention experiment, the participating residence hall provided students with 2 large trash bins that were picked up by housekeeping daily (one in the bathroom and one in the common living room). If students wanted to recycle, they were given a small recycle bin and it became the students’ responsibility to collect recycling and empty the bin. Students had to find a location for their bin, decipher what could be recycled, collect recycling, and empty on a regular basis—a much more laborious activity (mentally and physically) than throwing waste in the trash.

The emerging theory of decision-making suggested that students will recycle if it is easy, accessible, and they know what is recyclable—in other words they will recycle if it becomes automatic. On the other hand, students may not recycle if they have a limited understanding of their environmental impact, or a lack of social pressure. So, are clear instructions and an easy/accessible system enough to achieve zero waste in residence halls? Or do education and/or social pressure lead to higher diversion rates? The four interventions were designed to answer these questions. Interventions were incremental. That is, each intervention had increased involvement with students and thus, built in complexity. Design interventions 1–4 had the same baseline zero waste infrastructure and instructional signage. While, interventions 2, 3, and 4 built in complexity with increasing levels of environmental messaging and social pressure. The hypothesis was that higher-level interventions would have more influence on students’ compliance with the zero waste program.

The interventions were implemented as follows:

**Intervention 1: New Waste Collection Infrastructure.** The previous system made trash disposal very easy and recycling more difficult. In this new system (Fig. 3), the trash bin in the common room was converted to **recycling** and the trash bin in the bathroom was converted to **compost**. A small **landfill** bin was added to the bathroom for personal hygiene waste. The housekeeping staff emptied all three bins daily. Both the compost and recycle bins were accompanied by a simple instructional poster.
Intervention 2: Education. To further eliminate confusion about recycling and composting, intervention 2 utilized educational posters to provide general information about questionable materials (Fig. 4). These posters showed the environmental impact of recyclable and compostable materials and encouraged students to reuse and reduce. Posters were placed on the bathroom stall doors.

Intervention 3: Eco-feedback. To help students reflect on the impact their everyday practices had on their community and the environment, intervention 3 utilized social media to educate students on their behavioral impact, and suggest ways to make an even greater impact. Digital white boards were also placed beside the resident advisor’s (RA) room to allow students to ask questions and offer feedback. This gave students an opportunity to get involved in the conversation.

Intervention 4: Social Influence. To create a sense of peer-pressure, students volunteered to be Zero Waste Agents who made sure their suitemates complied with the new zero waste system. Casually but consistently the behavior and attitude of the Zero Waste Agents set examples for pro-environmental behavior.

Intervention Experiment

The participating residence hall consisted of eight floors and approximately 400 students. There were two floors and approximately 100 students per intervention. During the 30-day intervention experiment, a new logistical infrastructure was implemented (Fig. 5) where the housekeeping staff collected one large recycle bin, one large compost bin, and a small landfill bin daily. In addition to the new infrastructure (easy access and clear instructions), three higher-level design interventions were evaluated.
Figure 5: Logistics of waste collection during the 30-day intervention experiment

**Analysis**

The intervention effectiveness was measured and analyzed in two ways: (1) changes in practices—measured by overall waste diversion and accuracy of sorting, and (2) changes in perceptions—measured by reported knowledge, attitudes, and practices. Professional waste audits and weekly visual assessments were recorded to determine diversion rates and sorting accuracy. Questionnaires were administered before and after the interventions to assess changes in perceptions. 101 students (43 women and 59 men) responded to the pre-experiment survey and 26 students (16 women and 10 men) responded to the post-experiment survey. Data was analyzed for each individual intervention and all interventions as a whole.

**FINDINGS**

**Changes in Practices**

During the program, students sent an average of 71% of their waste to be recycled and composted, a significant increase compared to the 31% campus average in 2013. Figure 6 shows the waste distribution before the experiment (campus average), during the experiment (in a single residence hall), and the goal to achieve zero waste in 2030. The results show a significant step towards zero waste residence halls in a very short period of time.

![Figure 6: Results of experiment in comparison with campus average and campus goal](image)

Comparatively, the four interventions showed no significant difference in the amount of waste diverted, however, there was a significant difference in the accuracy of sorting (Fig. 7). The baseline...
intervention achieved 82% overall sorting accuracy. The highest-level intervention—using Social Influence—achieved 85% sorting accuracy, but showed no statistical difference from the baseline intervention. The second and third level interventions, however, both achieved 76% sorting accuracy and showed a statistically significant (and surprising) decrease of 6% from the baseline intervention. In addition to differences between interventions, across the board, sorting accuracy of recycling (62% average) was significantly lower than sorting accuracy of compost (92% average).

![Sorting Accuracy Across Interventions](image)

**Figure 7: Results of sorting accuracy for each intervention**

**Changes in Perceptions**

As a whole, students’ perceptions about recycling and composting changed significantly after experiencing the design interventions (Fig. 8). In general, students reportedly had a better understanding of how to recycle properly and tried harder to comply. After the experiment, they found recycling more rewarding and felt more strongly that it could positively impact their community and the environment. Students also felt more optimistic that by recycling they could motivate others to recycle. Comparing pre and post surveys, students in intervention groups 1&4 reportedly tried harder during the experiment, while students in intervention groups 2&3 showed no significant change in their effort.

![Student Perceptions Before and After Interventions](image)

**Figure 8: Changes in students’ perception before and after the intervention experiment**
DISCUSSION

Overall, having large, accessible recycle bins that were picked up daily by housekeeping drastically increased (more than doubled) the amount of recyclables collected—although sorting accuracy could be improved. To increase sorting accuracy, the authors believe it would be beneficial to have the compost bin directly next to the recycle bin in the common room. Students typically ate in the common room, and the main recycling contaminant was food waste. In order to dispose of food waste properly, students had to walk to the compost bin in the bathroom. The primary reason for having compost in the bathroom was to easily dispose of paper towels. However, if paper towels could be eliminated or minimized, the compost bin could be next to the recycle bin, making it easier for students to dispose of their food waste.

When comparing intervention effectiveness, student participation did not increase with each level as hypothesized. However, students in intervention groups 1 and 4 reportedly tried harder and achieved greater success during the experiment. Why is this? What did intervention group 1 and 4 have in common? To find out, we interviewed students at the end of the study and asked why the baseline intervention might have done as well as the highest-level intervention. One of the Zero Waste Agents mentioned that the RAs on the floors assigned to intervention group 1 and 4 were highly involved with their residents. Although the RA involvement was not a controlled variable, it was certainly an unavoidable influence that could vary widely from floor to floor. It seems that peer influence was present on all floors (not just intervention 4) in the presence of an RA, and that some RAs are better than others at getting their students to participate in activities; in this case, the zero waste pilot program.

It is important to note the limitations of the study. First, the intervention experiment was implemented in the middle of the school year. Students were accustomed to the existing waste system, and compared to starting a system at the beginning of the year, they could have been more resistant to change. Second, the study did not include a waste audit of the participating residence hall prior to the intervention experiment. Therefore, an assumption was made that the material stream and recycling rates in the residence hall did not widely vary from the campus-wide stream. Observations made prior to the intervention experiments confirmed that students were recycling 25-30% of their waste, however these limited data points could not be used for statistical analysis.

CONCLUSIONS

How close to zero waste can we get with a simple and efficient infrastructure? Is education as important as we think when it comes to encouraging recycling behavior? What kind of influence does social influence have on student’s recycling behavior? This study suggests that when people are faced with a choice, a large number will accept the default, the option that requires the user to do nothing [10]. A simple and efficient infrastructure can be a great start to achieving zero waste. And surprisingly, education may not be as important as we think, but social pressure can significantly influence students to recycle and compost.

In this study, a simple and efficient infrastructure was the foundation for a successful zero waste program. Many residence halls offered frequent pick-up of large trash (landfill) bins, but students took out recycling in small crates. Offering recycling and compost pickup made the recycling process easier and more accessible to students. In addition, appropriate bin size and bin placement were essential to the success of a zero waste program. In general, bin sizes should more accurately reflect a university’s material stream (which Ohio State determined to be 60% recycling, 30% compost, and 10% landfill waste) and bins should be placed in the room where the majority of that material stream is accumulated. Students also need clear and simple instructions.

Beyond instructions, additional education about recycling, composting, and environmental impact had little impact on the greater success of this zero waste program. Students did, however, show an interest in having access to additional information online. Perhaps additional information could be shared through currently used social media channels (e.g. links to zero waste information on an existing residence hall homepage) accessible to those students with a desire to know more. Additional
information that is available, but not invasive, may be the motivation some students need to become advocates for change.

Finally, social influences played a very influential part of students’ daily recycling practices. This study addressed peer-to-peer relationships and authority figures as influencers of student perceptions and behavior. A peer influence, especially from a mentor who is relatable and respected, can significantly motivate students to participate in pro-environment behaviors such as recycling. While changing the default from trash to recycling through a simple zero waste infrastructure was the first step towards increasing diversion rates, behavioral reinforcement from recycling advocates, especially resident advisors, significantly increased compliance.

This study specifically targeted the residential population at a large university in the United States, however findings from the study revealed significant considerations for comprehensive waste management as well as design intervention strategies that encourage pro-environmental behavior. This study focused on waste management, but the findings can be applied to many institutional behavior change endeavors.

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Session 7A : Passive design

PLEA2014: Day 3, Thursday, December 18
10:25 - 12:05, Auditorium - Knowledge Consortium of Gujarat
From Romance to Performance: Assessing the Impacts of Jali Screens on Energy Savings and Daylighting Quality of Office Buildings in Lahore, Pakistan

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ABSTRACT

Jali Screens are traditional window treatments used in vernacular buildings throughout South Asia and the Middle East. Historically, the screen treatments are successful in providing shade and privacy for building occupants in hot arid and hot humid climates. With interest in traditional building features, recent trends in contemporary buildings design have started to incorporate Jali screens or other screens as decorative façade elements. However, the use of these screens has been widely approached from the aesthetic and romantic attitude representing an architectural fascination with the vernacular. Their impact on overall building energy and daylighting performance, however, has been largely ignored. This paper reports on the results of a multi-methods research project to evaluate the impact of traditional Jali screens with various perforation ratios on energy utilization and daylighting quality in contemporary office buildings in Lahore, Pakistan. The study combined a field assessment of traditional Jali screen performance in historical settings with various geometries and an experimental simulation of the different screen perforations on contemporary offices' energy behavior and daylighting autonomy. The hypothesis studied is that Jali screens with 30%-50% perforations will provide an optimized condition between energy savings and daylighting quality in office buildings. Independent variables including building envelope insulation, shading factor, and perforation percentages of Jali screens were manipulated through different simulation models of an existing office building. The dependent variables in the form of overall energy utilization intensity (kbtu/sf/yr), daylighting autonomy, and annual solar exposure were analysed for the different screen attributes. Simulations, using computational energy modeling, have revealed that Jali screens impact cooling loads and improve visual comfort in office buildings. Moreover, it suggests that designers should look at traditional building strategies from a holistic perspective employing a whole-building approach including aesthetics and an intent to quantify its performance and learn from it without over-romanticizing it.
INTRODUCTION

Lahore, a modern financial center in Pakistan, is dominated with office buildings. These offices are air-conditioned throughout the year. In Pakistan, the current energy crisis makes evaluating building performance an urgent need in design practice. The climate of Lahore is typically characterized by a high intensity of solar radiation. Solar heat gain reduction is of primary concern as a means to reduce energy use and provide comfort to occupants in warm weather (Boake, 2014).

Unprotected glass curtain walls are not very climate friendly in warm and hot-humid Lahore. Typically occupants use blinds on the inside of the window to control glare only, while significantly increasing the total building energy when compared to external shading devices (Moeck et al.). Prior research based on the Lahore region did not use the weather data for Lahore, instead similar climate data was used to draw relevant conclusions. Figure 1 shows a psychrometric chart for Lahore, Pakistan (Source: Climate Consultant 5.5 (B1). While the climate of Lahore is such that comfort is only achieved 15% of the time; an additional 24% comfort time can be achieved through sun protection or shading of windows alone.

![Figure 1. Psychrometric Chart for Lahore, Pakistan (using ASHRAE Handbook of Fundamentals Comfort Model, 2005)](image)

Certain envelope-design strategies have already proved to serve the purpose of energy saving in buildings (Olgyay et al., 1957; Dekay et al., 2014). There are several prescriptive sets of building criteria available to attain the thermal and comfort benefits, and ASHRAE has published several of them (Zhivov et al., 2010). However, such standards pertaining to thermal comfort are not available in Pakistan and the thermal properties of building construction in buildings are very poor. Single glazed curtain wall systems with low thermal resistance envelope designs are still prevalent. A few buildings in the Gulf area and in Pakistan have performance claims, which are not backed by any hard numerical evidence (Boake, 2014).

Jali screen façades have been widely used as vernacular shading devices in the Pakistan, India and Middle Eastern countries. Previous studies have proved their climatic adaptation and environmental
performance (Elzeyadi, 1996). Jali, in Urdu language, means a perforation or perforated screen. Over the years, architects and builders have acknowledged its benefits as a screen that filters light and air, while allowing selective privacy. Traditional Jali facades are replicated and used in contemporary buildings in Lahore, Pakistan. However, there is a lack in understanding of their performances in a quantitative manner and unavailability of scientific means that could be used for developing new efficient designs that suit the modern facades of office buildings in Lahore. Figure 2, shows an example of a contemporary building in Lahore where Jali facades are used as ornament and daylight is blocked out. Fathy (1986) indicated that perforated screens, for example Mashrabiya in Egypt (Fig. 3) affect the quality of space and improve visual comfort in spaces by reducing glare. Several studies show that external screens reduce solar penetration as solar radiation is rejected before hitting the glazing (IESNA Lighting Handbook 2013; Kwok et al., 2011). The hypothesis of this study was that Jali Facades in Lahore would help achieve thermal comfort and as well as improve daylighting performance in office environments.

**Figure 2. Mall of Lahore (left) is a commercial building with ornamental Jali Facades, Lahore (Source: author); Figure 3. The House of Suhaymi (right) in Cairo, with one of the Mashrabiyas, Egypt (Source: Wikipedia accessed on September 16, 2014).**

**Research Setting - Traditional vs. Contemporary**

Three Jali screens were selected from typical vernacular architecture of Lahore. The Lahore Fort has the largest collection of Jali screens in place from the Mughal times (16th to 19th century). All three cases selected for investigation are west facing with a perforation ratio of 30%, 40% and 50%. Perforation ratio, for this study, is defined as the ratio of void to solid area of a screen. The depth of screen was fairly constant at 0.25’ (3 inches) and after an analysis of screen geometry (Fig. 6) the depth to width ratio of 1:1 was taken as most commonly occurring.

A typical office building was selected to act as the contemporary research setting. This base case building was located in the Commercial Area of Y-Block, Defence Housing Society in Lahore, Pakistan. This building is at the corner junction of two main roads with facades facing South and West composed of single pane unprotected glazing. It consists of 5 floors including Basement, Ground, Mezzanine, First, and Second typical floors (Fig. 4). For detailed daylighting analysis two rooms on the Second floor are selected as shown in Figure 4. Information on building characteristics such as location, orientation, environmental factors, envelope characteristics, installation systems, comfort ranges, schedules, and occupancy were gathered (Caccavelli, 2000; Butala, 1999; Gücyeter et al., 2012). A total building energy audit was acquired for the whole year and readings for daylighting measurements were taken at a 3’ (three feet) grid on working plane for the two offices at morning and afternoon time, on a typical sunny day in April.
RESEARCH METHODS

The impact of Jali screens on energy conservation and visual comfort of typical contemporary office buildings in Lahore, Pakistan formed the core of this investigation. Details of variables, which affect the energy of building, cooling and lighting, were identified and formed the sub-questions of the study and a review of the literature. The results from the field study impacted decisions taken during the experimental design stage. Figure 5 describes the parameters used in the experimental design stage. In order to simulate conditions accurately, this research employs dynamic energy simulation, starting with a building audit of the existing base case scenario, which was then fed into the simulation model to assess existing performance levels and create a calibrated model. Figure 5 shows the flow of methods employed for this research.

![Figure 4. Contemporary Research Setting: West Façade (left); South façade (right).](image)

Computational and environmental simulation software, IES Virtual Environment Pro (IES VE), program used in this experimental research (Kim et al., 2012) and has been verified in many publications (The American Institute of Architects, 2012; Elzeyadi, 2009). Only four modules of the package were used to carry out this investigation, which are “ModelIT”, “SunCast” for solar shading analysis, “Radiance” for dynamic lighting simulation and “Apache Sim” for thermal simulation (Muhaisen, 2006; Aldossary, 2014).

Next, Jali screens defined from the traditional research setting (traditional building cases) and designed for this experiment were tested through the calibrated model. The calibrated model was further validated with Target finder and the EUI values in the base case were found to be too high for a balanced experiment. High performance thermal constructions were employed and verified as having a significant impact on performance. Furthermore, all shading devices were based on the optimized base case model (Fig. 5).

Envelope design in Lahore is very leaky and has low R-value. High performance buildings require not only good shading design but also thermal constructions with higher R-values. Research has shown that with bad thermal construction and leaky envelopes, shading devices cannot achieve the same effect as a good thermal construction (Sourced from GCT High Performance Template) (Elzeyadi, 2008). High performance materials were used for further final simulation for testing all shading devices (Table 1).

| Table 1. High Performance Thermal Constructions used in Simulation Model |
|-----------------------------|-----------------------------|
| Roof                        | High Performance Roof [R40] |
| External Wall               | High Performance Wall [R-30]|
| External Glazing            | Low-e Triple Glazed [R-5]   |
| Ground Floor                | Super Insulated Floor [R-25]|

30th INTERNATIONAL PLEA CONFERENCE
16-18 December 2014, CEPT University, Ahmedabad
Further optimization was achieved through the use of dimming profile for lighting controls (High performance Template) (Elzeyadi, 2008). According to this template, a value of 360 lux was set on the work surface to optimize lighting controls such that maximum utilization of daylighting was achieved and electric lighting minimized during an ASHRAE work day of 8:00 am till 6:00 pm. Figure 5 shows the process through which the simulation model was calibrated and optimized to achieve the best results for assessment of Jali screen façades.

Jali patterns were investigated and derived in the traditional research settings. It was found that most shapes were derived from a hexagon in the Jali screens (Fig. 6). In order to simplify the process, therefore, basic shape of a hexagon was selected for the purpose of experiment. To find a screen configuration of highest energy saving potential, a range of solar screen designs was examined by performing computer simulation using IES VE dynamic simulation software.

**Figure 5. Flow Chart of Performance Monitoring, Calibration and Optimization**

**Figure 6. Jali Geometry Detail**

**ANALYSIS**

**Energy Performance and Thermal Comfort**

Initial data collection from base case contemporary building indicated that the temperatures were out of comfort range. Both diagrams (Fig. 7) show how the temperature recorded in the study rooms was
found to be out of the comfort zone defined by ASHRAE 2005 Comfort Model (Climate Consultant 5.5 B1) and Center for the Built Environment: CBE Thermal Comfort Tool.

To account for building energy consumption, Energy Utilization Index (EUI) was used to compare the energy benchmarking of building and design strategies. Mean EUI of commercial buildings in the US was calculated from Target Finder and used to compare with the base case EUI in Lahore (Fig. 8). EPA’s online Target Finder Calculator (EnergyStar) was used to find the base case building Site EUI for a similar climate zone in the US. Target finder US Base case was 77 kBtu/ft²/yr and the value of existing building is calculated at 254 kBtu/ft²/yr.

The base case contemporary building was then modeled with the existing construction techniques in the building as built in Lahore, Pakistan. The results of this simulation showed a high value of 80.3 kBtu/ft²/yr. When using better construction, i.e., using GCT High Performance template, as shown in Table 1, studies have shown significant impact on the energy performance of buildings (Elzeyadi, 2008). Introducing better thermal construction reduced the EUI to 67.68 kBtu/ft²/yr. Furthermore; the existing conditions of base case were not optimized for lighting and solar gain. By introducing a dimming profile of ASHRAE 8:00 am – 6:00 pm workday, the EUI was further reduced to 55.01 kBtu/ft²/yr (Figure 9).

![Figure 7. Psychrometric Chart (South - left) (West - right)](image)

![Figure 8. Building EUI comparison with Energy Star Rating](image)

External shading devices, three types of Jali screens, were then added to this computational building model. As shown in Figure 10, EUI improved with perforation ratio of 30% to 50%, with 50% Jali perforation screen as the best performer due to combination of solar heat reduction and daylighting potential.
Daylight Performance

Experiments for the previous simulations were conducted in Radiance module of IES VE dynamic simulation software. The times of the day were set to the 8:00 am to 6:00 pm workday, per IES standard a given preset in IES VE dynamic simulation software. The reference plane on which daylighting performance was simulated contained sensors at a height of three feet above floor (working plane). Dynamic daylight performance metrics were used to assess the illuminance ratios within the rooms. These simulations extended over the whole calendar year and were based on external, annual solar radiation data for the building site. The key advantage of “dynamic daylight performance metrics compared to static metrics is that they consider the quantity and character of climate and seasonal variations of daylight for a given building site together with irregular meteorological events” (Reinhart et al. 2006). Two metrics used in this research were Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) both defined by IESNA (IESNA Lighting Handbook) and found most suited for assessing daylighting quality in an office environment and solar penetration through the Jali screens.

South Orientation

When assessing through the Spatial Daylight Autonomy (sDA) metric, all shading strategies fulfilled the criteria of being 100% as shown in Figure 10 (Green – pass; red – no pass). There was sufficient daylighting to fulfill the minimum daylighting criteria. However, Annual Sunlight Exposure metric was not fulfilled barely towards the back of the room in 30% Jali perforation ratio. It is predictable due to the lesser lighter penetrating deeper on South. This indicated further shading in the deeper parts of the building.

West Orientation

In the west room, the Spatial Daylight Autonomy (sDA) could not be achieved in lower perforation ratios. For the optimum lighting requirement, dependence on electrical lighting increased, while impacting lighting energy (Fig. 10). Similarly in Annual Sunlight Exposure metric, 50% Jali perforation received maximum amount of direct beams of sunlight in comparison to lower perforation ratios (Fig.
Discussion

Energy was measured and assessed in the EUI metric (Fig. 9 & Fig. 10). The thermal construction of a building had a large impact on its energy performance. This study showed that by optimizing the thermal construction using Green Class Toolbox (Elzeyadi, 2008) high total energy savings were made possible. Earlier, it had been discovered during field research, that thermal constructions of buildings in Lahore is not up to ASHRAE standard. Installing standardized construction by using thermal and vapour barriers in building envelope should dramatically improve performance of buildings (Fig. 9). Solar shading devices on windows are significant components of vernacular building façades in Lahore, Pakistan. This research showed (Fig. 10) how each of the three Jali screen façades affected the total energy of the building. Out of the three screen geometries, it can be concluded from this study that the 50% perforation ratio performed best (1:1 perforation to depth). As the perforation ratio was increased from 30% to 50% whole building energy performance improved due to decreased reliance on electrical lighting for daylighting (Fig. 10 & Fig. 11). In comparison, 50% Jali perforation was the better option for a balanced energy approach to provide thermal comfort and provide optimum daylighting. The impact of Jali screen geometry on energy performance is significant to suggest that designers may use this research to improve thermal visual comfort in contemporary buildings and reduce dependence on electricity.

South Orientation

<table>
<thead>
<tr>
<th>sDA</th>
<th>Annual Sunlight Exposure</th>
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<tbody>
<tr>
<td>Base Case</td>
<td></td>
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<tr>
<td>30% Jali</td>
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<td>40% Jali</td>
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<tr>
<td>50% Jali</td>
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West Orientation

<table>
<thead>
<tr>
<th>sDA</th>
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<tbody>
<tr>
<td>Base Case</td>
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<tr>
<td>40% Jali</td>
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<td>50% Jali</td>
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Figure 11. South Orientation (left) Spatial Daylight Autonomy: (left) and . Annual Sunlight Exposure (right); West Orientation (right) Spatial Daylight Autonomy: (left) and . Annual Sunlight Exposure (right).

CONCLUSION

This research examined the effect of Jali Screen façades on the year round energy performance and
daylight performance through a dynamic simulation model. The conclusion is focused on the impact of shading devices beyond the aesthetic application; in particular, the geometry of Jali screens façades on Energy Saving and Daylighting Performance in contemporary office spaces in Lahore, Pakistan. For each of the two orientations, South and West, three Jali screens were designed and simulated. In order to draw a conclusion from this study, a holistic approach towards cooling and lighting energy is required, using a whole building design approach. While implementing Jali screens in contemporary façades, designers may seek aesthetic quality along with thermal and visual comfort. Masterbuilders had embedded this information in the various screens found in the traditional architecture of Pakistan, especially Lahore, and we can re-learn from these façade systems to develop a high-performance building design. Jali screens can be optimized for beauty and performance given the parameters are carefully designed.

REFERENCES


Concept, Design and Performance of a Shape Variable Mashrabiya as a Shading and Daylighting System for Arid Climates

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ABSTRACT

The design of a solar protection system that can minimize solar gains while maximizing daylight and view to the outside is particularly challenging in arid climates, such as in the Middle-East, where sand, wind and corrosion impose specific constraints. We propose a system that provides a trade-off for three requirements: (i) maximize diffuse sunlight and view to the outside, (ii) efficiently block direct sunlight and (iii) transform a fraction of it into diffuse light for indoor daylighting. Compliance with this last requirement provides a solution for the common problem of insufficient daylighting even in the presence of abundant solar radiation, which often forces occupants to fully close their shading system and use electric lighting. In addition, our design potentially copes well with these extreme environmental conditions and preserves local architectural character (mashrabiya-inspired design). In this paper, we establish quantitative specifications for these three requirements, provide the working principle of our shading and daylighting system and its design, which consists of a shape variable mashrabiya (SVM). We calculate and analyze the annual daylighting performance of our SVM and benchmark it against the performance of Venetian blinds and diffuse sunlight alone. Finally, we provide the minimum reflectance required for the SVM to comply with our third requirement. We built a mock-up of our SVM to investigate the validity of our simulation model.

INTRODUCTION

The abundance of solar radiation in arid regions like in the Middle-East requires a very efficient shading system, in particular when aiming to provide visual comfort and prevent excessive solar gains. In addition, the combination of sand, wind and corrosion due to prevalent condensation creates harsh environmental constraints. On the one hand, the static vernacular solution named mashrabiya (perforated shield with oriental motifs) is well adapted to these constraints but fails to meet our contemporary needs for visual comfort due to insufficient daylighting and view to the outside. On the other hand, a kinetic shading system like Venetian blinds meets the requirements for efficient shading and for visual comfort (minimal glare, adequate daylighting and maximum view to the outside). However, to avoid excessive solar gains, such a shading system must be placed outside of the window, where it cannot withstand the harsh local environmental conditions. More sophisticated contemporary technologies embedded in the window, like electrochromic glass, are in principle unsuitable for these climates due to their propensity to absorb solar radiation resulting in excessive solar gains. Therefore, the challenge is to design a kinetic shading system that can cope with these harsh environmental conditions.

We propose a solution relying on a simple strategy to deal with abundant solar radiation that is applicable in these specific climatic conditions. With clear sky conditions prevailing throughout most of the year in these regions, strong direct sunlight on a window must be blocked without compromise. We
believe that fine adjustments of the shading system with solar incidence angle are not strictly necessary, and not even desirable when striving to minimize solar gains. With this assumption, the shading system is closed in the presence of direct sunlight, and open when diffuse sunlight dominates. The sufficiency of such a binary function facilitates the design of a simple and robust kinetic shading system with the potential to cope with harsh climate conditions. Another important motivation for using a kinetic shading system with binary operation is the possibility to obtain a solar responsive system by exploiting a novel passive actuator. Applied as such, our approach would provide insufficient daylighting when blocking direct sunlight. This limitation, which is commonplace - independently of climatic conditions - in most shading systems, quite absurdly forces the occupants to use electric lighting despite abundant daylight availability. To tackle this, we devised a shading system that allows blocking direct sunlight while transforming a sufficient fraction of it into diffuse light for indoor daylighting. In addition to this key design-goal, we will devise a system that aims to preserve local architectural character.

In this paper, we provide the high-level requirements for this shading/daylighting system and explain its working principle. Then, we establish more detailed specifications and present the resulting design. We investigate the minimal reflectance required for the system to meet our daylighting goals and calculate annual daylighting performance. We close with a discussion of our results and benefits of this novel customized solar protection for arid climates.

SHADING AND DAYLIGHTING SYSTEM

High-level requirements

Our shading and daylighting system must comply with the following technological, functional, and architectural requirements: 1) ability to switch in a timely manner between an open and a closed configuration, in the absence and presence of direct sunlight, respectively; 2) maximal daylighting and view to the outside in the open configuration; 3) efficient shading and minimal solar gains in the closed configuration; 4) transformation of a sufficient fraction of the blocked incident direct sunlight into diffuse indoor daylight; 5) ability to withstand the harsh local climatic conditions; 6) potential for coupling our solar responsive system; 7) preservation of some local architectural character by using a mashrabiya-inspired design in both the open and close configurations. To reflect the above requirements, we will designate our system as \textit{mashrabiya} , abbreviated SVM.

Concept and working principle

Our SVM is made of three identical perforated opaque shields that can move relative to each other to switch between an open and a closed configuration (Figure 1). A shield consists of a bi-dimensional assembly of identical perforated motifs, each covering a square area with side-length $\ell$.

![Figure 1 Concept and working principle of the SVM. (a) Open configuration. (b) Closed configuration.](image)

The first shield is always motionless. In the open configuration (Figure 1 (a)), used when diffuse sunlight dominates, the shields are exactly superimposed and nearly in contact with each other. In the closed configuration (Figure 1 (b)), activated in the presence of direct sunlight, the second (S2) and third (S3) shields individually move along the vertical and lateral dimensions (x- and y-axis) by half of...
the motif length ($L/2$), respectively. Moreover, they both move in the $z$ dimension to create a gap of length $\Delta z$ between the shields, whose role is to allow multiple scattering reflections. As illustrated in figure 2 (a), with an appropriate design, this results in the transformation of a significant fraction of direct sunlight into scattered light. Such a direct into diffuse light transformation (DDT) function must be optimized to obtain sufficient diffuse indoor daylighting.

To simultaneously move a shield along the lateral ($x$ or $y$) and axial ($z$) dimensions, we devised a mechanism requiring few components and minimizing friction. It consists of a simple parallelepiped mechanical structure that allows switching between the two configurations by rotating the structure of an angle ($\gamma$), as depicted in figure 2 (c). This structure allows simultaneously moving a whole assembly of mechanically interconnected shields from a single rotation point (P).

We plan to produce the required mechanical couple by means of a solar passive actuation and detection system based on a combination of custom optics and phase change material, which is currently being designed in our group. Such a solar responsive system, which is essentially restricted to binary actuation, lends itself well to moving our SVM. Since solar irradiation decreases with the cosine of incidence angle, solar gains are significantly reduced at elevation angles above 60°. Glare issues generally also become less critical in this angular range. Therefore, we designed our solar responsive system to switch from open to closed configuration at angles for $\theta < 60^\circ$ and $|\varphi| < 60^\circ$ (Figure 2 (b)).

The combination of such a simple solar responsive system (no detector, motor, electronics), whose description is outside of the scope of this paper, with this simple mechanical structure, is key to obtain a robust enough system potentially able to cope with the harsh local climatic conditions.

SPECIFICATIONS AND DESIGN OF OUR SHAPE VARIABLE MASHRABIYA (SVM)

Specifications

Shading. Specifications for shading depend on performance objectives, which are related to climate and to the usage of the space considered. Therefore, shading specifications are largely case-dependent. Here, we consider a public space (lobby, hall etc.) located in arid regions, for which glare and solar gains must be minimized. Such an objective can be formulated by means of a quantitative requirement on the maximum fraction of direct sunlight traversing the SVM structure. In the open configuration, since all three shields are superimposed, we simply need to specify the shading ratio (complement of the perforation ratio) of a shield of the SVM. Since, in the closed configuration, the shading ratio depends on the viewing direction ($v$), it is defined as: $\Sigma / \Sigma = (\Sigma_2 \cdot \Sigma_1) / \Sigma$, where $\Sigma_2$ and $\Sigma_1$ are the illuminated and shaded surface portions of an area $\Sigma$ (see figure 2 (b)). To establish a specification we need to introduce a more complex metric that accounts for this angular dependence of shading. We define the shading efficiency factor ($\Gamma$) as a percentage corresponding to the average shading ratio ($\mu$) minus the standard...
deviation of this shading ratio ($\sigma$) for all viewing angles to be considered in the closed configuration, i.e. for $\theta < 60^\circ$ and $|\varphi| < 60^\circ$ (see above). Assuming a Gaussian distribution of these angular shading ratios, subtracting $\sigma$ implies that the probability to have angular shading ratios lower than a specified $\Gamma$ is of about 15%.

Based on these considerations and definitions, we establish, somewhat arbitrarily, the following two specifications with which our SVM must comply to best meet our high-level requirements #2 and #3:

A. In its open configuration, the shading ratio must be lower than 50%.
B. In its closed configuration, for $\theta < 60^\circ$ and $|\varphi| < 60^\circ$, one must have: $\Gamma > 90\%$

**Direct into diffuse light transformation function (DDT).** The DDT function efficiency ($\eta$) of the SVM is the ratio of direct sunlight transformed into diffuse light to the incoming direct sunlight in the closed configuration. Our specification for $\eta$ is based on a benchmark and can be expressed as follows:

C. The DDT function of the SVM must provide daylighting at least equivalent to that provided by diffuse sunlight without a shading system (benchmark), throughout a whole typical meteorological year across the entire specific space considered.

**Mechanical requirements.** To reduce complexity and cost, no more than three shields must be used. To allow a simple and robust movement between the open and close configurations, as well as mechanical compliance with our passive actuation system, the mashrabiya shields S2 and S3 must move laterally (x-dimension) and vertically (y-dimension), respectively. Diagonal motions are not allowed.

**Design and results**

The final design of our SVM is the result of a trade-off between the mechanical and optical (A,B,C) specifications established above, while aiming for a mashrabiya-inspired design. Compliance with our mechanical specifications (three shields and orthogonal motions) is not easy to obtain given the conflicting specifications on shading for the open and the close configurations (max. shading ratio versus max. shading efficiency factor), in particular with the requirement of having a distance between the shield ($\Delta z$) and a mashrabiya-inspired design. Moreover, the shading efficiency factor ($\Gamma$), which must be maximized to meet the requirement for the closed configuration, decreases with the inter-shield distance $\Delta z$, while the DDT function efficiency increases with $\Delta z$, as explained later. What further complicates the design is that $\Gamma$ does not vary as a function of $\Delta z$ in a predictable manner because of the relatively complex geometry of the mashrabiya-inspired shield.

**Figure 3** Resulting SVM design in (a) open configuration, and (b) closed configuration. (c) Plot of shading efficiency factor ($\Gamma$) and DDT function efficiency ($\eta$) against $\Delta z$, expressed in shield units $\Delta \ell = \ell/64$. Onset: Angular distribution of shading ratio at design trade-off distance $\Delta z_o = 14 \Delta \ell$.

For our design, we used an iterative procedure with sequential calculations of $\Gamma$ as a function of
Δz for different shield geometries till we found a viable trade-off. To get fast calculations of \(\Gamma(\Delta z)\), we created a code in Grasshopper that calculates the shading ratio for all combinations of θ and ϕ angles varying in steps of 5° within the angular range (θ < 60° and ϕ < 60°), i.e., 169 combinations. The best trade-off we obtained led to the shield geometry shown in figure 3 (a). The corresponding closed configuration is shown in figure 3 (b). With this trade-off, we obtained a shading ratio of 54.1% and a shading efficiency factor of 88.7%, both values out of specifications (<50% and >90%, respectively). Figure 3 (c) shows the room for trade-off in the closed configuration between the variables \(\Gamma\) and \(\eta\) with conflicting trends.

Figure 3 (c) shows the plot of the DDT function efficiency \(\eta(\Delta z)\), which corresponds to a fit across values calculated further in this paper. As shown in this figure, \(\eta\) increases with \(\Delta z\) with a horizontal asymptotic behavior while \(\Gamma\), calculated with our Grasshopper code, decreases with \(\Delta z\) in a similar way. The distance \(\Delta z\) is expressed in a dimensionless unit corresponding to a fraction of the shield length motif (ℓ), which is \(\Delta z = \ell/64\) (arbitrary choice). We used this unit because \(\Delta z\) ultimately only depends on the motif length, which is a priori unknown and remains a free design parameter (see below). In principle, to meet our specs for \(\Gamma\), \(\Delta z\) must be smaller than \(8\Delta\ell\) (figure 3(c)). For our trade-off, we preferred to have higher \(\eta\) at the expense of an only marginally lower \(\Gamma\) (88.7%) corresponding to \(\Delta z_d = 14\Delta\ell\), which is the inter-shield distance used in our design. The onset of figure 3 (c) provides quantitative insights into the shading ratio versus the angle of view (θ and ϕ) at \(\Delta z_d\).

Our design procedure has provided the shape of the shield and the relative size of the SVM structure (\(\Delta z_d/\ell\)). The absolute size of the SVM, i.e. \(\Delta\ell\), and in turn \(\Delta z_d\), was determined by a subjective appreciation of the most suitable scale of our SVM for best acceptability in its open configuration, with respect to interference with view to the outside and visual aspect in a room. To this aim, we carried out a brief survey based on a real-scale mock-up and computer rendering simulations. This resulted in a general consensus that a suitable motif size (ℓ) is of the order of \(\ell = 16\) cm. This value yields an amplitude of displacement \(\Delta x = \Delta y = \ell/2 = 8\) cm and a distance \(\Delta z_d = 14\Delta\ell = 14\ell/64 = 3.5\) cm.

**DAYLIGHTING PERFORMANCE**

To gain quantitative insights into indoor daylighting with our SVM, we need to evaluate the annual daylighting performance in a relevant case-study. Another specific goal is to determine whether our SVM - in its closed configuration - allows comparable or superior illumination than that provided by diffuse sunlight. First, we need to optimize the DDT function of our SVM.

**Optimization of DDT function**

The DDT function efficiency (\(\eta\)) of the SVM, i.e., the ratio of direct sunlight transformed into diffuse light to the incoming direct sunlight, mainly depends on three parameters: the angular intensity scattering distribution of the shield material - characterized by the “specularity” parameter (S) in RADIANCE, the distance between the shields (\(\Delta z\)), and the reflectance of the shield material (R).

To investigate the first two parameters (S and \(\Delta z\)), we opted for a brief sensitivity analysis by means of “point-in-time” simulations with the software DIVA-for-Rhino, which exploits RADIANCE algorithms. Light scattered by the SVM was measured as a function of S and \(\Delta z\) at a location free from any direct sunlight contribution (ceiling). First, the parameter S was varied in five equal steps of 0.2 between a Lambertian and a much more specular intensity scattering distribution (S = 0.1 and S = 0.9 in RADIANCE, respectively). Quite surprisingly, the simulations revealed that \(\eta\) is nearly independent of specularity. The parameter \(\Delta z\) was then increased in five even steps between \(\Delta z = \ell/10\) to \(\Delta z = \ell/2 = 8\) cm. The simulation results revealed that \(\eta\) increases with \(\Delta z\) with a horizontal asymptotic trend. As shown earlier, this is the specification on \(\Gamma\) that sets a limit on \(\eta\) leading to the optimal trade-off distance of \(\Delta z_d = 3.5\) cm. Due to lack of space, we do not provide all the details of this sensitivity analysis.

Given that \(\eta\) obviously increases with reflectance, such an analysis is not required for this
parameter. However, since the maximum reflectance value is practically limited by the availability of suitable materials and by ageing - especially when exposed to outdoor conditions - it is essential to determine the minimum value for R that allows for compliance with our specifications on $\eta$ (see above). One option to find the minimal R would be to carry out a sensitivity analysis by means of annual daylighting simulations. However, since these simulations are very time consuming (around eight days) with the available computer resources, and are thus impractical for such a sensitivity analysis, we opted for getting a rough estimate of the minimum R required using the method described below.

**Determination of minimum reflectance: method and results.** Our goal is to find out what is the minimal reflectance of our SVM that provides, in closed configuration, an illumination just superior to that provided by diffuse sunlight without any solar protection. Since our SVM is meant to be used in arid climates, we chose to carry out our investigation for Abu Dhabi (latitude 24.47°). Our method relies on point-in-time simulations with average values representative of the typical climate that prevails at this location. Calculation of the average diffuse sunlight - which corresponds to our benchmark - is based on the yearly average of all data for diffuse horizontal irradiance (between sunrise and sunset) provided in typical meteorological year (TMY) files. For Abu Dhabi this value was found to be equal to 130 W/m².

In a similar fashion, calculation of direct average sunlight illumination was based on the yearly average of all TMY data for direct horizontal irradiance with elevation and azimuth angles falling in the angular range corresponding to the closed SVM (same range as used for the calculation of $\Gamma$). We found a value of 479 W/m², which is used in our simulations at the mean angle of the range considered, i.e., at an elevation angle of 30°. Our calculations, which are performed with the Perez sky model in DIVA-for-Rhino, account for both the direct and the diffuse sunlight contributions.

Our simulation model consists of a rectangular volume with a square side covered by our SVM. We use one millimeter thick shields made of ten by ten motifs, corresponding to a size of 160 by 160 cm². To avoid direct sunlight, we calculated the illuminance as a function of the distance for the SVM ($I(z)$) along an axis centered on the ceiling-wall of our space, which is delimited by fully absorbing walls. The material of the shields had Lambertian scattering properties ($S = 0$, in RADIANCE).

**Results and analysis.** The results of our sensitivity analysis for the reflectance, obtained with point-in-time simulations using the method described above, are shown in figure 4 (a). The illuminance $I(z)$ calculated on the ceiling measurement axis is plotted for a few reflectance values (R=0.5, R=0.7, R=0.8, R=0.9) against our benchmark corresponding to yearly average diffuse sunlight in Abu Dhabi. These plots correspond to exponential fits through average illuminance values calculated at forty evenly spaced sensors along the ceiling measurement axis, which is approximately 210 cm long.

These results suggest that a reflectance larger than R = 0.7 gives an indoor illuminance slightly larger than that obtained with average diffuse sunlight conditions. Compliance with this key specification for R is demanding but still practically attainable with widespread materials.

Our relatively simple method can only provide rough figures for the benchmark and reflectance plots. Indeed, our point-in-time simulations are based on average quantities for diffuse and direct sunlight, and on a single average incidence angle for the latter. Moreover, we need to account for both spatial and temporal distribution of illuminance on the whole measurement plane. Annual daylighting simulations can provide more comprehensive and reliable figures, and improve our estimate of R.

**Annual daylighting performance**

**Method.** For the annual daylighting simulations, we considered a standard room with a West-facing glass wall. We analyzed and compared the annual daylighting performance obtained for three cases: a double pane glass wall without shading system, standard Venetian blinds and our SVM. The Venetian blinds are mounted on a double pane glass wall with 65% transmission, whereas the SVM in mounted on a double pane glass with low-E coating yielding 80% transmission. The room has a depth, width and height of 5 m, 3.52 m and 3.04 m, respectively. The sensor plane lies at a height of 85 cm with a clearance of 60 cm from the walls. This yields a sensor plane of 2.32 m x 3.8 m, which was divided into a grid of 160 sensors, each measuring 23.2 x 23.75 cm. The floor, walls, and ceiling were modeled
as Lambertian scattering surfaces with a reflectance of 0.3, 0.65 and 0.8, respectively. The SVM shields have a reflectance \( R = 0.8 \) and Lambertian scattering properties. The configuration of the SVM, as well as the orientation of the Venetian blinds, are determined by the angle of incidence of direct sunlight according to the acceptance angle specified for our solar responsive actuation system (see above).

For our calculations with the Venetian blinds, we used the same simplified model as implemented in the DAYSIM interface, in which three tilt angles (\( \beta \)) of the blinds are determined by the solar incidence angle (\( \theta \)) depending on specific angular thresholds. We used \( \beta = 0^\circ \) for \( \theta < 15^\circ \), \( \beta = 30^\circ \) for \( 15^\circ < \theta < 30^\circ \), and \( \beta = 60^\circ \) for \( 30^\circ < \theta < 90^\circ \), where \( \beta \) is taken relative to the window surface. This model uses standardized occupants behaviors. In the so-called “passive” behavior used here, the occupant leaves the blinds in their horizontal position (\( \beta = 90^\circ \)) for long times dominated by diffuse sunlight (e.g. in the morning for a West-oriented façade). An algorithm, which we wrote in Python, was used to determine the moments throughout a typical year (8760 hours) corresponding to the specific angles that determine the sequence of actuation for either shading systems considered (SVM and blinds). The illuminances corresponding to this sequence, which are calculated by DIVA-for-Rhino with the Perez sky model, are used for the calculation of temporal maps.

**Results and analysis.** Temporal maps are used to present the results of our annual daylighting performance simulations obtained for a double pane glass wall without shading system, with standard Venetian blinds, and with our SVM made of shields with reflectance \( R = 0.8 \) (Figure 4 (b)). The triangular color scale allows showing the Acceptable Illuminance Extent (AIE), introduced by Kleindeinst et al. 2012] to provide a visual representation of the fraction of our sensor grid that is above, below or within the illuminance range considered. Our range, which we call useful daylight illuminance autonomous (UDI-a), following Marjalevic’s definition, is defined by bottom and top boundaries of 500 and 3000 lux (sharp cut-offs), respectively [Mardjalevic, 2009].

Figure 4 Annual daylighting performance for a West-facing room. (a) Average-based point-in-time simulations for closed SVM. (b) Temporal maps for three cases, including closed SVM with shield reflectance \( R = 0.8 \). Triangular color scale allows showing spatial intensity distributions.

Without a shading system, illuminance exceeds our high boundary of 3000 lux nearly all afternoon-times (solar noon to sunset) for most of space, as expected for a West-orientation. During morning-times (sunrise to solar noon), illuminance falls within the UDI-a boundaries (500 – 3000 lx) for the whole space except at dawn-times. With Venetian blinds, assuming passive occupants behavior, illuminance falls within the UDI-a boundaries only in the middle of afternoon-times and below the low-
UDI-a boundary of 500 lux for the rest of time. At sunset-times, when Venetian blinds must block abundant direct sunlight, which quite absurdly yields insufficient daylighting, the DDT function of our SVM manages to ensure adequate daylighting. This key design-objective for our SVM was translated into a specification for the DDT function efficiency that we are now in a position to assess in more detail than with our simple investigation based on average point-in-time simulations. Comparing the illumination obtained with our closed SVM exposed to direct sunlight (afternoon-times) versus illumination produced by diffuse sunlight only, i.e. without shading system during morning-times, reveals that adequate illumination is reached in both cases. However, when considering the whole temporal map with spatial information, illumination with diffuse sunlight proves to be slightly superior than with our closed SVM made of shields with reflectance of 0.8 under direct sunlight. In principle, this reveals that the efficiency of our DDT function (\(\eta\)) is slightly below our specification and that the above mentioned simple investigation was too optimistic.

However, a thorough investigation (outside of the scope of this paper) revealed that our simulation provides reliable trends for spatial illuminance distributions but underestimates the amount of diffuse light scattered by the SVM, i.e. \(\eta\). Such a bias is caused by an insufficient number of simulation iterations imposed by the lack of available computational power. This investigation was based on the comparison of point-in-time simulations with corresponding measurements on a mock-up of our SVM. Further investigation is needed to estimate more accurately the magnitude of this bias and reliably account for it in our results. This mock-up was also used to get insights into aesthetics of our SVM.

**DISCUSSION AND CONCLUSION**

We have presented the design of a shading and daylighting system customized for arid climates focused on also preserving a Middle Eastern architectural character. Such a kinetic system design, which we named “shape variable mashrabiya” (SVM), strives to maximize visual comfort and minimize solar gains, while potentially coping with the harsh local environmental conditions. Our SVM enables to switch between an open and a closed configuration depending on direct solar irradiation. The latter configuration, which consists of a three-dimensional structure, blocks most incident sunlight while transforming a fraction of it into diffuse light used for indoor daylighting (DDT function).

Our results of annual daylighting performance simulations show that, thanks to its DDT function, our SVM provides adequate (within the UDI-a boundaries) and well-balanced (most of the time across the whole space) illumination, even in the presence of direct sunlight. In particular, in contrast to typical Venetian blinds, it provides sufficient daylighting under direct sunlight at low elevation angles. Considering that our simulations provide pessimistic figures for the DDT function efficiency (see discussion in last section), our results reveal that our closed SVM with shield reflectance of the order of 0.8 should provide comparable illumination than that obtained with diffuse sunlight. In addition to increasing daylight autonomy, i.e., allowing for energy savings, we believe that our SVM design bears some architectural value and aesthetic appeal that may favor its acceptability.

Future or ongoing work covers, among other things, the design and integration of the solar responsive system, the integration of an array of SVM into a facade, investigation of energy performance and field-tests to validate the robustness of our design in arid climates.

**ACKNOWLEDGMENTS**

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**REFERENCES**


Energy Efficient Hospital Patient Room Design: Effect of Room Shape on Window-to-Wall Ratio in a Desert Climate

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ABSTRACT

This paper reports on a research that utilized simulation techniques for identifying the most efficient hospital patient room designs and their associated window-to-wall ratios. Simulation of the energy consumption and daylighting performance of common patient room designs were conducted using a range of Window-to-Wall Ratios (WWRs). The paper focuses on arriving at solutions that balance between the reduction of energy consumption and the achievement of proper daylight distribution in the desert climate of Cairo, Egypt. Simulations were conducted using the Diva-for-Rhino, a plug-in for Rhinoceros modelling software to interface with the Energy Plus, Radiance and Daysim software. Results demonstrated that solar penetration is a critical concern affecting patient room design and window configuration in desert locations. Use of the outboard bathroom patient room design was found to be the least efficient among the tested alternatives. Although it has a smaller external wall size, it failed to provide energy consumption that is lower than that of the other options. Its best energy performance was 20% higher than that of the nested bathroom patient room design. However, the outboard bathroom design allowed for larger WWRs (70%-90%), which might prove useful for external view exposure purposes. The nested and inboard bathroom patient room designs provided better energy performance. However, this was on the expense of window size. The acceptable cases of these designs had smaller WWRs, (30%-40%). The results of this paper demonstrated the need for the careful consideration of the size of windows and openings in relation to different patient room designs. Simulation techniques can prove useful in this regard.

INTRODUCTION

Hospitals are typically considered one the most energy demanding building types. Patient rooms compose the largest volume of hospital buildings. The external walls of patient rooms represent the most significant part of the external surface area of these buildings. Windows can contribute significantly to the healing process and reduction of pain and length of stay in hospitals through the provision of daylight and allowance of external view (FGI, 2010). However, they can also contribute negatively to the energy consumption of these buildings, especially in desert climates, where the cooling load
represents a significant percentage of total energy consumption.

Sizing the windows of patient rooms should be carefully considered in relation to patient room shape. Some common patient room designs have a small external wall surface area with a large room depth, while others have larger external room surfaces and a reduced depth of the work area. The windows of patient rooms should minimize solar penetration, reduce overheating; yet at the same time maximize daylighting and patient access to external view. The objective is to reduce the total energy load while maintaining comfort and quality health care.

Literature addressed the effect of environmental aspects on healthcare delivery. Ulrich recommended that natural light improvement could help reduce stress and fatigue, while increasing effectiveness in delivering care, patient safety and overall healthcare quality (Ulrich, 1991 and Ulrich et al., 2004). In an attempt to develop patient room designs to create healing environments, the effect of natural daylight on the patients’ average length of stay in hospitals was investigated. Studied factors were patient’s average length of stay as an index of health outcome, and the differences in environment during daylight hours, such as illuminance, luminance ratio, and illuminance variation in the hospitals patient rooms (Choi et al., 2012).

In research work more relate to this study, energy efficient building envelope treatments were examined for a generic reference hospital in Thailand. Parametric analysis was conducted. The overall thermal transfer value, glazing material, Window-to-Wall ratio (WWR) and external shading devices were addressed. The annual energy savings due to increasing daylighting reached up to 15.4% and 11.3% for the electrochromic and green tinted glazing respectively (Chungloo et al., 2001).

Optimization of window opening in a hospital patient room was addressed in a research that aimed at providing daylighting, external view, while minimizing the energy consumption. An optimization methodology was demonstrated through parametric computer simulations to determine the optimum window design in the form of window width, sill and lintel heights and shading device depth (Shikder et al., 2010). The impact of using various window shading systems and different window glazing types on the energy consumption of a typical hospital Intensive Care Unit room space in Egypt was examined. It was found that energy savings reaching up to 30% could be achieved by the use of externally perforated solar screens and overhangs positioned at a shading angle of 45° (Sherif et al., 2013-a).

In another study, daylighting performance was simulated for a typical hospital Intensive Care Unit room space located in Cairo, Egypt. Several window configurations were simulated in the four main orientations, where the effect of adding shading and daylighting systems was examined. Successful window configurations were recommended for different window to wall ratios (Sherif et al., 2013-b).

The above review of literature demonstrates that a limited number of publications addressed with the relationship between hospital patient room designs and the associated window configurations. Research work concerned with this relationship in desert environments is almost nonexistent. Configuring the windows of patient rooms for energy efficiency, while providing acceptable daylighting levels, could pave the way for reaching more sustainable hospital designs.

**OBJECTIVE**

This paper aimed to compare the energy consumption and daylighting performance of common hospital patient room designs. Investigation focused on the design of windows facing the south orientation under the desert clear-sky of Cairo, Egypt. The larger aim was to arrive at satisfactory patient room designs that minimize energy consumption and maximize the utilization of daylighting, thus help improve the delivery of sustainable healthcare facilities.

**METHODOLOGY**

The methodology was divided into two consecutive stages. Stage one investigated the energy performance of the tested patient room design cases along with the alternative window configurations. Stage two concentrated on the analysis of daylighting adequacy for the cases which achieved acceptable performance in stage one. Three of the most common patient room designs were selected for
investigation. These were: Design A: the outboard bathroom patient room design; Design B: the nested bathroom patient room design; and Design C: the inboard bathroom patient room design. The tested rooms were assumed to have a similar floor area (22 m²). The layout, dimensions and parameters of the tested rooms are shown in Table 1 and Figure 1.

<table>
<thead>
<tr>
<th>Table 1. Parameters of the Tested Patient Room.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal Surfaces</strong></td>
</tr>
<tr>
<td>Walls</td>
</tr>
<tr>
<td>Ceiling</td>
</tr>
<tr>
<td>Floor</td>
</tr>
<tr>
<td><strong>Window Parameters</strong></td>
</tr>
<tr>
<td>Glazing</td>
</tr>
<tr>
<td>Sun Breaker</td>
</tr>
</tbody>
</table>

Seventeen window size values, expressed as Window-to-Wall Ratios (WWRs) were analyzed for each patient room design. The values ranged from 10% to 90%, at 5% increments. The shape and location of the tested windows alongside the external wall of the patient room space are illustrated in Figure 2. A horizontal sun breaker was assumed to be positioned on top to the window. Its overhang value provided a sun protection angle of 45°, as shown in Figure 3. This angle was based on the results of previous research work (Sherif et al., 2013 b).

Simulations were conducted using the climatic data of the city of Cairo, Egypt (30°6’N, 31°24’E, alt.75 m) that enjoys a year-round desert clear-sky. The city is characterized by a hot-arid desert climate,
according to Köppen-Geiger (2006). The tested patient rooms were assumed to be located on the second floor level of a hospital building, where windows were assumed to face no external obstruction. The external ground surface was assumed to have a 20% reflectance value. Grasshopper which is a plugin for Rhinoceros modeling software and a parametric modeling tool was used to automate the energy and daylighting simulation process. By activating this function, the Grasshopper plugin generated a parametric model for each WWR and ran a climate based analysis through DIVA interface. Energy simulation was conducted using the EnergyPlus software. Daylight simulation was conducted using the Radiance and DAYSIM software. The Diva-for-Rhino plugin for the Rhinoceros modeling software was used as an interface.

![Figure 3](image.jpg) The overhang of the shading device protecting the tested window.

Methodology of Stage One: Energy Consumption Analysis

The aim of this phase was to investigate the energy consumptions associated with the three tested patient room designs (cases A, B and C). The annual energy consumption resulting from the different WWRs of each patient room design was calculated. The cooling, heating and lighting energy consumption values were accounted for. The WWRs which resulted low energy consumption values falling within 3% from the lowest value for a certain patient room design were considered acceptable cases for such design.

Energy simulation parameters were selected to focus on studying the performance associated with room shape and window configuration. The effect of thermal transmittance through walls and ceiling from the adjacent spaces was neutralized. Thus, the thermal transmittance from all walls and ceiling, except that of the window wall, were set to be adiabatic. The effect of the adjacent rooms was considered to be of no relevance to the thermal performance sought in this comparative study. The building was assumed to be fully air conditioned and minimal thermal transmittance was expected from the other internal spaces that would have identical set conditions. The external wall was defined as a 0.35 m thick double brick insulated cavity wall with a U-value of 0.475 W/m² –k that carried the tested window at its center. The air conditioning system heating and cooling set points were assumed to be 22°C/26°C respectively. The occupancy time of the studied patient room was chosen to be all day, at a rate of 10 m²/occupant. The hourly lighting schedules that were generated through the annual Daylight Availability analysis by the Radiance and DAYSIM software were used as basis for artificial lighting energy calculations. This artificial lighting was set to be dynamically controlled by sensors according to daylighting adequacy.

Methodology of Stage Two: Daylight Availability Analysis

The aim of this stage was to evaluate the year-round daylighting performance of the cases that proved successful for each of the three design configurations in stage one. Simulation parameters used in investigations were: ambient bounces = 6; ambient divisions = 1000. The occupied time of the patient room was assumed to be from 06:30 AM to 10:30 PM. In this study, the reference plane on which daylighting performance was simulated was the patient bed level plane (0.90 m height). The spacing of the analysis grid was set at 0.7m * 0.7m. Four points were placed on the patient bed. The reference plane contained 46, 54 and 53 measuring points in each of the three tested patient room designs A, B and C respectively, as shown in Figure 1. The illuminance value was assumed to be 300 Lx (IESNA, 2000).
Three Daylight Availability evaluation levels were used (Reinhart & Wienold, 2011). First, the “daylit” areas were those areas that received sufficient daylight at least half of the year-round occupied time. Second, the “partially daylit” areas were those areas that did not receive sufficient daylight at least half of the year-round occupied time. Third, the “over lit” areas were those areas that received an oversupply of daylight, where 10 times the target illuminance was reached for at least 5% of the year-round occupied time. Two daylighting acceptance criteria had to be satisfied. First, 100% of the patient bed surface area should be “daylit”. Second, at least 50% of the patient room area should be “daylit”.

SIMULATION RESULTS

Results of Stage One: Energy Performance

The total annual energy consumption values expressed in Kwh/m² were calculated. The results are as shown in Table 2. It summarizes the energy consumption results in the south orientation at different WWRs for the three investigated room designs A, B and C. The cases that achieved the required threshold were highlighted with a light tone in the table.

Table 2. Total Annual Energy Consumption for Layout Designs A, B and C

<table>
<thead>
<tr>
<th>WWR%</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
<th>55</th>
<th>60</th>
<th>65</th>
<th>70</th>
<th>75</th>
<th>80</th>
<th>85</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design A</td>
<td>180</td>
<td>192</td>
<td>189</td>
<td>186</td>
<td>184</td>
<td>182</td>
<td>177</td>
<td>178</td>
<td>177</td>
<td>177</td>
<td>176</td>
<td>176</td>
<td>173</td>
<td>175</td>
<td>174</td>
<td>175</td>
<td>176</td>
</tr>
<tr>
<td>Design B</td>
<td>169</td>
<td>168</td>
<td>153</td>
<td>151</td>
<td>147</td>
<td>147</td>
<td>147</td>
<td>150</td>
<td>154</td>
<td>158</td>
<td>162</td>
<td>167</td>
<td>171</td>
<td>174</td>
<td>177</td>
<td>180</td>
<td>183</td>
</tr>
<tr>
<td>Design C</td>
<td>173</td>
<td>175</td>
<td>166</td>
<td>158</td>
<td>154</td>
<td>151</td>
<td>155</td>
<td>158</td>
<td>160</td>
<td>161</td>
<td>163</td>
<td>169</td>
<td>174</td>
<td>177</td>
<td>178</td>
<td>180</td>
<td>183</td>
</tr>
</tbody>
</table>

Use of design B that has a nested bathroom resulted in the lowest energy consumption among all three room design types. The consumption was as low as 147Kwh/m² in WWRs 30%-40%. Moreover, design C (inboard bathroom design) achieved a very close value of 151 Kwh/m² in WWR 35%. Use of these designs resulted in a better performance in comparison with Design A (outboard bathroom design) which failed to produce a value lower than 177 Kwh/m². Furthermore, use of Design A resulted in the highest energy consumption among all alternatives. It reached 192 Kwh/m² at 15% WWR. On the other hand, its consumption was lower than the other two alternatives at high WWR values. Using a 90% WWR with designs A and B resulted in comparatively larger energy consumption values, reaching up to 183Kwh/m².

On the other hand, the outboard bathroom design configuration (Design A) achieved larger window sizes and larger number of options in comparison with the other two layout configurations. The acceptable WWR range of Design A extended from 40 to 90%. Fewer acceptable WWR choices and smaller window sizes were identified for the nested bathroom configuration (Design B). These ranged from 20% to 45% WWR. A very limited range of WWRs was found acceptable in the inboard bathroom configuration (Design C), where only three WWR cases (30 to 40% WWR) met the required criterion. In design A, the bathroom location on the outboard wall reduced the size of the exposed external wall surface, thus reducing the thermal exposure of the patient's room to the hot desert climate. However, this was overcome by the increased artificial lighting energy load, as explained later. This was not the case in the nested and inboard designs, where the size of the external wall surface was much larger.

To explain the behavior described above, the lighting, cooling and heating consumption values were analyzed. As expected for a desert environment, cooling represented the highest values, followed by lighting electricity then heating loads, which were almost negligible as shown in Figures 4, 5 and 6.

The performance of design A is shown in Figure 4. The lighting electricity load significantly decreased with the increase of WWR. This could be attributed to the increase of daylighting use, which resulted in a reduction of artificial lighting. However, the nature of the patient room plan type resulted in overall higher levels of artificial lighting, with subsequent high cooling energy. On the other hand, the
cooling energy loads slightly increased with the increase of WWR. This allowed the acceptance of larger WWRs, reaching up to 90%. The use of an outboard toilet with the resultant small external wall surface dampened the effect of changing the WWR. This was observed in the gentle curve slope of the cooling energy consumption for WWRs 20%-90% that it is almost flat.

The performance of Design B is shown in Figure 5. The lighting electricity load decreased at a constant rate with the increase of WWR, while the cooling energy loads increased considerably with the increase of window to wall ratio (WWR). This is observed in the considerable increase and the curve slope of the cooling and the total energy use from 40% to 90% WWR. This could be attributed to the design of this patient room type that has a nested toilet that is associated with a larger external wall surface. This increased solar exposure and allowed the window transmitted solar energy.

The energy consumption of patient room Design C is shown in Figure 6. This design was found to produce behavior almost similar to that of Design B. Both share a large exposed external wall. It was noticed, thought that the cooling energy of design C was slightly higher than that of Design B. This could be attributed to the cooling load resulting from the slightly increased lighting electricity.
Results of Stage Two: Daylight Availability Analysis

In this stage, the cases that achieved successful energy performance in stage one were evaluated for daylighting adequacy. Results are shown in Table 3. In Design A, acceptable daylight availability was only achieved at large WWRs. Only 5 of the tested cases passed the daylight availability test in this case. On the other hand in Design B, 4 of the 5 tested cases resulted in acceptable daylighting performance. In Design C, all of the three tested cases resulted in an acceptable daylighting performance.

Table 3. Percentage of “Daylit” Area Relative to Patient’s Room and Bed Plane Areas

<table>
<thead>
<tr>
<th>WWR %</th>
<th>Design A</th>
<th>Design B</th>
<th>Design C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Room</td>
<td>Bed</td>
<td>Room</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>30</td>
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<td>35</td>
<td>41</td>
<td>54</td>
<td>62</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
<td>25</td>
<td>57</td>
</tr>
<tr>
<td>45</td>
<td>54</td>
<td>57</td>
<td>62</td>
</tr>
<tr>
<td>50</td>
<td>43</td>
<td>48</td>
<td>43</td>
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<tr>
<td>55</td>
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<tr>
<td>90</td>
<td>43</td>
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</table>

For more detailed discussion, eleven cases were analyzed for the outboard bathroom design (Design A). Simulation results revealed that the amount of acceptable “daylit” areas was directly proportional to the increase of WWRs values. Only large windows achieved adequacy in the case of the outboard bathroom design. For WWRs between 70% and 90%, the “daylit” area reached 72% of the space area, especially at 85% WWR. The “partially daylit” areas dominated the patient room, where it reached 50% of the space in average (40% to 65%). However, it decreased gradually until it became unnoticeable at 85% WWR (15% of the space). In contrast, the “overlit” area was almost constant (13% as an average) in the tested WWRs.

On the other hand, when the bathroom was located in-between two adjacent patient rooms (Design B: The nested bathroom), only four cases from five energy efficient ones achieved adequacy (30% to 45% WWRs). The “Daylit” area reached 80% of the space, at a WWR value of 45%. Although, the “daylit” area of the patient bed plane achieved adequacy in the 25% WWR case, it was unacceptable in relation to the overall patient room area testing (41% “daylit” area). The “Partially daylit” area decreased gradually until it almost disappeared (1%), in the case of 40% WWR.

For the inboard bathroom design (Design C), the three energy efficient cases (30%, 35% and 40% WWRs) were acceptable for daylighting performance. The “daylit” area values for the patient room space were almost similar (60% at an average). For the three design configurations, the "over lit" area percentages did not exceed 15% in average for overall the patient room space in all accepted daylight availability cases.
CONCLUSION

The energy and daylighting performance of three common patient room designs were simulated. The performance resulting from use of a range of window sizes (expressed as Window-to-Wall Ratios - WWRs) under the clear-sky desert sun of Cairo, Egypt was examined for each of these room designs. Table 4 summarizes the range of WWRs that were recommended for each patient room design for satisfying the energy and daylighting criteria. In addition, the balanced WWRs that satisfy both energy and daylighting criteria at the same time were identified.

Results of this study demonstrated that solar penetration is a critical concern affecting patient room design and window configuration in desert locations, like in Cairo, Egypt. Use of the outboard patient room design was found to be the least efficient among alternatives. Although it has a smaller external wall size in comparison with the other alternatives, it failed to provide an energy consumption that was lower than that of other two tested room designs. Its best energy performance was 20% higher than that of the nested bathroom design. This could be attributed to the increase of artificial lighting that resulted from allocating the bathroom along the external façade in the outboard bathroom design. However, the outboard design allowed for larger WWR values. This might prove useful for external view exposure purposes. Although the nested bathroom and inboard bathroom designs provided better energy performance, this was on the expense of window size. The acceptable cases of these designs had smaller WWRs, between 30% and 40%.

The results of this paper demonstrated the need for a careful consideration of the size of windows and openings in relation to different patient room designs. Simulation Techniques proved useful in identifying the window configurations that satisfy both the energy and daylighting requirements at the same time.

<table>
<thead>
<tr>
<th>Table 4: Recommended WWRs for Patient Room Designs A, B and C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient Room Designs</td>
</tr>
<tr>
<td>Energy</td>
</tr>
<tr>
<td>Daylighting</td>
</tr>
<tr>
<td>Balance</td>
</tr>
</tbody>
</table>

REFERENCES


Study on the Microclimatic Conditions and Thermal Comfort in an Institutional Campus in Hot Humid Climate

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ABSTRACT

The built form alters the microclimate significantly which in turn affects the outdoor thermal comfort. The outdoor thermal comfort depends on the ability of the materials to absorb solar radiation (albedo) and the geometrical arrangement of the buildings and its morphology. The aim of this study is to investigate the influence of the built geometry and its morphology on the outdoor thermal environment in an institutional campus in the hot humid city of Chennai. The study is twofold. Firstly, the impact of built geometry on the microclimatic conditions was assessed through field measurements and secondly a questionnaire survey on thermal sensation in the campus environs of Sathyabama University was conducted to study the subjective response of students to the outdoor thermal environment in a hot humid climate. The field measurements included the monitoring of meteorological parameters such as air temperature Ta, relative humidity RH, wind speed v and mean radiant temperature Tmrt. Outdoor thermal comfort conditions were assessed through the physiologically equivalent temperature (PET) index, during daytime at different built morphology. The influence of various built parameters such as Sky view factor (SVF), building materials, green cover, etc., on microclimatic conditions and the daytime thermal sensation were assessed. This study also attempts to identify various passive design options in order to arrive at favourable microclimatic conditions and to improve pedestrian comfort conditions during daytime in an institutional campus.

INTRODUCTION

The built form alters the microclimate significantly which in turn affects the outdoor thermal comfort. Built form is characterized by replacement of the natural earth’s surface by hard impervious layer; buildings and its geometry; and the properties of the dense construction materials. Also, the outdoor thermal comfort depends on the ability of the materials to absorb solar radiation (albedo), the geometrical arrangement of the buildings and its morphology. The dense construction materials stores the heat and increases the surface temperature, the building geometry (defined by the ratio of height of the buildings to the width of the street) traps the incident solar radiation, the hard impervious pavements, roads and parking lots increases the surface runoff of water and the reduced vegetation increases the air temperatures at the microclimate level thus influencing the thermal comfort of the pedestrians. Enhancement of the outdoor thermal comfort is possible through careful analysis of the built form and its influence on the microclimatic parameters. Therefore, this paper aims at investigating the influence of the built geometry and its morphology on the outdoor thermal environment in an institutional campus in the hot humid city of Chennai.

Lilly Rose Amirtham is a Professor & Head at the Faculty of Building & Environment, Sathyabama University, Chennai, India. Ebin Horrison is a research Scholar and Surya Rajkumar is a Postgraduate student at the Department of Architecture, Faculty of Building & Environment, Sathyabama University, Chennai, India.
BACKGROUND LITERATURE

At the micro level, building geometry shows an intimate relationship with air temperature, and Oke (1976) states that the thermal climate at the canopy layer depends on the characteristics of the individual site and not on the temperature at boundary layer. The height-to-width ratio and the street orientation with respect to solar radiation, was found to have a great influence on the timing and magnitude of the energy regime of the individual urban surfaces (Nunez and Oke 1977). Oke (1981) states that the rate of cooling at the street level depends on two parameters: the Height – width ratio (H/W, street geometry) – the ratio of typical height of the buildings to typical width of the neighboring streets and the sky view factor - the fraction of the sky hemisphere visible from a location at the street level in an infinitely long urban street canyon. Arnfield (1990) compared the effects of urban geometry and thermal properties of the construction materials and found that the canyon geometry is the predominant factor and the thermal properties of the materials enhance the differences in the cooling rates generated by different street geometries. The canyon radiative geometry contributes to a decrease in the long-wave radiation loss from within the street canyon due to the complex exchange between buildings and the screening of the skyline and decreases the effective albedo of the system, because of the multiple reflection of short-wave radiation between the canyon surfaces (Oke et al 1991). Ahmed (1994) found a decrease in air temperatures by 4.5K with an increase in the H/W ratio from 0.3 to 2.8, in the hot humid city of Dhaka, Bangladesh, in summer. Also, the aspect ratio and the street orientation determines the time of exposure to direct solar radiation and the occurrence of extreme heat stress (Ali-Toudert and Mayer 2006). Shashua-Bar (2006) indicated that the thermal effects of built form, vegetation and colonnades, in streets and in courtyards depend on the envelope ratio (i.e.,), the overall geometry factor. Johansson and Emmanuel (2006) analyzed the influence of street canyon geometry on the outdoor thermal comfort in Colombo, Sri Lanka and the study revealed that the differences in air temperatures were higher during the day, especially in the afternoons when compared to the night and a maximum difference of 7°C was found between sites.

It is difficult to predict the actual thermal sensation of humans because of the varying climatic conditions in the outdoors and the changes in the personal factors such as the clothing and activity level. PET – a universal outdoor thermal comfort index (Jendritzky et al 1990, Matzarakis et al 1999), is defined as the “Physiologically Equivalent Temperature at any given place (outdoors or indoors) and is equivalent to the air temperature at which, in a typical indoor setting, the heat balance of the human body (work metabolism 80 W of light activity, added to basic metabolism; heat resistance of clothing 0.9 clo) is maintained with core and skin temperatures equal to those under the conditions being assessed” (Mayer and Hoppe 1987).

The field of research pertaining to outdoor thermal comfort conditions especially at the street level is relatively new. Matzarakis and Mayer (1998) investigated the thermal component of different urban microclimates in Freiburg, Germany and found that the heat stress levels of the human beings depend mainly on the shading effects and clothing factors. Ali-Toudert et al (2005) found that the heat stress in unobstructed locations is high, when compared to sheltered urban sites in Beni-Isguen, Algeria. Ali-Toudert and Mayer (2006) found the dependence of thermal comfort on the design of the street, including geometry, orientation and other design strategies, such as the galleries and horizontal overhangs. Gulyas et al (2006) examined the outdoor thermal comfort conditions in the complex urban environment of Szeged, Hungary using the RayMan model and found a difference of 15°C to 20°C in the PET index due to the radiation differences in sites that were shaded differently by buildings. Emmanuel and Fernando (2007) insisted that the mitigation strategies adopted by urban designers should be based on human comfort (determined by both MRT and air temperature), rather than on simply attempting to control air temperature alone. Lin et al (2010) indicated that low SVF and sufficient shading with tress and buildings can improve the thermal comfort during summers. Bourbia and Boucheriba (2010) highlighted the importance of street design in Constantine-Algeria and found a difference of 3–6°C in air temperatures between the streets with varying geometry. Also, the wind speed reveals a significant impact in the relationship between the MRT and the SVF, even though solar access has a strong relationship with SVF than the wind speed (Kruger et al 2011). The study on the seasonal effects of urban street shading by Hwang et al (2011) revealed that shading effects provided different thermal sensation at different seasons and suggested that improvement of comfort conditions in urban streets...
should be based on the requirements of seasonal shading levels. Amirtham et al (2011) found that the differential heating which occurred due to the different aspect ratios of the street canyons resulted in different climatic conditions in urban built forms.

Studies relating to the impact of urban geometry on human comfort conditions in India are very few and deals mostly with indoor comfort conditions. Chowdhury and Ganesan (1983) identified that physiological strain over most parts of India is due to the heat and accounts for nearly 80% of the stress. Jauregui (1991) characterized different human climate conditions in the tropical cities using the Effective Temperature index (an index of heat stress on the human body) and found that the comfort levels are significantly reduced while walking on the streets due to the high radiation levels. Thus, this study attempts to contribute to the understanding of the relationship between built form, air temperatures and comfort conditions in an institutional campus in the hot humid city of Chennai, India.

AREA OF STUDY

Sathyabama University is an institutional campus in the suburbs of Chennai experiencing hot humid climate. The maximum air temperatures during summer (May and June) varies between 38°C and 42°C and the minimum air temperatures during winter (December and January) varies between 18°C and 20°C. The average monthly relative humidity ranges from 63% (June) to 80% (November) and the vapour pressure varies between 22.6hpa and 32hpa.

The institution houses several academic blocks of varying street geometry enclosing open spaces and streets for interaction. Five different locations in the campus were selected considering various parameters such as the percentage of vegetation, orientation of streets and canyon geometry (H/W ratio). The street geometries identified for the study ranged from 0.5 to 2 (H/W ratio). The thermal properties of the built surfaces were similar in all locations. Figure 1 shows the measurement locations in the campus and Table 1 shows the characteristics of the selected locations.

![Figure 1](image_url) Measurement locations in the Campus

METHODOLOGY

The impact of built geometry on microclimatic conditions was assessed through field measurements. The air temperature and relative humidity data were measured continuously on an hourly basis using HOBO dataloggers (HOBO U20 Temp/RH) in the selected locations. The wind speed and the cloud cover data from the Nungambakkam Meteorological station were used for the study as the above data could not be measured at study area. Microclimatic variations of the selected locations were analyzed for a hot day in May (summer). The influence of urban morphology on outdoor thermal comfort conditions is calculated through the most commonly used outdoor thermal comfort index - Physiologically Equivalent Temperature (PET) (Matzarakis et al 1999, Emmanuel 2005, Johansson 2006). RayMan Pro model (Matzarakis et al 2007, 2010) has been used to calculate Physiologically Equivalent Temperatures as it takes into consideration all environmental factors influencing thermal comfort. The model calculates the radiation fluxes within the complex urban environments based on the time of the day and year, meteorological parameters (air temperature, humidity, degree of cloud cover), surface morphological conditions (geographical locations, building geometry, albedo of the surrounding surfaces, sly view factor) and personal data (age, height, weight, clothing, activity level.)
Table 1. Characteristics of the Measurement Locations

<table>
<thead>
<tr>
<th>Site</th>
<th>Plan</th>
<th>Section</th>
<th>SVF</th>
<th>H/W</th>
</tr>
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<td><img src="image6" alt="Section" /></td>
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<td>0.5</td>
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<tr>
<td>Location 5</td>
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<td>0.271</td>
<td>1.67</td>
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</tbody>
</table>

The 200m X 200m grid along with their shadow patterns and Sky View Factor (SVF) are shown in Figure 2. Also, a questionnaire survey on thermal sensation in the selected locations was conducted to study the subjective response of students on outdoor thermal environment. The subjective response of respondents and PET Index were compared to identify the appropriate built geometry for thermally comfortable environment.

RESULTS AND DISCUSSIONS

The influence of urban morphology on outdoor thermal comfort conditions were analyzed with respect to parameters such as orientation, street geometry (H/W ratio) and percentage of vegetation. The air temperature and PET variations at five selected locations are shown in Figure 3. Mayer et al (2009) states that the atmospheric conditions are modified by the urban processes and built form; and results in increase or decrease in ambient air temperatures which is a function of various parameters such as weather, time and day of the year, street geometry and built structure. Amongst the five locations in the campus, location 1, 3 & 5 are oriented in the N-S orientation and location 2 & 4 are oriented in the E-W direction.

Air Temperature and PET Analysis

The air temperature and PET were analyzed with reference to orientation, street geometry and percentage of vegetation of selected locations.

Orientation, The selected streets in the campus were oriented in the N-S and E-W directions. The air temperatures in the E-W oriented street at location 2 were higher than N-S oriented streets (location 1,3,5) through out the day (8.00hrs to 16.00hrs). Even though location 4 had similar orientation and
street geometry as that of location 2, temperatures were almost similar to that of N-S oriented streets except at 14.00hrs which could be attributed to the shading of the instrument. The variation in the air temperatures with respect to orientation (E-W vs N-S) were higher at during daytime when the sun’s radiation is at the maximum ranging from 1.47°C at 10.00hrs to 3.7°C at 14.00hrs. The outdoor comfort conditions with respect to PET values also varied from 2.1°C at 10.00hrs to 6.6°C at 14.00hrs. The study also found that PET values were lesser than air temperatures at 6.00hrs and 18.00hrs thus reinforcing the fact that absence of direct solar radiation increases the comfort conditions i.e., thermal sensation. The PET values were as less as 3.39°C when compared to air temperatures at 6.00hrs.

Vegetation, Except locations 4 & 5, the absence of vegetation in other locations nullifies the cooling effect through shading and evapotranspiration. Even though the street geometry and orientation
(E-W) of locations 2 & 4 were same (H/W = 0.5), their thermal recordings varied up to 3.28°C at 14.00hrs due to presence of vegetation at location 4. The N-S oriented streets at location 1 & 5, also experienced significant thermal differences of about 2.3°C at 14.00hrs, attributed mainly due to the presence of significant vegetation at location 5.

![Air temperature and PET variations at various locations](image)

**Figure 3** Air temperature and PET variations at various locations

**Street geometry**, The variations in air temperatures with respect to height to width ratio increases gradually from 8.00hrs (1.1°C) to 14.00hrs (3.7°C) and reduces from 18.00hrs reaching almost similar temperatures at 6.00hrs. The H/W ratio is inversely proportionate to air temperatures and PET values, i.e., higher the H/W ratio lesser the air temperatures and PET values. Thus the study reveals that narrow streets are comfortable during daytime due to internal shading of buildings in hot humid climates, thus improving the outdoor comfort conditions.

The comfort conditions expressed by PET values were higher than the air temperatures by 8.5°C during daytime (8.00hrs to 16.00hrs) attributed to the presence of intense solar radiation. In the absence of direct solar radiation, the human thermal sensations represented by PET values were lesser than the air temperatures upto a maximum of 3.39°C lesser than the air temperatures. Analysis also revealed higher variation in PET values when compared to temperature differences at location 2 & 3 at 14.00hrs. For a temperature difference of 3.7°C between location 2 & location 3 at 14.00hrs, PET differences of 6.6°C existed at the same locations. This indicates that even slight variation in air temperatures can have a significant impact in the comfort conditions (PET) during daytime.

Location 2 experienced the maximum temperature and PET values at 14.00 hrs owing to its E-W orientation of the street, H/W ratio of 0.5, SVF of 0.623 and absence of vegetation. Also the concrete pavements and absence of shading by trees and buildings added to the discomfort. Almost all the five locations were above the upper limit of discomfort of 33°C as stated by Ahmed (1994), during daytime (between 07.00 hrs and 17.00hrs). The temperature in the PET index increases with the increase in ambient air temperatures and the difference between the same is as high as 8.5°C at 14.00hrs. At 6.00hrs the PET was lesser than the air temperature by 3.05°C at location 4 which recorded the minimum temperature. This clearly reveals that the outdoor thermal comfort index has a significant impact with direct solar radiation. PET index during night time was comfortable and was well within the upper limit of comfort (33°C) and was also lesser than the ambient air temperatures.
**Questionnaire Survey and PET Analysis**

The questionnaire survey revealed that the respondents experienced the heat stress during daytime as the PET varied from 34.6°C to 44.9°C between 8.00hrs and 16.00hrs. The thermal sensation at locations 3 & 5 was almost tolerable at 14.00hrs due to internal shading by buildings and trees. The N-S orientation of these locations had a significant impact on the thermal sensation. Location 1 which was also oriented in N-S direction experienced higher discomfort due to its street geometry with SVF of 1. The thermal perception of the respondents was too warm at locations 1 & 2 due to the absence of internal shading. Also the reflective nature of the abutting buildings had a significant impact on the thermal sensation in the above locations. In general the thermal perception at locations 1, 2 & 4 were not satisfied and the users experienced heat stress. The overall conditions inside the campus are acceptable for the users near the locations 3 & 5 due to the N-S orientation and the presence of vegetation, thus providing a tolerable environment at these locations.

**CONCLUSION**

The air temperature and the PET trends in the campus revealed that the nights were comfortable when compared to day. During daytime, all the streets were uncomfortably hot with the PET values well above the upper limit of the comfort zone. As the daytime comfort was found to have a significant correlation with the street geometry (SVF), presence of vegetation and orientation, the study indicates the significance of improving the daytime comfort in the campus, by stipulating appropriate built geometry and orientation in the new developments in campus. Also if the concept of internal shading is adopted in the existing built form, it can improve the comfort conditions to a significant level. Based on the study, recommendations pertaining to some of the aspects of built form have been suggested to improve the outdoor thermal comfort conditions at the campus.

- N-S oriented streets are comfortable when compared to E-W orientation. If E-W orientation is essential in the design, then appropriate shading of streets through shaded corridors, projected balconies, and vegetation can improve the pedestrian comfort considerably in campus.
- Shading through vegetation significantly reduced air temperatures and PET values during daytime irrespective of the orientation.
- Narrow streets oriented in the N-S direction reduced the heat stress during daytime as they reduce the time of exposure to direct intense solar radiation. Also the internal shading of buildings accelerated the comfort conditions at pedestrian level.

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>PET</td>
<td>Physiologically Equivalent Temperature (°C)</td>
</tr>
<tr>
<td>H</td>
<td>Height of building (m)</td>
</tr>
<tr>
<td>W</td>
<td>Distance between buildings in a street canyon (m)</td>
</tr>
<tr>
<td>SVF</td>
<td>Sky View Factor</td>
</tr>
<tr>
<td>OUT_SET*</td>
<td>Outdoor Standard Effective Temperature (°C)</td>
</tr>
<tr>
<td>SET*</td>
<td>Standard Effective Temperature (°C)</td>
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</tbody>
</table>

**REFERENCES**


Session 7B : Performance evaluation and design feedback

PLEA2014: Day 3, Thursday, December 18
10:25 - 12:05, Compassion - Knowledge Consortium of Gujarat
The Ability of Current Rating Tools to Guarantee Sustainable Successes: Balance and Perspective

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ABSTRACT

The use of assessment and rating tools by design teams is increasing. In a parallel development, demonstration projects aimed at improving sustainability in building are being increasingly endorsed. This paper addresses the question of whether projects that have been assessed and rated are necessarily worthy of designation as ‘sustainable successes’, leading to enhance the reproducibility of up-front sustainability measures, ultimately broadening the base for sustainable building.

Within the field of contemporary European sustainable group housing, actual projects that have been assessed and rated are explored and positioned relative to recognised demonstration and best practice projects. Focus lies primarily on projects supported and rated by the BREEAM (Building Research Establishment Environmental Assessment Method). In order to increase the reliability, outcomes are verified by cases rated with other multi criteria sustainability tools. The study is conducted from the perspective of the architect-designer, focusing on actual sustainable design measures and features as comparative parameters with reference to the two most tangible pillars of sustainable building (i.e. ‘Planet’ and ‘People’).

The results of this illustrative study indicate that the assessment and rating tools that are currently available cannot guarantee full success with regard to sustainability. Projects that have been assessed and rated do not necessarily constitute ‘best-practice projects’. The analysis raises several issues regarding sustainability tools and suggests perspectives with regard to ‘design attitude’. Promising perspectives involve appropriate and integrated design measures, a conceptual approach and, most importantly, architectural solutions.

INTRODUCTION

Once they realise the necessity of an integral approach to sustainability, architect-designers are faced with a complex task. Multi-disciplinary actors in the construction industry are undertaking frantic efforts to facilitate this task by focusing on the development of assessment and rating tools. The use of these tools is increasing, not only as a means of evaluating buildings with regard to their sustainability, but also as a design supporting tool (Abdalla, Maas, Huyghe and Oostra, 2011). Parallel to the development of such incentives, multiple authors and public organisations are endorsing the importance of demonstration projects in the quest for more sustainable building (Buijs & Silvester, 1996) (Feminas, 2004) (Van Hal, 2000).

Two issues are relevant in this regard. First, the outcome of an assessment is highly dependent upon the set of components and indicators incorporated into the selected tool. For this reason, some projects might not cover the full scope of sustainability. Second, ‘demonstration and best-practice projects’ are
receiving considerable attention in both the popular media and the scientific literature. Nevertheless, their performance with regard to sustainability has rarely been tested according to the most prominent and widely used multi-criteria assessment methods. Combined with the increasing general interest in sustainability tools, this could mortgage the recognition of the sustainability value and benefits that such projects offer.

This study focuses on actual projects that have been assessed and rated according to the BREEAM (Building Research Establishment Environmental Assessment Method). The main objective of this chapter is to explore and position these projects relative to renowned European demonstration and best-practice projects. This positioning can provide a preliminary answer to the question of whether projects that have been assessed and that have achieved high ratings are necessarily worthy of designation as best-practice projects that intended to enhance the reproducibility of up-front sustainability measures, ultimately broadening the base for sustainable building. The analysis raises several issues and suggests perspectives with regard to ‘design attitude’.

METHODOLOGY

The research and argumentation of this study can be characterised as a cross-case comparison in tabular form. Case-study methodology is appropriate for investigating contemporary phenomena (e.g. sustainable building) (Yin, 1994). In order to increase reliability, multiple projects are considered. The study is conducted from the perspective of the architect-designer, focusing on actual sustainable design measures and features as comparative parameters with reference to the two most tangible pillars of sustainable building (i.e. ‘Planet’ and ‘People’).

The literature contains no consensus regarding the content and naming of sustainable design measures and features. A self-compiled set was therefore made for this study. The determination of these comparative parameters, the analysis of the comparison and the formulation of issues and perspectives is based on empirical observations, as well as on a review of literature regarding selected demonstration and best-practice projects. These resources are supplemented by a tentative theoretical description of sustainable building in the European context. This abductive reasoning can be seen as an iterative process between the collection and analysis of empirical material and the study of theory in literature (Feminas, 2004).

Assessment and rating tools are intended to evaluate performance related to various aspects of sustainability. This study examines projects that have been assessed and rated according to the most prominent and most widely known and used system in Europe: BREEAM (“BREEAM Meest Toegepaste Certificering”). In this system, credits are awarded in nine categories and added together to produce a single overall score, positioned along a scale ranging from ‘Pass’, ‘Good’ and ‘Very Good’ to ‘Excellent’ and ‘Outstanding’.

As suggested in the literature, demonstration projects should meet the following conditions: repeated evaluations, an open and public character and the intention to act as a demonstration project from the beginning, as well as a special character (Buijs & Silvester, 1996) (Van Hal, 2000) (Keating & Peach, 1989).

The projects addressed in this study were selected from within the field of grouped housing in Europe. Specific features of these projects (e.g. overlapping scales, collectivity) contain embedded aspects of sustainability, as well as opportunities for realising additional sustainability measures, although they are also accompanied by critical barriers.

From the projects that have been assessed and rated by the BREEAM, the following were selected for this study: ‘De Balk van Beel’ in Belgium and ‘Sanderstead Road’ in the United Kingdom. Both are compared according to the self-compiled set of comparative parameters. Another project featuring typological similarities to ‘De Balk van Beel’ was added to the research in order to enhance the specificity of the comparison and to illustrate the stated perspectives: ‘Kronsberg’ in Hannover (Germany).

This study, derived from an ongoing doctorate dissertation (Janssens, ongoing) is illustrative and primarily representative of the selected case studies and of the assessment and rating tool. The
methodology of using comparative parameters, based on Feminas (2004), is considered relevant, although it is not the only approach possible. The set of comparative parameters is neither exhaustive nor definitive. Finally, the perspectives suggested within the specific theoretical framework should be seen as one of many possible solutions.

IDENTIFICATION OF SELECTED ASSESSED AND RATED PROJECTS

The ‘De Balk van Beel’ involves the pilot construction within an ongoing new neighbourhood development (‘Tweewaters’) in Leuven. The project comprises four upper floors containing 101 different housing units. The ground floor contains shops and services for the neighbourhood. Upon completion of the design, the project was assessed using the ‘International Bespoke 2010’ version of the BREEAM, which resulted in an ‘interim design stage’ certification. The design achieved a score of 87.81%, which corresponds to an ‘outstanding’ rating. The development achieved 100% of the available credits in the categories of ‘Management’, ‘Health & Wellbeing’ and ‘Land Use & Ecology’, and it scored over 90% in the categories of ‘Energy’ and ‘Transport’.

The new housing development ‘Sanderstead Road’ is located on a derelict brownfield in the London Borough of Croydon. It comprises a three-storey block of 38 one-bedroom and two-bedroom flats, partly constructed over three new ground-floor commercial units, with two blocks of three-storey semi-detached, four-bedroom houses in the courtyard area. Assessment using the ‘EcoHomes 2006’ version of the BREEAM resulted in an ‘interim design stage’ certification. The overall score of 75.41% corresponds to an ‘excellent’ rating. The project team performed well across all categories, particularly in relation to ‘Materials’ and ‘Management’.

![Figure 1](image)

**Figure 1** Selected cases for the cross-comparison: left ‘De Balk van Beel’; right ‘Sanderstead Road’. Source: Bart Janssens

CROSS-CASE COMPARISON

Table 1 provides a tabular comparison of sustainable design features and measures of the selected BREEAM projects with exemplary practices in Europe. Data are subdivided into two categories: ‘embedded sustainability features’ and ‘added sustainability measures’. The first category covers features that are at least partially inherent in the field of grouped housing. The second category includes measures added through some level of deliberate effort, either at the neighbourhood level or at the building level. A description of the complete list of comparative parameters and a thorough discussion of the comparison is not possible within the limited length of the paper. As this comparison represents the basis of the argument of this research, it will be discussed and documented in depth during the oral presentation.
<table>
<thead>
<tr>
<th></th>
<th>Exemplary practices</th>
<th>BREEAM projects</th>
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<td><strong>Embedded sustainability features</strong></td>
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<tr>
<td>High density (≥ 50 units per net hectare)</td>
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<td></td>
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<tr>
<td>Extensive range of housing types</td>
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<td>Semi-private courtyards with residential quality</td>
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<td>Transitional zones private-collective-public</td>
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<td>Well monitored collective spaces</td>
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<td>Well monitored public spaces</td>
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<td>Combined heat and power plant</td>
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<td>Open storm-water system: ponds, open canals</td>
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<td>Storm-water infiltration units</td>
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<td>Constructed wetland (e.g. helophyte filter)</td>
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<td>Cycle &amp; pedestrian friendly routes by design</td>
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<td>Electric recharging plug-in points for cars</td>
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<td>Building level</td>
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<td>Bioclimatic design (e.g. compactness, orientation)</td>
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<td>Micro-climatic spaces: glazed balconies, greenhouses</td>
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<td>Solar accessible large windows</td>
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<td>Green roofs/façades</td>
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<td>Sun-protection louvers, greenery</td>
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<td>Sun-protection fabric</td>
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<td>Storage facility and recycling station</td>
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<td>Internal spatial flexibility</td>
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<td>Sound insulation (improved imposed standards)</td>
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<td>Ecologically responsible materials (≥ 80%, BREEAM, or Cradle to Cradle when available)</td>
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<td>Rain-water recycling system</td>
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<td>Energy-efficient and water-efficient appliances</td>
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<td>Low energy performance level (40-60kWh/m²)</td>
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<td>High-efficiency natural gas condensing boiler</td>
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<td>Natural ventilation (e.g. wind cowls)</td>
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<td>Solar panels</td>
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<td>Sub-metering for energy use</td>
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<td>Real-time energy monitoring</td>
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<td>Home delivery boxes</td>
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<td>Electronic butler service</td>
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<td>One-key access</td>
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<td><strong>Implemented measures</strong></td>
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<td><strong>Postponed or expired measures</strong></td>
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ANALYSIS OF THE RESULTS FROM THE CROSS-COMPARISON

As revealed in the cross-case comparison, the selected BREEAM projects lack most of the sustainability features that they are assumed to include. Little or no attention is paid to the intermediate scale or to the collective or semi-public space. With regard to the list of additional measures, the projects incorporate few, if any bioclimatic design principles, while other measures exceed most of the project examples contained in the cross typology (e.g. real-time energy-monitoring systems and home-delivery boxes). Many similarities can be observed with regard to low energy performance and provision of energy-efficient and water-efficient appliances.

The measures prevailing in the demonstration projects and the BREEAM projects differ in terms of their overall character. While most demonstration projects assign priority to tangible, architectural solutions, the BREEAM projects tend to focus more on relatively technological measures (e.g. open storm-water systems versus storm-water infiltration units; wind cowls versus mechanical systems).

The selected BREEAM projects show only limited aspects of social sustainability. The lack of embedded sustainability features and the nature of the sustainability measures applied result in the absence of ‘people features’. The assessment of projects with a tool containing components and indicators that emphasise a more social approach to sustainability (or even a better-balanced set of components) would change performance in terms of sustainability.

As demonstrated in comparative studies, most tools have their own content, areas of focus and methods (Fowler & Rauch, 2006) (Saunders, 2008). The outcome of an assessment depends heavily upon the set of components and indicators which are included in the selected tool. Yet included aspects of sustainability are listed and rationally tackled in the hope of achieving intended desired rating. In many cases, design teams resort to technological and even highly innovative measures. This can have two consequences. First, such strategies increase investment costs. Second (and often related to the first consequence), there is a true risk that measures will be postponed or will even expire during the further design and/or construction process. The analysis of the ‘De Balk van Beel’ reveals that certain key measures have been cancelled (e.g. electronic butler service) or transferred to future neighbourhood developments (e.g. combined heat and power plant, recycling station, kitchen gardens) (Janssens, 2013). Other measures are mentioned only as options (e.g. storm-water infiltration unit) or seem to be to innovative (e.g. home delivery boxes). The BREEAM score obtained during the design phase hence does not necessarily guarantee the building’s final sustainability performance. Particular measures can prove to have different outcomes during the construction and usage phase. This finding corresponds to results reported by Ding (2007) and by Abdalla et al (2011).

By promoting designs oriented towards solving single problems, assessment and rating tools apparently steer architects/designers towards less than optimal measures. Creativity comes at the expense of easy ‘add-on’ technological solutions, thus eliminating opportunities and inspiration for liveable, creative and efficient living and working environments. This single-problem approach to sustainability is likely to result in sustainability decay, as illustrated by the BREEAM projects addressed in this case study.

PERSPECTIVE AND ILLUSTRATIVE VERIFICATION

Gaining efficiency and decisiveness will require a shift in focus from checklists and performance criteria to practical sustainability measures, which are more appropriate for architect-designers. The ‘design attitude’ of architects/designers with regard to sustainability should shift from measures intended to resolve single problems towards multiple integrated measures, concepts and architectural solutions. The practice of finding ‘promising combinations’ is the common ground for both sustainable transition and sustainable design (Tjallingii, 1996). Thinking in terms of design combines possible solutions from disciplines that are fundamentally different (Cross, 2006) (Van Bakel, 1995).
Measures are deliberate and distinct decisions intended to fulfil specific requirements and to achieve desired features. Measures that serve several requirements can increase efficiency, diminish (or even eliminate) objections to implementation and reduce the risk of postponement and/or expiration. As described by Janssens and Van Dorst (2012), ‘Beneficial Pattern Measures’ (BPM) are building-design measures that have positive effects on multiple targets. Applied to sustainability, BPMs aim to satisfy both environmental (‘Planet’) and social (‘People’) pillars/components/indicators (Figure 2). Common BPMs in European demonstration projects include ‘glazed balconies’ and ‘greenhouses’, often as components of the lighting, heating, cooling and/or ventilation design. With regard to the ‘People’ aspects of sustainability, these measures enhance social contact between owners and passersby, in addition to their ability to enhance social control, create potential spaces for identification and expansion, and provide a transitional zone between public and private spaces. These primarily ‘Planet’-oriented measures also address a wide range of ‘People’ aspects.

Despite the use of BPMs, individual sustainability measures cannot address the full range of sustainability issues, and they often generate sub-optimal solutions. Multiple measures must be combined in a mutually reinforcing manner, resolving any disadvantages or bottlenecks. ‘Beneficial Multiple Pattern Measures’ (BMPM) combine several promising BPMs into successful sustainability packages. In many cases, the BPMs that are outlined (e.g. ‘glazed balconies’ and ‘greenhouses’) are replaced by simplified versions (e.g. ‘large windows’). In the demonstration project ‘BO-01’ in Malmö (Sweden), an ‘open storm-water system’ was placed in front of the buildings, broadened and supplemented with ‘plants’ near ‘large windows’ (Figure 3). In addition to being an interesting and attractive feature in an urban context, this solution is able to regulate privacy. The creation of a distance and the presence of plants avoid the need to cover the windows, thus preventing them from losing their previously stated potential for serving important functions.

Given the context-specific nature of every assignment, BMPMs must be composed and combined into an integrated approach with regard to all predefined requirements, terms and conditions. A conceptual approach is crucial when working with ‘integrated multiple measures’. The development of concepts prevents inefficiencies in later design stages, and it increases the likelihood of sustainable success in a cost optimal way (Rovers, 2008). Concepts facilitate the successful implementation of measures by focusing on the achievement of several objectives in an integrated manner (Figure 2). This can be defined as a ‘Beneficial Pattern Concept’ (BPC).

![Figure 2](image)

**Figure 2** Figurative representation of ‘Beneficial Pattern Measures’ (BPM) and ‘Beneficial Pattern Concepts’ (BPC). Source: Bart Janssens (2013)
The ‘Kronsberg’ project contains architectural solutions within a strong conceptual approach. Dwelling units were placed back-to-back, facing east and west, and separated by a covered atrium (Figure 3). During a test case for research by design, the atrium was optimised with regard to sustainability. It was also implemented and developed into a full BPC (‘the bioclimatic street’) for a typology resembling that of ‘De Balk van Beel’. Verification of architecture and sustainability revealed that the concept is effective and efficient, coupling aspects of sustainability (e.g. water, ecology, energy, health, comfort, social value and architectural design) with regard to both environmental and social sustainability.

Figure 3  Left: example of a ‘Beneficial Multiple Pattern Measure’ (BMPM) in ‘BO-01’ in Malmö: ‘open storm water system’ – ‘plants’ – ‘large windows’. Right: example of a ‘Beneficial Pattern Concept’ (BPC) in ‘Kronsberg’ in Hannover: ‘the bioclimatic street’. Source: Bart Janssens

The development of new measures and the optimisation of existing measures and concepts could be stimulated against the background of a theoretical and practical framework based on knowledge concerning particular sustainability measures (e.g. scope, promising combinations, deferability, adaptability, added ability). Architect-designers can indulge their creativity, thereby broadening the base for sustainability, ultimately generating a sustainable transition for the built environment.

FINALIZING REMARKS

Outlook verification: In order to increase the reliability, outcomes will be verified by other cases, which will be discussed and documented in depth during the oral presentation. Research will be based on empirical performance data derived from occupied buildings. Within the BREEAM assessed and rated projects, ‘Futura’ (Zoetermeer, The Netherlands) will be investigated. Within other multi criteria sustainability tools, following projects will be reviewed: ‘Cortinghborg’ (Groningen, The Netherlands) rated by ‘GPR Gebouw’; ‘Eco-Life’ (Kortrijk, Belgium) rated by ‘Vlaamse Maatstaf voor Duurzaam Wonen en Bouwen’; ‘Les Dominos’ (Lyon, France) rated by ‘HQE’.

Future research and discussion: There are a number of future research and discussion topics concluded to be relevant. First, in order to prevent the introduced BPMs, BMPMs and BPCs in becoming as impenetrable and convoluted as the ticked boxes of most multi criteria assessment and rating tools, a clear and ‘architect-designer friendly’ knowledge structure is needed. Second, when setting out such knowledge structures it is most important to rely on factual evidences in order to avoid preconceptions. Because of the often occurring discrepancies between the results of assessments and actual performances of designs/buildings, research should study actual ‘real-life’ buildings more closely. Sustainability tools should learn and improve from past projects. Third, the focus in next steps in the development of assessment and rating tools is plural: the improvement of methods of evaluation and shortlisting of relevant and appropriate criteria for each project, the recognition and accountance for synergies between performance criteria, a more holistic audit (full sustainability scope) and monitoring.
approach, etc. In tackling these issues focus should be on architectural and contextual measures and issues in order to encourage integrated ‘People-Planet solutions’. A system thinking approach between assessment tools and knowledge structures, i.e. matching evaluation criteria and e.g. BPMs, is believed to be promising.

**Preliminary conclusion:** This illustrative study on selected BREEAM projects demonstrates that current assessment and rating tools cannot guarantee complete success in the area of sustainability. Projects that have been assessed and rated do not necessarily constitute ‘best-practice projects’. Most current tools have a unilateral focus on checklists and/or performance criteria for a selection of sustainability aspects, thereby encouraging the practice of designing to solve single problems. In many cases, this can lead to a single orientation with regard to sustainability, possibly leading to sustainability decay. Tools can facilitate success in sustainability, on the condition that their constituting components and indicators cover the full scope of sustainability, and provided that architect-designers are aware that sustainability arises from engagement with the complexity of the situation, and not from checklists. A theoretical and practical illustrative framework with regard to an ‘integrated multiple design attitude’ indicates that, regardless the use of sustainability tools during or after the design process, the keys to success in sustainability include knowledge about and the implementation of appropriate and integrated design measures, a conceptual approach and, most importantly, architectural solutions. Research is needed on a suitable knowledge structure and the linkage with optimized assessment and rating tools.

**REFERENCES**


Numerical study: How does a high-rise building affect the surrounding thermal environment by its shading?

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ABSTRACT
In rural Japanese cities, many old and densely populated urban districts have been replaced by high-rise residential buildings because of urban redevelopment. High-rise building affects the sunshine conditions and wind environment of the surrounding areas. These problems have been already discussed; however, it is rarely discussed how high-rise buildings affect the outdoor and indoor thermal environment of their surroundings. Particularly, shading is a serious problem in winter because it makes the outdoor environment colder and increases the energy consumption for heating of adjacent buildings in addition to daylight shortages.

The shading effect of a high-rise building on the outdoor and indoor thermal environment in winter is simulated by a 3D CAD-based thermal environment simulator. As a result of the simulation, shading effect by high-rise building at noon extends widely to the area approximately 200m away in the north, but the 7 °C difference in the mean radiant temperature in the shaded area is caused by the surrounding space geometry and material. Also, in the northern or western street of high-rise building, many shops exist and their façade with large windows make the shading effect on the building heat load more remarkable. The building heat loads of these buildings are more than 30% larger than that in the case when the high-rise part is removed.

INTRODUCTION
In rural Japanese cities, many people used to live in densely populated urban districts near train stations with many prospering businesses nearby. However, because of decreasing district population and development of suburban areas, many district buildings were vacated and replaced by high-rise residential buildings, and many businesses closed.

High-rise buildings cause problems such as preventing access to sunlight, and creating strong wind conditions, and affect the landscape. When constructing high-rise buildings in Japan, the building height is regulated by the Building Standards Law. The law has a regulation about indexes such as duration of solar shading and sky factor from the viewpoint of access to sunlight. Moreover, in several cities, environmental assessments are required when the height of high-rise buildings is greater than 100 m. For these assessments, wind conditions are simulated using CFD (RANS).

As previous studies, Saito (2003) researches the effect of high-rise building on the illuminance and
sky factor on the surroundings. Also, Curreli (2011) researches solar access in densely built urban environments. However, it is rarely discussed how high-rise buildings affect the outdoor and indoor thermal environment of their surroundings. As mentioned above, shading is a serious problem in winter. In particular, shading by high-rise building makes the neighboring outdoor environment colder, and increases the energy consumption for heating.

This study reveals the shading effect of a high-rise building on the outdoor and indoor thermal environment in winter using numerical simulations. The building heat load is calculated considering the effect of the outdoor thermal environment. An urban district with and without high-rise buildings are reproduced using the 3D CAD system and then compared.

**METHODOLOGY**

**Target urban district**

The target district is in Tsuchiura city, which is approximately 60 km from Tokyo in the north, and is located in the city center near Tsuchiura Station. The district has high pedestrian traffic and several shops. Low-rise shops and residential buildings were closely built, and commercial and high-rise residential buildings were first built in 1997. Furthermore, parking lots have replaced many of the original houses and shops. The height of the high-rise building in the target district is 109 m, with a north-facing open space for events. The high-rise building affects the thermal environment of the surrounding outdoor spaces, particularly the thermal radiation environment of sidewalks and parking lots. Moreover, it affects the thermal environment of the surrounding buildings, and the shading owing to the high-rise building increases the energy consumption for heating.

**Simulation method**

In order to reveal the effect of shading owing to the high-rise building on the thermal environment of outdoor and indoor spaces, we analyzed the thermal environment in the target urban district using an in-house 3D CAD-based thermal environment simulator (Jiang H. et al., 2009; Asawa T. et al., 2008).
We collected spatial geometry and material data for 2009 and constructed 3D CAD models of the site at a scale of 1:500 (Sato R., et al., 2009). Two models were constructed; the first (current case) reproduces the current state, whereas the second (removed case) reproduces the state when the high-rise part is removed from the high-rise building.

Next, we calculated the outdoor surface temperature distribution in the target district under clear sky conditions in winter using the 3D CAD-based thermal environment simulator (Weather condition: Fig. 2). First, the 3D spatial forms of buildings, trees, and other structures and the 2D ground surfaces are divided into voxel mesh grids (mesh size: 400 mm). Then, the outdoor surface temperature for each grid was determined by solving the unsteady-state 1D heat balance equation in the vertical direction of the surface. The terms of the heat balance equation are direct solar radiation, sky solar radiation, reflected solar radiation, atmospheric radiation, longwave radiation exchange with surroundings, convective heat transfer, latent heat transfer, and conductive heat transfer. Each radiation is calculated by the ray tracing method, and the convective heat transfer is calculated assuming outdoor uniform distribution for the outdoor air temperature and wind velocity.

![Figure 2 Weather conditions](image)

The thermal radiant field in the urban district is evaluated using mean radiant temperature (MRT) at a height of 1.5 m. The MRT is calculated using the following equation, as the shortwave and longwave radiation absorbed by humans. $R_{\text{human}}$ is the solar radiation and longwave radiation absorbed on the human surface, calculated from equation (2).

$$MRT[^{\circ}\text{C}] = \sqrt[4]{R_{\text{human}}/\sigma} - 273.15 \quad (1)$$

$$R_{\text{human}} = a_1 \left( \frac{A_p}{T_{\text{human}}} \cdot I_d + \sum_{i=1}^{6} W_i(I_{Si} + I_{ri}) \right) + a_2 \sum_{i=1}^{6} W_i(\text{L object}_i + \text{L sky}_i) \quad (2)$$

Furthermore, the building heating loads, which consider the effect of surrounding buildings and trees, are calculated using the calculated total radiation and surface temperature distribution on the building’s external surfaces. To evaluate the effect of the outdoor thermal environment on the building’s indoor thermal environment, each building floor is assumed to be a single room. We further assume that the air-conditioning system is set at 20 °C all day in winter, and the internal heat gains’ schedule is based on the standard model of the Architectural Institute of Japan (Architectural Institute of Japan, 1985).
RESULTS AND DISCUSSIONS

Effect on the thermal radiation environment of the outdoor space

Surface temperature distribution

Figure 3 shows the surface temperature distribution in the two cases at 12:15. In the current case, where the high-rise building shades the surrounding urban area, its shade extends 200 m toward the north. Because of the shade, the sidewalk (s1) surface temperature at 12:15 (Fig. 3) is 5 °C, which is 10 °C less than that of the removed case.

On the ground of the parking lot, the surface temperature is different at each spot that is shaded by the high-rise building. Such differences depend on the duration of the shading of the high-rise building. In the current case, the surface temperature of the east side of the parking lot (p1) is 5 °C lower than the rest. On the other hand, the surface temperature of the west side of the parking lot (p2) is greater than 10 °C because the asphalt pavement accumulates heat by solar radiation in the morning.

In some parking lot which is not shaded at 12:15, the cold accumulation owing to the morning solar shading remains on the ground. As a result, the surface temperature at 12:15 in the parking lot (p1) adjacent to the shaded area decreases by 5 °C compared with the removed case. The area where the surface temperature decreases owing to cold accumulation occupies approximately 25% of the parking lot (p1) area.

Mean radiant temperature distribution

Figure 4 shows the mean radiant temperature distribution and surface temperature distribution in the outdoor space shaded by the high-rise building. At the sidewalk (s1), the mean radiant temperature for the current case decreases by more than 15 °C compared with the removed case owing to shading and decrease in surface temperature. In the parking lots shaded by the high-rise building, the mean radiant temperature in the current case also decreases compared with the removed case. However, the mean radiant temperatures of the parking lots differ in the shaded area of current case and the difference is 7 °C. At point X, the mean radiant temperature is 0 °C, which is 7 °C lower than the air temperature.

![Figure 3 Surface temperature distributions at 12:15](image-url)
This is attributed to the ground that is shaded by the high-rise building and the surrounding buildings, and the building wall with low surface temperature (see View K in Fig. 4). On the other hand, at point Y, the ground surface temperature is more than 10 °C higher than that at point X, and the surrounding building wall keeps the surface temperature high owing to heat accumulation (see View M in Fig. 4). As a result, the mean radiant temperature at point Y of the current case is 7 °C higher than that at point X.

**Effect on the building heat load**

The relation between the daily solar radiation, which is received by the windows, and the heat load of each building is examined to demonstrate the effect of shading by the high-rise building. We focus on the building that is shaded by the high-rise building for more than 1 h and calculate the building heat load. Figure 5 shows the daily solar radiation distribution in each case and the increasing rate map of the building heat load. Figure 6 shows the diurnal change in the solar heat gain and heat load in the buildings. In this district, many buildings have large windows in the southern or eastern facades, which face the street in the north or west of the high-rise building. As shown in Fig. 5, in the building shaded by the high-rise building for more than 2 h, the daily solar radiation on the building southern facade is 5 MJ/day lower in the current case than in the removed case. Hence, these buildings with large windows increases by more than 30% in the heat load.

The shading effect on the building heat load depends on not only the distance from the high-rise building and but also the window location and site conditions. When the building is close to and has no windows facing the high-rise building, such as building (a), the rate of increase in the building heat load is within 5% despite being shaded by the high-rise building for more than 2 h.
Figure 5 Increasing rate map of building heat load and daily solar radiation distribution in each case

Figure 6 Diurnal change in the solar heat gain and building heat load in buildings (b),(c)
On the other hand, although building (b) is 170 m away from the high-rise building, the rate of increase in the building heat load is 10%. This is because building (b) has windows facing the high-rise building and the adjacent parking lot has no buildings or external objects as shown in Fig. 6.

In addition, different building materials are not affected in the same manner by shading. In reinforced concrete buildings, with large heat capacity, increasing building heat load is observed when shaded by the high-rise building as well as at other times. In building (c), the building heat load is larger than that in the removed case after the building is shaded. The building heat load of building (c) in each time from 1 p.m. to 8 p.m. is approximately 30% higher than that at 11 a.m., which is the time when the building is shaded.

**CONCLUSION**

The shading effect of a high-rise building on the thermal radiation environment in the outdoor space around it and the neighboring buildings heat load in winter is discussed and the following conclusions are reached.

- Shading effect by high-rise building at noon extends widely to the area approximately 200 m away in the north and the lowest mean radiant temperature in the shaded area decreases 7 °C lower than air temperature. However, in the same space, the shading negative effect on the thermal radiation environment is mitigated by the surrounding space geometry and material. In particular, in the space close to the building wall and ground, which is heated because of solar heat accumulation in the morning, the mean radiant temperature keeps equal to the air temperature.

- In the target district, the northern and western street of high-rise building have many shops with southern or eastern façade with large windows, and these shops are affected more remarkably by high-rise building. The heat loads of these buildings are more than 30% larger than that in the removed case.

- Even for buildings 170 m away from the high-rise building, shading effect on the building heat load is not so little when the building is adjacent to the parking lot and has large window. In this condition, the building heat load increased by 10% compared with the removed case.

The following will be considered for our future work.

- Combine simulation with CFD simulation and study the wind and cold air distribution around the high-rise building.
- Perform simulations of the thermal environment in summer.

**REFERENCES**


NOMENCLATURE

\[ I_d = \text{Direct solar radiation on surface } i \ [W/m^2] \]
\[ I_{sl} = \text{Sky solar radiation on surface } i \ [W/m^2] \]
\[ I_{ri} = \text{Reflective solar radiation on surface } i \ [W/m^2] \]
\[ L_{object_i} = \text{Longwave radiation on surface } i \ [W/m^2] \]
\[ L_{sky_i} = \text{Atmospheric radiation on surface } i \ [W/m^2] \]
\[ S_{human} = \text{Surface area of the human body } [m^2] \]
\[ A_p = \text{Effective radiation area (Underwood C. R. & Ward E. J., 1966) } [m^2] \]
\[ \alpha_t = \text{Solar absorption of the human body } [-] \]
\[ \alpha_2 = \text{Emissivity of the human body } [-] \]
\[ W_i = \text{Weighting factor } [-] \]
\[ \sigma = \text{Stefan–Boltzmann coefficient } [-] \]

Subscript

\[ i = \text{microcube surface (assuming human body)} \]
Potential for Net Zero Energy Neighbourhoods in the Ahmedabad Urban and Solar Contexts

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ABSTRACT
Many net zero buildings have been proposed in different parts of the world. However, there is an argument that an individual building is not the right scale to develop Net Zero Energy Housing. The neighbourhood scale has the potential to integrate not only individual building systems, but also multi-building systems as well as of integrating neighbourhood geometry. This scale also offers opportunities for load sharing between buildings and diversity in functions. Inspite of India having a rich solar energy resource, there are no Net Zero Energy Neighbourhoods being developed. This paper tests the potential of three existing neighbourhoods in Ahmedabad, with different building typology and geometry, to achieve Net Zero Energy status by way of retrofitting Photovoltaic Technology. After a review of historical energy bills to assess the energy demand, the PVSyst software package (version 6.0) is used to test the potential performance of solar retrofits in the three different neighbourhoods. The results show that each of the three neighbourhoods can achieve Net Zero Energy status by retrofitting PV Panels. However, the investment cost and payback periods are prohibitive for the economic contexts of the three neighbourhoods. The paper further proposes neighbourhood scale retrofitting strategies. It also proposes government support policies, based on the neighbourhood scale, to overcome the cost limitations in achieving Net Zero Energy status.

INTRODUCTION
Carlisle, Geet and Pless (2009,4) define a Net-Zero Energy Neighbourhood, as “One that has greatly reduced energy needs though efficiency gains such that the balance of energy for vehicles, thermal, and electrical energy within the community is met by renewable energy”. There are mainly two approaches to achieve a Net Zero Energy Neighbourhood. The first one is designing a neighbourhood considering environmental requirements and providing various technologies to balance the energy use and production. Another approach is providing system retrofits in existing neighbourhoods such that the energy produced by renewable sources is equal to the total energy used in the neighbourhood. Retrofit in building terminology usually refers to introducing new technology for a building to be more efficient. Keirstead and Shah (2013, 47) states that since buildings are long-lasting infrastructure, much of the existing building stock will need to be improved if short and medium-term energy efficiency and greenhouse gas reduction targets are to be met. In addition to the benefits achieved by retrofitting individual buildings, area-wide retrofit schemes can offer further benefits in terms of supply-side
technologies, optimisation of area wide availability of renewable sources, economics of scale and project finances. However, financing of neighbourhood-scale and individual retrofits of renewables is currently expensive. Today, this technology is not widely applied due to high cost of implementation and long payback periods. Some examples of the neighbourhood approach include Masdar and Bedzed. Masdar in UAE is proposed as a carbon neutral city planned for 40,000 residents. It aims at sustaining 90% energy demand through Photovoltaic energy, while the rest will be sustained by other renewable sources. Although planned to achieve Net Zero Energy, the parts of it that have been executed have succeeded in some aspects but failed in others. Bedzed, designed as Britain’s first net Zero Energy Community, also had failures which include its inability to use renewable resources for the combined heat and power plant; occupants behaviour of adding portable heaters resulting in higher than predicted energy consumption. This paper tests the potential of three existing neighbourhoods in Ahmedabad to achieve Net Zero Energy status by retrofiting PV Technology. The neighbourhoods have different housing typology and geometry.

SOLAR POTENTIAL OF AHMEDABAD FOR RETROFITTING PV PANELS

In India, the solar radiation is abundant throughout the year; hence introducing solar photovoltaic technology in existing neighbourhood can reduce non-renewable energy demands. Ahmedabad is situated in the hot semi-arid climate zone of West India and is considered to have summer all year with average temperature of about 27°C to 41°C. It receives high solar radiation (Fig 1) especially in the south direction, hence has high potential for solar energy generation.

For testing the solar potential of the city to achieve a nZEN, a range of Neighbourhoods have been selected according to variation of housing typologies that exist in the city. The first neighbourhood type is the “POL” house – the traditional houses of Ahmedabad, consisting of a number of houses, facing the street and forming a cul-de-sac. Each house is connected to the street by a verandah (semi open space). This study is carried out in “Desai ni pol” situated on the eastern part of Ahmedabad. The second selected neighbourhood type is the apartment, which has grown rapidly in the city due to increased density and land prices. Many different kinds of apartments exist in the city ranging from low cost to luxury apartments with multiple Bedrooms. This study is carried out in Ambawadi apartments located in Western Ahmedabad, in a vicinity of mainly residences with few institution and commercial developments. The neighbourhood has six apartments with a large open space near the entry. Each apartment has three floor levels with four residences on each level. The third selected neighbourhood has the bungalow housing typology, which is spreading fast on the western side of the city due to ample availability of land. Many bungalows exist with large open spaces in the form of gardens with good potential to generate solar energy. However, shading is high in this neighbourhood due to trees. This study is carried out in Rushil bungalows located in western Ahmedabad near SG highway. The neighbourhood has 12 bungalows, each with a garden in the front and a covered backyard.

ENVIRONMENTAL CHARACTERISTICS OF THE SELECTED EXISTING NEIGHBOURHOODS

**Pol:** Each house has a deep long plot, sharing the longer wall with neighbouring houses, thereby reducing exposure to sun. Dense placements also offer mutual shading to the houses. The courtyard lets the hot air of the house to escape out and allows fresh air to enter. It also provides diffused light to the inner areas of the house. The tripartite windows maintain the inner temperature by allowing the cool breeze to enter and
providing shade from direct sunlight. A rainwater-harvesting tank is also located below the central courtyard which helps cool the temperature of the courtyard.

**Ambawadi Apartments:** These apartments have low energy demand due to their orientation and planning. The periphery of the each floor has balconies, creating an offset for the main living spaces. Generous overhangs protect the houses from direct sunlight, keeping the houses cooler. Moreover each apartment block offers shading to the other block thereby reducing direct exposure of facades.

**Rushil Bungalows:** These bungalows have very few environmental considerations in their design. They have few openings with overhangs, providing shade from direct sun. However, most openings are not shaded, exposing the façade to direct solar radiation, and therefore heating the house fast in summer.

![3D Massing of the selected neighbourhoods of Pol Houses, Ambawadi apartments and Rushil bungalows respectively](Source: Authors)

![Photos of Pol Houses, Ambawadi apartments and Rushil bungalows respectively](Source: Authors)

For this study, seasonal variation of metered energy bills for selected houses in each neighbourhood was collected and averaged out to arrive at the energy used per household. The energy used per household was multiplied with the number of houses in the neighbourhood to arrive at the total energy used by the neighbourhood. Table 1 compares the energy consumed in each neighbourhood.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy / House / Month</td>
<td>270 kWh</td>
<td>525 kWh</td>
<td>1550 kWh</td>
</tr>
<tr>
<td>Number of Houses</td>
<td>32</td>
<td>72</td>
<td>12</td>
</tr>
<tr>
<td>Average number of Persons/House</td>
<td>6</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Energy in Common Uses</td>
<td>-</td>
<td>-</td>
<td>825 kWh</td>
</tr>
<tr>
<td>Energy of Neighbourhood / Month</td>
<td>8640 kWh</td>
<td>37800 kWh</td>
<td>19,425 kWh</td>
</tr>
<tr>
<td>Energy of Neighbourhood / Year</td>
<td>103,680 kWh</td>
<td>4,53,600 kWh</td>
<td>2,33,100 kWh</td>
</tr>
<tr>
<td>Energy consumed per Person</td>
<td>540 kWh</td>
<td>1575 kWh</td>
<td>4856.25 kWh</td>
</tr>
<tr>
<td>Floor area / House</td>
<td>60 Sq. m</td>
<td>75 Sq. m</td>
<td>150 Sq. m</td>
</tr>
</tbody>
</table>

Table 1 shows that Neighbourhoods 1 and 2, which are low and middle income housing respectively, have less floor area and hence less energy used per person, when compared to Neighbourhood 3, which is upper middle class housing. Hence it could be concluded that energy used per person is greatly dependent on floor area of units and the lifestyle of residents in each Neighbourhood. From all three selected neighbourhoods, the Pol has the least energy consumed per person.
nZEN POTENTIAL: SOLAR ENERGY PRODUCTION AND COST

The shadow studies done in this research suggest that in the Pol house and Ambawadi apartments, the street and the space in between buildings respectively, remains shaded during most of the year, except for noon when the sun is overhead. Similarly in Rushil bungalows the open gardens and main access road remains shaded during most of the day by trees and vegetation.

Hence in all three neighbourhoods, the roof has maximum potential for direct as well as diffused solar radiation. In addition to the roof, the open space in Ambawadi apartments and open gardens and access road in Rushil bungalows have potential for direct and diffused solar radiation respectively. Hence in this study, roof area of all neighbourhoods is considered for solar energy generation.

Table 2 compares the energy produced using monocrystalline panels in each neighbourhood based on available roof area. It suggests that the Energy Produced/Year in Desai Ni Pol and Rushil bungalows, by using entire available roof area, is much more than the requirement of the entire neighbourhood. In Ambawadi apartments, the Energy Produced/Year is almost equal to the requirement of the entire neighbourhood. However, if energy demand increases in future, the neighbourhood can use its open spaces for solar energy production.

Table 2 suggests that there is a direct relation between plot coverage and the excess energy produced - the lower the plot coverage (Neighbourhood 2 and 3), the lower the excess energy produced. The more compact the neighbourhood with higher plot coverage and less obstructions, the more the excess energy produced. With proper balance of these factors during the initial design stage, one can achieve nZEN. Table 2 also suggests that the full roof potential to produce solar energy for Desai ni pol, Ambawadi apartments and Rushil bungalows is 14, 1.2 and 3.7 times more than the present demand. Hence, all three neighbourhoods have potential to convert into nZEN as well as produce excess energy.

Similarly, Table 3 compares the investment cost of solar energy production in each neighbourhood. It suggests that in Desai ni pol, Ambawadi apartments and Rushil bungalows the cost that each household
would pay annually to achieve nZEN is 2, 1.5 and 1.3 times respectively more compared to the current cost. Also, unit cost of energy increases in all neighbourhoods with retrofitting solar PV.

**Table 3. Comparison of Investment and Loan as per Energy Demand of Neighbourhoods [Pol (1), Ambawadi apartments (2), Rushil bungalows (3)]**

<table>
<thead>
<tr>
<th>Present Yearly Cost/ Household</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof Area according to Energy Demand</td>
<td>14,400 INR</td>
<td>31,200 INR</td>
<td>1,26,000 INR</td>
</tr>
<tr>
<td>Module Cost</td>
<td>33,95,561 INR</td>
<td>122,44,109 INR</td>
<td>63,03,898 INR</td>
</tr>
<tr>
<td>Support Cost</td>
<td>25,96,605 INR</td>
<td>113,69,530 INR</td>
<td>58,53,619 INR</td>
</tr>
<tr>
<td>Inverter and Wiring</td>
<td>7,98,956 INR</td>
<td>34,98,317 INR</td>
<td>18,01,114 INR</td>
</tr>
<tr>
<td>Transport and Mounting</td>
<td>37,04,577 INR</td>
<td>120,72,796 INR</td>
<td>70,98,285 INR</td>
</tr>
<tr>
<td>Total Investment/Neighbourhood</td>
<td>104,95,699 INR</td>
<td>391,84,752 INR</td>
<td>210,56,916 INR</td>
</tr>
<tr>
<td>Payback Period</td>
<td>22.7 Yrs.</td>
<td>17.4 Yrs.</td>
<td>13.9 Yrs.</td>
</tr>
<tr>
<td>Yearly Cost for Neighbourhood after Loan</td>
<td>10,39,780 INR</td>
<td>32,493 INR</td>
<td>20,68,237 INR</td>
</tr>
<tr>
<td>Yearly Cost/ Household upto 20 Yrs.</td>
<td>32,493 INR</td>
<td>52,613 INR</td>
<td>1,72,353 INR</td>
</tr>
<tr>
<td>Unit Cost</td>
<td>10.01 INR/kWh</td>
<td>8.33 INR/kWh</td>
<td>8.84 INR/kWh</td>
</tr>
</tbody>
</table>

**NET ZERO ENERGY BUILDING (nZEB) VS NET ZERO ENERGY NEIGHBOURHOOD (nZEN); COST AND CHALLENGES**

Table 4 compares the nZEN approach versus the nZEB approach with respect to cost limitations and the potential energy generation through solar panel retrofits. It shows that taking a neighbourhood approach is much more advantageous, as it provides availability of more shared renewable resources on site and energy sharing between houses thus helping to achieve Net Zero Energy. It provides more solar access with availability of multiple rooftops and common spaces including open space and streets, when compared to individual buildings, hence providing more unshaded potential area for PV installation. The unit cost of energy is also lower in nZEN approach compared to the nZEB.

**Table 4. Comparison of Grid Connected nZEB vs. nZEN: Energy Output vs. Cost [Pol (1), Ambawadi apartments (2), Rushil bungalows (3)]**

<table>
<thead>
<tr>
<th>Annual Energy Demand / Building</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Annual Cost / Building</td>
<td>14,400 INR/Yr.</td>
<td>37,40,000 INR/Yr.</td>
<td>1,26,000 INR/Yr</td>
</tr>
<tr>
<td>Yearly Investment for nZEB (PVSyst)</td>
<td>50,398 INR/Yr.</td>
<td>7,80,690 INR/Yr.</td>
<td>2,34,137 INR/Yr</td>
</tr>
<tr>
<td>Yearly Investment for nZEN/ Building</td>
<td>32,493 INR/Yr.</td>
<td>6,31,361 INR/Yr.</td>
<td>1,72,353 INR/Yr</td>
</tr>
<tr>
<td>Unit Cost For nZEB</td>
<td>15.55 INR/kWh</td>
<td>10.33 INR/kWh</td>
<td>12.59 INR/kWh</td>
</tr>
<tr>
<td>Unit Cost For nZEN</td>
<td>10.01 INR/kWh</td>
<td>8.33 INR/kWh</td>
<td>8.84 INR/kWh</td>
</tr>
</tbody>
</table>

**Table 5: Stand Alone Systems for Individual Buildings Based on Annual Energy Required [Pol (1), Ambawadi Apt (2), Rushil Bungalows (3)]**

<table>
<thead>
<tr>
<th>Infrastructure</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module Cost</td>
<td>1,62,899 INR</td>
<td>3,10,813 INR</td>
<td>7,75,776 INR</td>
</tr>
<tr>
<td>Battery Cost</td>
<td>4,73,709 INR</td>
<td>9,04,122 INR</td>
<td>26,43,603 INR</td>
</tr>
<tr>
<td>Regulator Cost</td>
<td>82,911 INR</td>
<td>1,30,322 INR</td>
<td>2,77,008 INR</td>
</tr>
<tr>
<td>Transport/Fitting</td>
<td>6,21,833 INR</td>
<td>9,77,418 INR</td>
<td>20,77,560 INR</td>
</tr>
<tr>
<td>Total Investment</td>
<td>13,41,353 INR</td>
<td>23,22,676 INR</td>
<td>57,73,947 INR</td>
</tr>
<tr>
<td>Yearly Investment</td>
<td>50,398 INR/Yr.</td>
<td>7,80,690 INR/Yr.</td>
<td>2,34,137 INR/Yr</td>
</tr>
<tr>
<td>Yearly Cost For nZEB</td>
<td>15.55 INR/kWh</td>
<td>10.33 INR/kWh</td>
<td>12.59 INR/kWh</td>
</tr>
<tr>
<td>Yearly Cost For nZEN</td>
<td>10.01 INR/kWh</td>
<td>8.33 INR/kWh</td>
<td>8.84 INR/kWh</td>
</tr>
</tbody>
</table>

Comparing the cost of Stand-alone nZEB (Table 5) with Grid connected Neighbourhood scale retrofits (Table 3); nZEN turns out to be more economically viable. The cost that each household ends up paying annually for a Stand-alone nZEB is about 7-10 times more than that required for an nZEN. This reduced cost in the neighbourhood approach happens because of sharing of infrastructure required for connecting the system to the Grid. The cost of batteries required for storage of excess energy, transport and maintenance is high, as required in Stand-alone systems, acting as a major barrier for nZEB.
Barriers and Challenges

Though connecting to the grid offers incentives of using electricity all year round and selling the excess energy, in India, it faces a few challenges. For an owner, a single point of contact from financing, to operation and maintenance is required for solar PV to be more prominent. However, presence of multiple partners forms a major barrier. Similarly, there might be a problem of ownership in shared rooftops and long-term leasing for solar power generation due to fixed incentives. Moreover, the connection of multiple PV systems to the grid might also have stability issues, hence making it vital to monitor it to avoid its collapse. Also monitoring of energy being fed into the grid to avoid misuses is important. Power generated from other sources if fed into the grid, can lead to a collapse of the feed-in-tariff model. Likewise, availability of different types of devices of diverse quality, for net metering, creates a barrier for precise measure. Hence, establishing a “star rating system” for devices is fundamental for its success. According to the Technology Strategy Board in UK, neighbourhood retrofits also face challenges due to lack of awareness amongst owners about sustainability and long term gains. The biggest challenge to realise this approach is reaching a mutual agreement amongst families within the neighbourhood regarding investing in this technology. Moreover, lack of competition, choice and availability of materials, higher than expected cost are other challenges making it difficult to implement this technology.

COMPARISON OF USING ALTERNATIVE PANEL TYPES

In order to overcome the cost limitation, since monocrystalline panels are the most expensive PV panel, using different panel types might be a useful option for these neighbourhoods to attain Net Zero Energy. Table 6 suggests that in Pol houses and Rushil bungalow, the amount of energy produced by Polycrystalline and Hybrid Panels is enough to meet demand. However, Table 7 indicates that the cost difference is not sufficient when compared to Monocrystalline panels. The cost of energy per unit also increases by using a less efficient panel. Hence, though using an alternate panel type limits the excess energy produced, the cost of its realisation is more compared to the current cost of the neighbourhood.

Table 6: Comparison of Energy Potential by using Alternative Panel types on entire roof area available [Pol (1), Ambawadi apartments (2), Rushil bungalows (3)]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Demand</td>
<td>1,03,680 kWh</td>
<td>4,53,600 kWh</td>
<td>2,33,100 kWh</td>
</tr>
<tr>
<td>Monocrystalline</td>
<td>14,75,212 kWh</td>
<td>5,40,151 kWh</td>
<td>8,70,243 kWh</td>
</tr>
<tr>
<td>Polycrystalline</td>
<td>13,83,012 kWh</td>
<td>5,06,392 kWh</td>
<td>8,15,853 kWh</td>
</tr>
<tr>
<td>Hybrid</td>
<td>9,22,008 kWh</td>
<td>3,37,594 kWh</td>
<td>5,43,902 kWh</td>
</tr>
</tbody>
</table>

Table 7: Comparison of Unit Cost (INR/kWh) and Yearly Cost (INR/Yr.) using Different Panel Types on entire Roof area Available [Pol (1), Ambawadi apartments (2), Rushil bungalows (3)]

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>1: INR/Yr.</th>
<th>2: INR/kWh</th>
<th>2: INR/Yr.</th>
<th>3: INR/Yr.</th>
<th>3: INR/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Cost</td>
<td>-</td>
<td>2.8 - 4.3</td>
<td>-</td>
<td>2.8 - 4.3</td>
<td>-</td>
</tr>
<tr>
<td>Monocrystalline</td>
<td>111,94,544</td>
<td>7.59</td>
<td>43,10,750</td>
<td>7.98</td>
<td>66,73,778</td>
</tr>
<tr>
<td>Polycrystalline</td>
<td>107,87,085</td>
<td>7.80</td>
<td>41,44,648</td>
<td>8.18</td>
<td>64,19,822</td>
</tr>
<tr>
<td>Hybrid</td>
<td>87,02,963</td>
<td>9.44</td>
<td>32,92,894</td>
<td>9.75</td>
<td>51,18,930</td>
</tr>
</tbody>
</table>

SOLUTIONS FOR OVERCOMING COST LIMITATIONS

In order to overcome the cost limitations, an important step would be to reduce energy demand by increasing the efficiency of building envelope. Provision of shading devices for openings and use of better insulating materials in walls and roof would help decrease the overall demand of the three neighbourhoods. In addition, provision of neighbourhood scale retrofits like using efficient streetlights, offering better transportation networks, reducing energy required in pumping ground water, etc. would further help reduce the energy demand of the neighbourhood. After reducing the demand, below are few
other ways, which would help overcome the cost limitations of neighbourhood retrofits.

1) Selling the Excess energy to the Government

In each of the three Neighbourhoods, the roof area available has potential to produce excess energy. If the excess energy could be fed into the grid and sold to the government, the payback period and cost could be reduced to a large extent. The State already has a number of privately owned power plants, which sell energy to the state government. According to the Gujarat Electricity Regulatory Commission (GERC) the current rate of buying solar power for all PV Plants commissioned between 1st April 2014 to 31st March 2015 is reduced to 8.03 INR. If each of these neighbourhoods sells their excess energy to the government at the given rate, the yearly instalment would reduce to a large extent. For example in the Pol, yearly instalment on the loan, for the demand energy roof area, would be 32,493 INR. However, after entire roof area installation and selling of excess of energy the neighbourhood has to pay 5660 INR/Yr. (Table 8).

Table 8 shows the reduced price that each neighbourhood has to pay after selling excess energy to the government. Hence, in this way major part of the investment amount could be borne by the government, while the residents could pay the remaining amount. However, there are some barriers in this approach – the main one being convincing the government to invest in the neighbourhoods.

Table 8: Selling Excess Energy to the Government [Pol (1), Ambawadi Apts (2), Rushil Bunglows (3)]

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Excess Energy</td>
<td>13,71,532 kWh</td>
<td>86,551 kWh</td>
<td>6,37,143 kWh</td>
</tr>
<tr>
<td>Money Received by selling</td>
<td>110,13,401 INR/Yr.</td>
<td>6,95,004 INR/Yr.</td>
<td>51,16,258 INR/Yr.</td>
</tr>
<tr>
<td>Excess Energy at Rs 8.03/kWh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yearly Cost / Neighbourhood</td>
<td>111,94,544 INR/Yr.</td>
<td>43,10,750 INR/Yr.</td>
<td>66,73,778 INR/Yr.</td>
</tr>
<tr>
<td>Yearly Cost/ Neighbourhood (After selling Excess Energy)</td>
<td>1,81,143 INR/Yr.</td>
<td>36,15,746 INR/Yr.</td>
<td>15,57,520 INR/Yr.</td>
</tr>
<tr>
<td>Yearly Cost/ Household (After selling Excess Energy)</td>
<td>5660 INR</td>
<td>50,218 INR</td>
<td>1,29,793 INR</td>
</tr>
<tr>
<td>Present Yearly Cost/ Household</td>
<td>14,400 INR</td>
<td>31,200 INR</td>
<td>1,26,000 INR</td>
</tr>
</tbody>
</table>

2) Public Private and Neighbourhood Partnership

Currently few retrofitting strategies have been established in India to promote solar power generation in the domestic context. In Gujarat, the city of Gandhinagar has been promoted as the first solar city, where they aim to produce 5MW of energy through public and private rooftops. The city has tried the Public Private Partnership concept, wherein the private developers would be given access to rooftops of 25 public buildings and around 250 private houses. City dwellers would be given a “green incentive” of INR 3/kWh of energy produced on their privately owned rooftops after Solar PV installations. This serves as a useful strategy of combining private and public investors to invest in solar power generation on local rooftops. However, since this strategy is limited to individual buildings, the roof area available is less giving no neighbourhoods scale energy benefits to house owners. Regarding neighbourhood scale retrofitting strategies, this approach should prioritise installations at the neighbourhood rooftops that are most exposed to solar radiation and should distribute such solar exposure benefits to all dwellings across the neighbourhood. A phased installation approach would potentially help low-income dwellers to distribute capital installation costs for longer periods, thus reducing their monthly repayments.

3) Government Policies, Initiatives and Incentives

Many countries have tried to promote and fund retrofits within the government policies. For example, the UK Government’s “Green Deal plan” is a financing mechanism that allows consumers to repay through saving on energy bills for energy saving home installations. Even within India, the Jawaharlal Nehru Nation Solar Mission is an important initiative by the government to promote solar power wherein it targets at producing 20,000 MW of grid connected solar power by 2022. Under the mission, private companies are offered incentives to invest in solar power, by reducing customs duty on solar PV by 5% and exempting excise duty on Solar PV. This is expected to reduce the overall cost of a rooftop solar
panel installation by 15–20%. The government also provides Generation based incentives (GBI) and 80% accelerated depreciation income tax benefits on solar energy production. Moreover, the Ministry of New and Renewable Energy (MNRE) in India provides 30% subsidy on the cost of installation of solar PV power plant in all states. However, existing policies target large-scale production of solar power plants and not the domestic sector. Hence, more policies are required, targeting urban neighbourhoods, providing incentives directly to the residents, and helping them achieve Net Zero Energy.

CONCLUSIONS

From the research, it can be concluded that all three neighbourhoods in Ahmedabad have immense potential to produce solar energy and achieve nZEN status. This paper has tested the initial potential of the neighbourhoods and provided rough estimates of investment. The key limitation of this technology is the cost factor and methods have been suggested to overcome this within the solar and economic context of Ahmedabad. With a proper mix of environmental considerations at a design stage- considering orientation, plot coverage and density of a neighbourhood, the energy demand can be restricted. This, followed by government support to implement this technology, by either buying excess power from local neighbourhoods instead of private power plants, or by offering incentives to private and public investors for investing in it at the neighbourhood scale, would help each of these urban neighbourhoods in Ahmedabad to achieve Net Zero Energy. The work suggests that further research is needed to explore links between plot coverage and solar energy in Ahmedabad in order to inform policy on neighbourhood planning to benefit from the conflicting requirements of solar exposure and shading. Further work is also needed on cost reduction strategies to make solar PV more accessible to low income neighbourhoods.

REFERENCES


ABSTRACT

The proper adjustment of the architecture to the climate is one of the basic characteristics of vernacular building. Nowadays this area received an important support through the application of cutting-edge technology. Still, despite the clearly visible change of attitudes towards nature, more detailed analysis often lead to the conclusion that the arising buildings are very rarely based on extensive studies of local bioclimatic conditions. The purpose of this paper is to discuss how the traditional ways of adapting dwellings to the climate are combined with advanced technology and applied in contemporary bioclimatic buildings. Three important case studies are briefly presented in order to demonstrate that the relevant distinguishing feature of bioclimatic architecture is to go beyond the scheme of low-energy buildings, constructed from renewable materials and meeting the conditions of sustainable development certification systems. It is much more vital for the true green design to implement the structures in the ecosystem in such a way that they become an integral part of it. Thus understood bioclimatic architecture is logical, well adapted to the climate and therefore also economical. It creates great opportunities and should be perceived as the solution for the developing countries (as well as for the whole world).

INTRODUCTION

The idea of bioclimatic architecture is closely related to the proper adjustment of the dwelling to the climate. That is also one of the characteristics of vernacular building, based on the traditional ways of adapting architecture to the specific climatic conditions. Vernacular architecture is directly linked to the available resources that influence building techniques (Balbo, 2013, p.37). Furthermore, it is customized to the functional needs and cultural background of the inhabitants. The main difference between vernacular and bioclimatic building lies in the ability to select the technological solution most appropriate to the climate. In traditional architecture that kind of knowledge has been naturally transferred from one generation to another. In bioclimatic building the concept of architecture optimally adapted to the local conditions received an important support through the application of advanced technologies. Due to the combination of traditional climatic solutions and cutting-edge technology, bioclimatic dwelling is well suited to the needs of the contemporary user. The other difference involves proper understanding of complexity and sensitiveness of the natural environment. Bioclimatic architecture is based on holistic approach, including in-depth environmental analysis. Ultimately, the bioclimatic building should become an integral part of the ecosystem and ensure the symbiosis between the cultural and natural processes. However, despite clearly visible change of attitudes towards nature, the alarming datum is that more detailed analysis of projects often lead to the conclusion that although the idea of so-called sustainable design is manifested all over the world, in fact, the arising edifices are
rarely based on extensive studies of bioclimatic conditions as the wider aspect of the problem is
sometimes simplified (or even ignored) within the design process oriented towards the energy
certification achievement (e.g. Telles, 2012).

Analysis of the various solutions, used in similar climatic conditions, combined with the
application of contemporary knowledge allows to develop and to implement technologies that will help
to customize the newly erected buildings to the requirements of the modern user. Two biggest challenges
in this area are connected with the indoor climate and lighting (McIntyre, 1980; Mahdavi, 1996).
Adequate lighting of the interiors with the use of daylight not only positively affects the user comfort,
but also has a significant impact on reducing electricity consumption. Although this aspect is considered
by the designers more often than the natural cooling, the proper use of daylighting should be further
promoted.

The necessary factors of the comfortable indoor microclimate are: thermal comfort, proper air
humidity, adequate air exchange rate, the correct oxygen content (this parameter can be improved for
example by the introduction of green plants inside the building) etc. In most of developing countries the
challenges of thermal comfort derive from the necessity of cooling the indoor air. Despite many
criticism, the plant air conditioning systems are so widespread that they are most frequently applied in
purpose to provide low temperature and low humidity in the buildings (Mahdavi, 1996). That kind of
cooling is commonly used, especially in the offices, retail spaces or public buildings, regardless the high
costs, electricity consumption, environmental impact and without considering the application of natural
systems, based on local bioclimatic conditions. In many cases the only difference between conventional
and so-called sustainable building is limited to the fact a part of electric energy for air conditioning
systems comes from photovoltaic panels or other renewable sources.

**NATURAL VENTILATION SYSTEMS IN HOT CLIMATE**

Cooling systems in vernacular architecture in hot climate zones are based on natural ventilation.
Among various schedules observed in traditional dwellings there are three basic models distinguished by
Sørensen, that may be applied in contemporary bioclimatic architecture (Sørensen, 2008). These are:
1. Cross ventilation based on the pressure difference across the building shown in Figure 1a.
2. Chimney ventilation based on the stack effect i.e. underpressure caused by the rising hot air
shown in Figure 1b.
3. The wind catchers and wind towers based on overpressure and underpressure presented in
   Figure 1c.

![Figure 1](image.png)

**Figure 1** Basic models of natural ventilation. Based on Sørensen (Sørensen, 2008).

In many regions some modifications improve these basic systems. In hot and humid regions, e.g. in
Thailand, many traditional houses are openwork and built on high stilts, so that the cross ventilation is
combined with the elevated floor as described by Tantasavasdi and presented in Figure 2 (Tantasavasdi
et al., 2001; Tantasavasdi et al., 2007). In Japan, where the temperatures are lower, the floor is slightly
raised above the ground. In both cases the air flows under the building to cool it in summer and – in case
of the Japanese house – to separate it from the ground in winter. Also in both dwelling types the roof
drainage systems (made of natural materials) allow for collecting rainwater.

Different solutions may be observed in hot and dry climatic conditions of Arab countries where the
wind towers and wind catchers are quite common. They may be additionally combined with simple but
effective evaporative cooling systems described by Hassan Fathy (Fathy 1986) as shown in Figure 3. On the basis of these solutions some holistic concepts for bioclimatic architecture were created. The leading architectural workshops in this area are Mario Cucinella Architects (MCA) and TR Hamzah & Yeang.

Figure 2 Natural cooling in Thailand. Based on Tantasavasdi (Tantasavasdi 2001).

Figure 3 Evaporative air cooling system in Egypt. Based on Fathy (Fathy 1986).

ENVIRONMENTAL STRATEGIES IN THE CENTRE FOR SUSTAINABLE ENERGY TECHNOLOGIES (CSET) DESIGNED BY MCA

Centre for Sustainable Energy Technologies (2006-2008, Ningbo, China) was designed by Mario Cucinella Architects in cooperation with School of the Built Environment, University of Nottingham. The edifice is located in the Nottingham University new campus in Ningbo and it is dedicated to “(...) the diffusion of sustainable technology including solar power, photovoltaic energy, wind power and so forth” (Giorgi, 2006, p.90). The building itself represents advanced environmental strategies developed in direct relation to the local context. A very interesting hybrid system was applied in the project. It is based on the knowledge gleaned from vernacular architecture of hot climate areas (both dry and humid) and successfully combined with high-tech, environmentally safe technology. The non-conventional air-conditioning systems are supported with the cutting-edge technologies for the exploitation of renewable energy sources. The project was created with an intention to take the maximum advantage of the local bioclimatic conditions and to minimize the environmental impact of the building. Following the results of the local climate analysis, the designers developed the structure that allows to reduce the energy demand for heating in winter and cooling in summer. During the intermediate seasons (spring and autumn) the natural ventilation, triggered by a series of automated openings, provides comfortable temperatures and humidity, so there is no need to use plant air conditioning systems. Regarding the climatic conditions it was essential to establish the proper thermal insulation and create massive structures with high thermal capacity. The crucial part of the heating and cooling concept was the carefully controlled air movement within the building.

In hot and humid summer the passive cooling strategies are applied. Thereby the usage of plant systems is significantly diminished and limited only to the hottest days. During the warm part of the year the layer of the ground, located below the land surface, is colder then air. The incoming air is pre-cooled naturally when passing through the earth-to-air heat exchanger constructed in the form of a series of pipes buried in the ground as shown in Figure 4. Subsequently the air is further cooled and dehumidified by the air handling unit (AHU). Similarly the ventilation air coming through the air inlet in the tower is cooled and dehumidified by the AHU placed in a coverage. A solar chiller that pre-cools the external air for the tower ventilation is powered by hot water from solar tubes. Thus prepared air is distributed throughout the building. The chimney effect fastens the air exchange and the warm air is removed through the windows placed in the double skin south façade.

High thermal inertia of the green roof in the lower part of the building prevents overheating while thermal mass of the concrete surfaces supports the coolness distribution. The geothermal heat pump
produces cold water for cooling the concrete floors. The radiant cooling from the ceilings is effective and healthy so that the mechanical cooling is required exclusively for pre-cooling the incoming ventilation air. In such a way the correct passive cooling design of the building and the high inertia of its concrete structure provide optimal indoor microclimate during summer.

The angles and materials of the southern part of the building were designed to pre-heat ventilation air in winter. The external air inlets are located on the ground level, at the bottom of the double skin façade so that during sunny days the air is naturally heated by the passive solar gains. After reaching the appropriate temperature the air is distributed in the edifice. Other air inlets are situated in the ground, outside the building. The incoming air is pre-heated by the earth-to-air heat exchanger. Further heating is provided by the geothermal heat pump, which is powered by energy from the photovoltaic panels. The air heating system is integrated with the radiant air-conditioning ceiling. The radiating coils embedded in the floors are activated when it is necessary to heat ventilation air. The heat is stored by the concrete ceiling slabs and released gradually to provide proper thermal comfort during the day. The northern façade is well insulated to avoid heat loss during the cold season of the year. The heat transfer coefficient of the opaque walls is 0,25 W/m²K and of transparent parts 1,2 W/m²K.

![Figure 3](image)

**Figure 3** Centre for Sustainable Energy Technologies (CSET, 2006-2008, Ningbo, China) by MCA, environmental strategies – summer. Drawing © MCA.

The whole building envelope was designed in favor to provide maximum usage of natural light as it was possible without glare and overheating during summer. Such solution reduces the use of artificial lighting and thus also the electric energy consumption. All the necessary artificial lighting systems are characterized by high luminous efficiency and low power consumption. Electricity, required to power that lighting as well as the office equipment, comes from especially redesigned photovoltaic system. The energy surplus produced during maximum solar radiation periods can be stored in batteries or sold to the nearby sports center. The BEMS (Building Energy Management System) controls the building operation and manages active and passive systems to optimize comfort level, while reducing energy consumption.
All the environmental strategies were chosen in purpose to create contemporary bioclimatic building that provides proper balance between local climate factors (sun angle, air and earth temperature in different seasons, wind, humidity), ecosystem (plants and species of the area), technology (including renewable energy sources) and the occupant needs (indoor comfort, reference to Chinese culture). The educational value of the project is connected with promotion of the concept of bioclimatic architecture that derives from the environmental studies and therefore is very well adapted to the natural and cultural context.

**BIOCLIMATIC ARCHITECTURE AND ECOSYSTEMS**

It should be noted that while sustainable development program in architecture strongly accentuates local aspects, under the label of sustainable architecture there is often an attempt to create a global golden rule of architecture. The evaluation methods are inherently characterized by some averaging, but the creation of the built environment truly adapted to the bioclimatic conditions requires an individual approach. Conducting environmental analysis is necessary each time for the specific location. Moreover, due to dynamic nature of ecosystems, analyses should be repeated and changes monitored (Yeang, 1996). Increased attention is given to the relationship between the architecture and the ecosystem (Hart, 2011). Ken Yeang, one of the most important creators and promoters of bioclimatic architecture, notes the necessity of integration of the following Eco Infrastructures:

1. Green - connected with natural habitats and the environmental biodiversity.
2. Gray - related to engineering that include sustainable energy and technologies oriented towards low environmental impact as well as zero CO\textsubscript{2} emissions.
3. Blue - concerning water management, rainwater harvesting and gray water recycling.
4. Red - referring to human culture i.e. law regulations, social norms and habits, user comfort, standard expectancy, materials as well as the human impact on the environment.

Each part of infrastructures described above is analyzed and developed in close relation to the existing ecosystem, with the intention to restore, preserve and enrich its equilibrium and biodiversity. Proper implementation of that strategy into the bioclimatic design leads to the authentic adaptation of architecture to the local context. Thus created holistic approach is an important distinguishing feature of bioclimatic architecture.

**RELATION TO THE ECOSYSTEM ON THE EXAMPLE OF SOLARIS BUILDING DESIGNED BY TR HAMZAH & YEANG**

Holistic and consequent approach to bioclimatic architecture can be observed in Solaris (2011, Singapore,) designed by TR Hamzah & Yeang. This 79-meters high structure is situated in Fusionopolis, in the area of the former military base which now became a fast developing business and research area of Singapore. Since the existing ecosystem was seriously damaged, one of the main goals of the architects was to restore and enrich its biodiversity in purpose to create equilibrium of the natural and built environment. Therefore the continuous perimeter ramp, with a length of 1500 meters, was designed to introduce maximum amount of green area into the building. The landscaped ramp established the link between One-north Park that reaches directly the building façade and Solaris towers. The higher tower has 15 and the lower 9 floors. Both of them house research facilities and offices. All the areas of the building are connected to the spiral ramp and passively ventilated atrium. The service path that goes through the ramp provides direct access for plants maintenance and is used as the linear park that leads up to the roof gardens on the top of each tower. This continuous landscaped spiral with a minimum width of 3 meters was designed for the benefit of the environment, as it enables fluid movement of small organisms between green areas of the edifice and thus contributes to biodiversity and health of the ecosystem. At the building corners the ramp expands to the terraces. As a consequence total landscaped area of the project covers 8,363 m\textsuperscript{2}, with the site area 7,734 m\textsuperscript{2}. That results with 108% ratio of landscape to site area and 95% of the landscaped area located above the ground level.
Bioclimatic concept combines traditional solutions developed for hot and humid climate zones with the most contemporary technology and knowledge. The climate-responsive façade design is based on studies of local climatic conditions, including the sun-path analysis. The specific building location at the equator and the east-west sun-path affected specific requirements of the façade shading. The first element of this strategy is the ramp with deep overhangs and the abundance of shade plants. The second solution in favor of the ambient cooling are the sunshade louvers with shape and depth determined directly by the solar-path analysis. The louvers and the green ramp created a pleasant buffer space which significantly reduced solar gains and glares. Consequently the heat transfer through the low-e double-glazed façades was also considerably decreased. The external thermal transfer value (ETTV) of the whole system is 39 W/m².

Figure 4 Solaris (2011, Singapore), by TR Hamzah & Yeang, bioclimatic section. © TR Hamzah & Yeang.

An atrium situated between the two towers is fully passively cooled and supports natural ventilation and daylight distribution within the internal areas of the building. An operable glass-louvered skylight system was installed on the roof over the atrium to enable stack effect cooling. Computational Fluid Dynamics (CFD) simulations were carried out to provide optimal thermal comfort with the controlled air flow in the atrium. Simultaneously, the active energy use was diminished. Both the louvers and the rainscreen walls are controlled by climate-responsive sensors to ensure protection against the precipitation and to allow natural ventilation during the rain. The atrium is directly connected to the landscaped area on the ground floor, linked to One-north Park which allows for cross ventilation. In order to provide optimal daylight penetration within the building's interior, the diagonal solar shaft was designed. It crosses the structure from the top of the higher tower down to the street level. The solar shaft gained more attractiveness with the landscaped terraces situated inside. Additional daylight is received from the façade shading louvers that create also double light-shelves and redirect the light into the building. To optimize the system performance a series of sensors measure the illumination level. When the sensors register a sufficient amount of daylight, the artificial lighting is automatically switched off. Thereby the energy consumption is reduced. As pointed out by Council on Tall Buildings and Urban Habitat (CTBUH), the reduction in overall energy consumption in Solaris building reached 36% compared to relevant precedents (CTBUH, 2012).

Due to the large amounts of vegetation located within the building, it was necessary to solve the
problem of irrigation in an efficient and environmentally safe way. Based on the concept of bioclimatic design the attention was focused on the high average of rainfall in the area. Consequently a large-scale rainwater recycling system was proposed. Rainwater is harvested on the roof via symphonic drainage and on the perimeter ramp with the drainage downpipes. It is then stored in rooftop tanks and at the lowest basement level, beneath the place called Eco-cell. Eco-cell is located on the ground level at the building's north-east corner, at the beginning of the ramp. It allows for penetration of natural light and ventilation air as well as for the plants extension into the car-park area below. A total storage capacity of Solaris rainwater tanks is over 700 m$^3$, which almost entirely covers the demand for watering plants. An integrated fertigation system provides plants with essential organic nutrients.

The project of Solaris building is adapted to local context on many levels. Similarly to CSET the design concept is based on analysis of the environmental factors, such as sun-path, sun angle, temperature and humidity. Moreover, the project’s bioclimatic strategy seriously takes into account the individual character of the ecosystem, including the need to restore and enrich its biodiversity. Consequently, the idea of bioclimatic architecture is created in equilibrium with the natural environment.

Two edifices described above: CSET and Solaris, are pioneering on a global scale. Promotion of such an approach is extremely important, as it helps to establish a model for developing countries. However, it is worth to notice that on a local scale it is possible to create bioclimatic architecture also with much lower budget. Solutions based on contemporary knowledge and technology, well inscribed into the local conditions and determinants, can be implemented at minimal cost. An impressive example was set by MCA who designed the school in Khan Younis, in the Gaza Strip.

![Diagram of Kuwait School in Khan Younis](image)

**Figure 5**  Kuwait School in Khan Younis (Gaza Strip, from 2014) by MCA. © MCA.

**KUWAIT SCHOOL IN KHAN YOUNIS, GAZA STRIP, BY MCA.**

The project of Kuwait School in Khan Younis (Gaza Strip, from 2014) was developed by MCA in partnership with UNRWA (The United Nations Relief and Work for Palestine Refugees in the Near East), with the financial support of the Kuwait Fund for Arab Economic Development. The aim of the concept was to create a green school that will provide high user comfort for 1500 children and will be totally safe for the natural environment. As the project is dedicated to the challenged area of Gaza Strip, where an access to most of resources is very limited, all the materials have to be affordable and locally sourced. The lack of fresh water is a very serious problem in Gaza Strip. Electricity is produced from
generators that cause environmental pollution. To deal with this facts Cucinella proposed the pilot project to promote green approach, which may be “part of the solution to the demographic boom in Gaza where people are struggling to build homes and schools with the resources they have” (Aburawa, 2012). Therefore an off-grid building, possible to build only with locally available and renewable resources was designed. All the construction systems are as simple as possible, avoiding excessive use of advanced and expensive technologies. The only exception concerns the implementation of photovoltaic cells, solar panels and thermal technologies that improve the quality of life without harming the environment.

The Kuwait School was designed as bioclimatic building, well adapted to the local climate and environment, with an intention to enhance the biodiversity of the ecosystem. The whole construction was created in such a way that its elements support bioclimatic strategies. The concrete foundation slab provides thermal mass. Low-cost pillars designed to increase inertia, are made of concrete-earth blocks pre-casted on site, with a diameter of 2,2 m and the inner cavity filled with ground from the excavation. Vaulted slabs are made of compressed earth block. Thus formed flat arches represent traditional and very simple building technique which does not require any formwork. Overhanging roof is made of inexpensive steel beams and reflective corrugated metal sheets. The overhang allows for natural ventilation and shades the earth-brick walls. Thermal control in the building is achieved with the earthen walls and floors providing thermal mass and protecting the interiors against direct solar gain during hot days as well as against cold winds. Further elements that prevent overheating are the façade shading panels and the overhanging roof. Air pipes, located beneath the foundation slabs, cool the ventilation air in summer and heat it in winter. 18 solar chimneys fasten the exhaust air extraction from the building. Finally, the inner courtyard was designed to create pleasant green area, support natural ventilation and reduce heat island effect.

Electricity, necessary to power electrical devices, will be provided by 1272 m$^2$ of amorphous photovoltaic cells located on the roof. Hot water for the heating coil will be delivered from 100 m$^2$ of the vacuum solar heaters. The classrooms will be naturally illuminated with daylight. Such designed building will have zero CO$_2$ emissions, will use zero oil and its heating demands will be 7 kWh/m$^2$ per year with 0 kWh/m$^2$ per year for cooling purposes.

The rainwater harvested from the roof will be used for the hygienic purposes. It will be stored in an underground tank. The recycled waste water will be used for flushing toilets (grey water) and for the plant irrigation (black water). This strategy will result in reducing water demand by 60 %. Each year water savings will bring 4600 m$^3$/y from waste water and 486 m$^3$/y from rain water.

In the project there are numerous references to the local tradition that makes it more accessible to residents and allows to express respect for their cultural heritage.

CONCLUSION

In the three case studies presented above traditional solutions developed in vernacular architecture were used as the inceptive idea as well as the source of inspiration for contemporary bioclimatic buildings. Basic methods of passive cooling and natural ventilation, commonly used in hot climate areas, were hybridized to achieve the optimal performance. In purpose to obtain the high level of indoor microclimate comfort, corresponding to modern user expectancies, advanced technology was applied. In first two edifices their budget allowed for some exemplary technological solutions, especially regarding climate responsive façade design as well as air preparation and distribution throughout the building. In CSET the non-conventional air-conditioning systems were supported with cutting-edge technologies for the exploitation of renewable energy sources. In Solaris the issue of restored, enriched biodiversity and the equilibrium of natural and built environment was of the utmost importance. The project of Kuwait School proved that the contemporary knowledge and technology, well inscribed into the local conditions and determinants, can be implemented at minimal cost. While photovoltaic cells, solar panels and thermal technologies were used to improve the quality of life, the whole architectural conception is based on passive strategies, simple construction methods and locally available, renewable resources.

The study presents the concept of bioclimatic architecture through the proper balance between
traditional ideas and modern technologies. This notion allows for practical and creative usage of contemporary knowledge transfer. Nowadays original methods, dedicated to various climatic determinants, developed and verified in different parts of the world, can be supported and improved by the application of cutting-edge technologies. Although in-depth analysis of local biological and climatic conditions should always be a starting point, the worldwide information exchange can result in entirely new hybrid systems designed for the specific location needs. It is worth to note that such an approach may be used also in the areas where the lack of indigenous examples hinders the selection of the most appropriate bioclimatic solution solely on the basis of vernacular buildings studies. Therefore the contemporary bioclimatic architecture can be defined as one that combines traditional knowledge about ways of adapting dwellings to the climate with advanced research, design and technological methods in purpose to create the built environment maximally integrated with the natural environment and especially with the ecosystem in which it is placed.

It should be emphasized that buildings that are well adapted to bioclimatic conditions do not exceed the budget for comparable facilities while their environmental impact is minimal. Growing respect for ecosystems results with architectural projects that enhance biodiversity for the benefit of natural and cultural environment. Thus understood bioclimatic architecture creates great opportunities and should be perceived as the solution for developing countries (as well as for the whole world).

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Occupant Feedback in Energy-Conscious and ‘Business as Usual’ Buildings in India

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ABSTRACT

Buildings account for 30% of energy consumption in India, and it is estimated that 70% of the projected commercial building stock by 2030 is yet to be built. The recently established five-year US-India Centre for Building Energy Research and Development (CBERD) project aims to address the barriers for adopting low energy consuming strategies in buildings in India, while exploring the lessons that can also be applied to the US context. This paper evaluates the performance of two energy-conscious (EC) and two ‘business as usual’ (BAU) buildings in Ahmedabad, India using a combination of physical measurements, and a web-based occupant survey. The survey includes questions about Indoor Environmental Quality (IEQ): thermal comfort, indoor air quality, air movement and acoustics; it also asked questions about adaptive controls such as windows and fans.

The EC buildings performed well in many categories compared to the ‘business as usual buildings’. One of the EC designed buildings in particular performed exceptionally well compared to the CBE database which consists of over 600 buildings mainly from the US but also from 9 other countries. In the other three buildings, dissatisfaction prevailed mainly with acoustic quality and office layout due to lack of speech privacy and visual privacy, but this is common across the larger database. More than 70% occupants were satisfied with thermal comfort in all except one of the BAU building and of the occupants who were uncomfortable mostly cited air movement being too low as the reason for discomfort.

INTRODUCTION

Building construction is rapidly growing in India, primarily in the commercial sector with office type work. The construction boom, along with the hot climate and increase in purchasing power in metropolitan cities such as Mumbai and Chennai, has led to an unprecedented growth in air conditioner unit sales at almost 20% per year (McNeil and Letschert 2008; Sivak 2009). Studies are being done with Governmental support to evaluate energy efficient ways of providing comfort (Manu et.al. 2012). The Center for Building Energy Research and Development (CBERD) project is a joint initiative of the US Department of Energy and Indo-US Science and Technology Forum that aims to address the barriers for adopting low energy consuming strategies in buildings in India, while exploring the lessons that can also be applied to the US context. In order for low-energy space conditioning strategies to be widely adopted, it is crucial that occupant comfort and well-being are simultaneously maintained or enhanced, and occupant feedback is an invaluable source of information for investigating these impacts. Of particular interest is the use of windows and fans, since air movement is a very cost efficient way of providing comfort.

Occupant feedback is also helpful in diagnosing prevailing issues in a building. For instance, it has been found that in air-conditioned buildings, a large number of occupants are dissatisfied with the temperature in their workspace during summer because it is too cold (Abbaszadeh et.al. 2006; de Dear
et al. 1991). Appropriate action can be taken to address this issue by identifying if there are specific zones in the building that have cold dissatisfaction complaints due to over-cooling. The energy savings accrued by changing the air-conditioning unit setpoint even by few degrees could be significant, especially in warm climates (Hoyt et al. 2009).

In this paper, we present the results from a post occupancy evaluation of two energy conscious (EC) and two ‘business as usual’ (BAU) offices using the Center for the Built Environment (CBE) online survey tool and physical indoor temperature measurements. We evaluate the satisfaction in each category and benchmark the performance to the CBE database of 600 buildings. This study is intended to be a pilot for a larger study which will be scaled up to cover buildings with different passive systems in different climates of India.

**METHODOLOGY**

**Building selection**

India has a varied range of office building types, starting from those that are purely naturally ventilated to those that are highly energy intensive and use air conditioning throughout the year. This range includes mixed mode buildings that use air conditioning during extreme conditions and operate in natural ventilation mode for the rest of the year. Buildings that may be air conditioned for all twelve months but have efficient system and operation or employ unconventional air conditioning systems also fall in this varied mix of office building typologies. The buildings for this study were selected for the purpose of covering this range as best as possible.

In India, a ‘business as usual’ office building is likely to have several climate-responsive strategies such as external shading to reduce solar heat gain, interior blinds for controlling glare and visual comfort, operable windows for natural ventilation, and some attention to daylighting. All four of the buildings studied here have these features.

That said, not all Indian buildings have been designed to optimize the performance of these passive features, or to make a conscious attempt with the active mechanical systems to reduce energy consumption. The two buildings in our study that did at least one of these things are being characterized as energy-conscious (EC) design. The other two buildings are being characterized as ‘business as usual’ BAU, noting again that a BAU building in India will already have more climate-responsive features than its counterpart in the U.S. The wall construction is similar in all four buildings, made predominantly of brick masonry with cement plaster on both sides.

EC-1 is the office of an architecture firm. It takes the approach of relying on passive features to maintain thermal comfort inside and is most likely the least energy intensive out of the four buildings. It was designed to primarily operate in fully naturally ventilated mode, but was later retrofitted with air conditioners following the installation of computers. The building has a high vaulted roof structure over the studios that facilitates better ventilation. It has large openings on the north set higher in the building, while the lower openings on south are smaller to reduce direct radiation from entering the space. In the low ceiling areas, clerestory windows provide diffuse daylight across the day. In other places, glass brick is sometimes used to provide diffused daylight. Both the operable windows and pedestal fans are operated by the occupants. The building mass is compact, and the building is partially underground, further reducing the impact of direct radiation. Glazing is approximately 25% of the wall area. The vaulted roofs have an air cavity filled with ceramic fuses (9” long conical pieces mixed with concrete) to provide thermal insulation, and the entire roof is covered with high SRI tile. The immediate surrounding is heavily landscaped with dense trees and water bodies, generating its own microclimate. The building has window air conditioners and operates as a switch-over type mixed mode building where occupants turn off the air conditioner and open the windows when the outdoor conditions are suitable for natural ventilation. The total floor area is spread across four levels, including the mezzanine level. The lower and first floor is occupied by the permanent staff while the mezzanine floor is occupied by temporary staff such as interns and international scholars. 48 of the 54 permanent staff participated in survey, all of them located on lower
EC-2 is a building design and consulting firm. It is a LEED Platinum building, but took an entirely different approach than EC-1 in their energy-conscious design. The firm we studied occupies the seventh floor of a 11-story building that has the usual business-as-usual features described previously. Other than installing double-glazed windows, EC-2 did not attempt to optimize the envelope, but instead reduced their energy consumption by addressing the active systems that serves their air conditioned office space. They have a very efficient HVAC system, demand controlled ventilation, energy-efficient lighting and lighting controls, and occupancy sensors. Like all the buildings in our study, EC-2 has operable windows, but they are not often used by the occupants as the air conditioning is used across the year. There are no interior fans. The wall construction is much more heavily glazed than EC-1 (51-75% of the wall area). In spite of the high WWR and lighting controls, the building seems to rely more on artificial lighting than natural daylighting. The materials used in EC-2 conform to LEED 2.1 specifications such as low VOC paints, coatings, adhesive, sealants and fabrics, green label carpets and cleaning materials. 31 out of the 91 occupants answered the survey.

Both of the following BAU buildings are similar in that they have not made any conscious attempt in either the envelope, active system, or control strategies to reduce energy consumption. However, even without explicit lighting controls, they both rely mostly on natural lighting for the majority of the occupied hours. Both buildings also have ceiling fans (which are not being provided most of the time in newer, sealed buildings in India).

BAU-1 is an office of a computer software developer firm in a heavily urbanized area, located on eighth floor of an 11-story building (similar to EC-2 being on an intermediary floor of a taller building). It is representative of the most energy intensive building with a business-as-usual envelope and air conditioning system and operation. The office has a variable air volume (VAV) type central air conditioning unit that is on throughout the year. The walls are heavily glazed, with the WWR being almost identical to that in EC-2 (51-75% of the wall area). The windows are operable and have a reflecting glass. As in the other buildings, BAU-1 has interior blinds and exterior shading. 27 out of the 140 occupants answered the survey.

BAU-2 is an office of a building construction and MEP consulting firm in a less dense and more vegetated area, located on ground and first floor of an 8-story building. It has a variable refrigerant flow (VRF) type central air conditioning unit, operable windows and ceiling fans. The glazing area is in between the other examples (30-50% of the wall area). The windows have a clear glass, compared to the reflective glazing of BAU-1. While the air-conditioning in BAU-1 operates almost continuously throughout the year, in BAU-2 occupants have a choice to operate it when indoor becomes uncomfortable. 40 out of the 46 occupants answered the survey.

CBE web-based survey tool

The CBE web-based survey tool is an efficient way of remotely getting occupant feedback on indoor environmental quality (IEQ) and various other aspects of the building. Participation in the survey is voluntary and occupants can choose not to answer any question. The questions in the survey were designed after extensive inputs from facility managers and designers so as to report the most useful feedback (Eisenhower 2000). The survey consists of a core module with eight IEQ categories and additional modules such as window and fan usage. Since the surveys were being administered in India, the phrasing of the questions and options were tailored to suit the local culture and parlance. The survey asked occupants to rate their satisfaction during summer with these different aspects on a 7-point scale that ranged from -3 (Very dissatisfied) to 0 (Neutral) to +3 (Very satisfied). The tool also has a unique feature that is helpful for diagnostic purposes; when an occupant votes to be dissatisfied in any category, the tool automatically follows up with branching questions that ask about the reasons for dissatisfaction. Details about the building features such as floor area, number of occupants, LEED compliance and type of HVAC system, envelope and glazing are filled out by the building manager separately. More details about the CBE survey tool can be found in (Zagreus 2004). A list of the most relevant survey questions is illustrated.
in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Questions asked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal comfort</td>
<td>Satisfaction with temperature, ability to control temperature, thermal comfort</td>
</tr>
<tr>
<td></td>
<td>during summer</td>
</tr>
<tr>
<td>Indoor air quality</td>
<td>Satisfaction with air quality (i.e. stuffy/stale, cleanliness, odors)</td>
</tr>
<tr>
<td>Air movement</td>
<td>Satisfaction with amount of air movement</td>
</tr>
<tr>
<td></td>
<td>Importance of having an operable window to the user</td>
</tr>
<tr>
<td></td>
<td>Times adjusted (daily, weekly, monthly)</td>
</tr>
<tr>
<td></td>
<td>Time of adjustment</td>
</tr>
<tr>
<td></td>
<td>Reasons to ‘open’ or ‘close’ a window</td>
</tr>
<tr>
<td>Window usage</td>
<td>Satisfaction with operable windows (summer and winter and monsoon)</td>
</tr>
<tr>
<td></td>
<td>Importance of having an operable window to the user</td>
</tr>
<tr>
<td></td>
<td>Times adjusted (daily, weekly, monthly)</td>
</tr>
<tr>
<td></td>
<td>Time of adjustment</td>
</tr>
<tr>
<td></td>
<td>Reasons to turn ‘on’ or ‘off ’ a fan</td>
</tr>
<tr>
<td>Fan usage</td>
<td>Satisfaction with ceiling fans, Times adjusted during summer(daily, weekly,</td>
</tr>
<tr>
<td></td>
<td>monthly), Time of adjustment, Reasons to turn ‘on’ or ‘off ’ a fan</td>
</tr>
<tr>
<td>Acoustics</td>
<td>Satisfaction with noise level and sound privacy</td>
</tr>
</tbody>
</table>

RESULTS

Weather

Figure 1 shows the boxplot of outdoor dry bulb temperature (DBT) based on the ISHRAE weather file (EnergyPlus webpage). Ahmedabad experiences a semi arid climate with predominantly three seasons: summer, monsoon and winter. April to June is the summer season where the mean DBT is above 30 °C with a highest recorded value of 44 °C. Summers are dry with a mean relative humidity (RH) of 53%. July to October is the monsoon season where the mean monthly DBT is 28 °C and mean RH is 70%. November and March are the two transition months with mean DBT of 26 °C and mean RH of 47%. December, January and February are the winter months where the mean DBT is comparatively lower at 21 °C and mean RH is 52%.

Summary of occupant feedback in all the four buildings

Figure 2 shows the percentile scores compared to the overall CBE dataset, and Figure 3 shows the mean percentage satisfied per survey category in each building (Occupants voting +1 and above were counted as satisfied). In both, green colors designate better performance and orange designates low performance. Figure 2 illustrates that EC-1 (which uses more passive strategies to achieve its energy efficiency) is the best performer of the four buildings, and compared to the CBE database ranked fairly well in most of the survey categories except for ‘office layout’ and ‘air movement’ satisfaction. EC-2 (using improved active systems to achieve low energy consumption) did relatively well in thermal comfort, acoustics, and lighting performance, but ranked low in office layout, air quality and workspace satisfaction. Of the BAU buildings, BAU-1 is the lowest performer of the four buildings across most of the categories, while BAU-2 ranked relatively well in thermal comfort and lighting, but low in air movement satisfaction.

For illustrative purposes in Figure 3, a satisfaction percentage below 70% is assumed to be the threshold for concern. This is more flexible that the conventional 80% satisfaction threshold used in thermal comfort standards, for example. Figure 3 shows that 70% or more occupants were satisfied in EC-1 in all survey categories except for office layout and air movement. It’s interesting to note that even though acoustic satisfaction was in the 95th percentile in Figure 2, this is based on only 78% of the occupants being satisfied, as shown in Figure 3. That is because acoustics generally receives the lowest satisfaction scores in the database, so even 78% is considered quite good, and was also unusually high.
compared to the other four buildings. The reasons for that are not entirely clear, although the high valuted roof could possibly be a factor. The dissatisfaction with office layout was related mainly with visual privacy (too many people walking around in the work area) and the amount of workspace available for work (this may be due to this being a traditional architecture firm that requires a lot of workspace for paper drawings). The dissatisfaction with air movement prevailed mainly because of the lack of sufficient air movement (rather than air movement being too high), and the inability to control it. However, these complaints were limited to only two zones, D and E. This was surprising since these zones have pedestal or bracket fans, both of which should be adequate to increase air movement close to the person, even more effectively than stratification created by the vaulted roof. This may suggest that even though these fans are available, there are reasons that people are not using them or they are not located properly.

In EC-2, although the building was in the 90th percentile of the CBE database for thermal comfort, this is associated with only 71% of the occupants being satisfied. This is because this is a pervasive problem in buildings, and thermal issues are usually the #2 complaint (following acoustics). Of the IEQ categories, occupants were most satisfied with lighting, but the highest satisfaction ratings had nothing to do with IEQ (i.e., office furnishings, general building satisfaction, and cleanliness/maintenance). The satisfaction percentage in EC-2 was lowest with acoustics, air quality, office layout and air movement. Lack of sound privacy was the main reason for acoustic dissatisfaction while it was the lack of visual privacy for the dissatisfaction with office layout. A few occupants from EC-2 opined that the air was stuffy/stale, not clean and had a bad odor; the source for bad odor was mainly from the toilets. However, the complaints were limited to one particular zone. With regards to air movement satisfaction, occupants were mainly dissatisfied with amount of air movement (saying they preferred to have more air movement) and the ability to control the amount of air movement. This is not surprising given that this building does not have fans.

BAU-1 is having the biggest challenges with their workplace conditions; less than 70% of the occupants were satisfied in all the categories except for workspace satisfaction, where it was 77% (Figure 3). Higher satisfaction may, in part, be due to this office having relatively low occupant density (10 sq.m. per person, compared to a more typical 6.5 sq.m. per person for India). Amongst the dissatisfied categories, acoustic quality, office layout and thermal comfort were the categories in the lowest satisfaction range; around 50% or less. Similar to EC-2, lack of sound and visual privacy were the main reasons for dissatisfaction with acoustics and office layout respectively. Overall thermal comfort satisfaction was very low in BAU-1 compared to the other three buildings. Those who were dissatisfied cited multiple reasons of discomfort such as incoming sun, air movement being too low and the heating/cooling system not responding quickly to the thermostat.

Occupant response in BAU-2 was in sharp contrast to BAU-1; 70% or more occupants were satisfied with all categories except acoustics (Figure 3). Sound privacy was once again the main source of dissatisfaction. An important point to note with regards to acoustics dissatisfaction in EC-2, BAU-1 and BAU-2 is that occupants were less dissatisfied with noise levels as compared to sound privacy (both of these questions make up the combined metric for acoustic quality); this pattern is common across the CBE database.
Thermal comfort during summer

Ahmedabad experiences hot summers. Occupants were asked about their thermal comfort opinion ‘in general’ and specifically during summer. However, to understand thermal comfort during the extreme climate, evaluating thermal comfort satisfaction in summer is more crucial than in general. Using the 7-point satisfaction scale described earlier, Figure 4 (a) – (e) shows the mean thermal comfort response in each zone (labeled alphabetically) of EC-1, EC-2, BAU-1 and BAU-2 respectively (note that BAU-2 has two floors). The color corresponds to the mean value and the numeric is the number of votes in each zone. Figure 5 (a) – (e) shows the distribution of indoor temperature during occupied hours monitored from February – April 2014 in each building. The color and numeric both represent the mean value of indoor temperature while the green dot represents the sensor location.
More than 70% of the occupants were satisfied with thermal comfort during summer in 3 of the buildings - EC-1 (N=46), EC-2 (N=31) and BAU-2 (N=37) - while only 50% were satisfied in BAU-1. The most cited reason for thermal discomfort in all the four buildings was air movement being too low. The mapping in Figure 4 helps in identifying the zones where the mean satisfaction vote is less than zero. For example, lowest satisfaction occurred in zone B in EC-1, zone B in EC-2 and zone D and G in BAU-1. However, these zones had two or less number of responses and thus these findings are only illustrative, and nothing conclusive can be said.

The mean value of indoor temperature during occupied hours monitored from February – March was between 26 – 29 °C. The distribution was mostly uniform across all the zones in the building except for EC-2 where the core zones were cooler than the perimeter zones. This could be very likely because EC-2 had the widest floor plate compared to the other three buildings.

In all four of the buildings, occupants voted that room air conditioners and window blinds/shades were the controls that they were most frequently adjusted. During summer, the majority of the occupants said they either drank something cool or covered the window to keep themselves comfortable.

**Window and fan usage**

Windows and fans are two cost efficient ways of providing comfort in warm climates, and are common in buildings in India. Occupant satisfaction feedback regarding both these adaptive actions is of interest mainly during the summer. Figure 6 shows the percentage satisfied with operable windows and ceiling fans in all four buildings during summer. Looking first at windows, overall, greater than 70% satisfaction with operable windows was only achieved in BAU-2. A few occupants from EC-1 said the windows were inaccessible and there were things blocking the window. This was surprising since EC-1 is the building that paid particular attention to using passive, architectural strategies to achieve low energy use. In EC-2, the LEED Platinum building where the focus was more on efficient active systems, occupants said most of the windows were fixed and in BAU-1 some of the reasons which made it difficult to use windows were the inability to open windows fully and complaints from co-workers. The most frequently cited reasons for opening a window in all the four buildings were, ‘to feel cooler’, ‘to increase air movement’ and ‘to let in fresh air’. Interestingly, the prevailing reasons to close a window were ‘to feel cooler’, ‘outdoor temperature getting warmer than indoors’ (both of these related to having air-conditioning on during a hot day), and ‘to reduce outdoor noise.’ These reasons show that window interaction is driven predominantly by outdoor temperature, air quality and noise levels.

Looking now at fan usage, overall, more than 70% were satisfied with fans during summer in three
of the buildings - EC-1, BAU-1 and BAU-2 (the satisfaction with fans was low in EC-2 because the building did not have any). The most cited reasons to turn on a fan in EC-1, BAU-1 and BAU-2 were ‘to feel cooler’ and to ‘increase air movement’ while the reason to turn off a fan was to ‘reduce air movement’ and because ‘a co-worker requested it.’ These are all as one might expect, and the majority of the occupants in EC-1, BAU-1 and BAU-2 said they were very sure of having the desired effect when they interacted with fans.

**DISCUSSION**

The occupant feedback surveys revealed that one of the energy conscious buildings (EC-1) was performing well (i.e., it had a satisfaction percentage of above 70% in 8 out of ten categories.) Overall, in all of the buildings occupants were primarily dissatisfied with the acoustics and office layout, which is common across the entire CBE database. Acoustic dissatisfaction is an important area that needs to be carefully evaluated since it is often seen as a potential barrier for natural ventilation. One of the arguments against having natural ventilation in a city like Ahmedabad is that operable windows would bring in outdoor noise. However, the survey results show that occupants were more dissatisfied with sound privacy than noise levels, which has more to do with the open plan layout. In terms of the sources of noise that bothered workers, people talking on phone and overhearing private conversations were the most frequently cited sources of acoustic dissatisfaction, rather than outdoor noise.

Another result worth noting is that all the buildings ranked low in the air movement satisfaction category compared to the CBE database, and the lack of air movement was repeatedly cited as the reason for thermal discomfort. Occupants were also dissatisfied with the ability to control air movement and opined that they needed more of it. This dissatisfaction prevailed mainly in zones that did not have fans, which means more attention needs to be given to providing sources of air movement in these buildings. Amongst those who had fans, the main reasons to turn on a fan were to feel cooler and increase air movement. Moreover, when asked about the confidence of having the desired effect on turning on a fan, the majority of the occupants voted that they were confident about this effect. This shows that occupants perceive fans as fast-acting and they rely on it for achieving comfort in a short span of time. Windows on the other hand were opened to let in fresh air in addition to feel cooler and increase air movement. There was a consistent opinion about the reasons to close a window, i.e. when the outdoor got warmer than the indoors. The key take-away from this result is that the occupants preferred to have air movement and when there was a combination of windows and fans in use, they worked well in providing it.

The results also revealed an interesting aspect of occupant satisfaction in EC and BAU buildings. Given that BAU-2 performed better than EC-2, this indicates that one cannot necessarily conclude that a building designed for better energy efficiency will result in better occupant satisfaction as well. In addition to needing to pay more attention to air movement and other indoor environmental factors, there could possibly be latent factors such as interior layout, work culture, and connection to the outdoor views that are important (all of these were better in BAU-2).

This study is a pilot for further research where surveys will be conducted across buildings in different climates of India. Although spatial mapping of thermal comfort and temperature is a powerful method of diagnostics, we were not yet able to generalize about the impact of relevant building design issues due to the uneven distribution of the number of responses (i.e., zones where occupants voted to be dissatisfied with thermal comfort had very few votes.) The scaled up study will consider ways by which we will ensure a minimum number of responses from each zone.

**CONCLUSIONS**

Indoor Environmental Quality (IEQ) parameters were evaluated in two energy-conscious (EC) and two ‘business-as-usual’ (BAU) buildings in Ahmedabad. The EC building that utilized more passive architectural approaches performed well in most of the categories compared to the buildings in the CBE database, the other three buildings had multiple categories of concern. Overall, the occupants expressed maximum dissatisfaction with sound and visual privacy. They were mostly satisfied with thermal comfort.
except in one BAU building. Those who were dissatisfied most frequently cited ‘air movement being too low’ as the reason for dissatisfaction. In buildings that had fans, it was perceived to be a fast acting way of providing comfort. Fans were operated mostly due to thermal and air movement needs while windows were operated due to indoor air quality and acoustic reasons in addition to the two former reasons.

ACKNOWLEDGEMENTS

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Assessment of Air Velocity Preferences and Satisfaction for Naturally Ventilated Office Buildings in India

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Yash Shukla [CEPT University]
Rajan Rawal [CEPT University]
Leena E. Thomas [University of Technology, Sydney]

ABSTRACT
Free-running buildings (i.e. naturally ventilated buildings with no mechanical systems for heating or cooling) have the potential to be much more energy efficient than air-conditioned buildings. This paper is based on approximately 3200 instantaneous thermal comfort and 1500 long term background survey datasets from a large scale field study conducted in free-running Indian office buildings. Responses to air movement satisfaction and air movement preference questions, together with concurrent measurements of indoor environmental parameters of air and globe temperature, relative humidity and air velocity are used for this study. The paper gives an insight into the operation of ceiling fans and windows, and the range of air velocity experienced by office workers in free-running office buildings. It gives the relationship between measured indoor air velocity, concurrent air and globe temperature and relative humidity. Instantaneous responses are correlated with the on-site observations on window and ceiling fan operation, as well as indoor environmental measurements. The assessment of preferred air velocity from ceiling fans and operable windows as an adaptive measure in this paper contributes to the development of better designed free-running office buildings in India.

INTRODUCTION
India is a rapidly growing economy with a population of more than 1.2 billion which marks 17.6% increase in 10 years. According to the Indian Census of 2011, the country has about 46 cities with population of over 1 million (Census Organization of India) and many more cities will join this list in a matter of a few years. People need buildings to live and work. The growth in population, therefore, is linked to the rapid increase in building construction and infrastructure demand. Building construction and operation requires energy, for most part, in the form of electricity. Coal, a non-renewable resource, is the primary source of electricity in the country. To sustain the GDP growth at 7-8% (projected average), energy security must be ensured. On the other hand, global climate change and the environmental degradation points to the need to chart a more responsible growth path. It is clear that in the current scenario of climate change, energy efficiency in buildings is the most important ‘energy source’ for India.

The primary end use of electricity in buildings is to provide thermal comfort to occupants through air conditioning. It is therefore important to focus on what constitutes thermal comfort for people in buildings. ASHRAE defines it as ‘a state of mind that expresses satisfaction with existing environment’. It also prescribes standard thermal comfort conditions for air conditioned and free-running buildings (ASHRAE, 2010). In India, the National Building Code (Bureau of Indian Standards, 2005) provides construction guidelines, administrative regulations, development control rules and general building...
requirements related to fire safety, materials, structural design, plumbing and building services. The Energy Conservation Building Code of India (Ministry of Power, 2007) prescribes minimum standards for energy efficiency in buildings, soon to be mandated across the country. None of these codes propose an explicit thermal comfort model for India. Some individual researchers have worked in this area but their work is limited to residential studies in selected regions of the country (Singh, Mahapatra, & Atreya, 2011; Indraganti, 2010). The dearth of extensive field studies to understand thermal comfort in offices across all climate zones of India led to the conception of the India Model for Adaptive Comfort (IMAC) study in 2011 (Manu, Shukla, Rawal, de Dear, & Thomas, 2014 forthcoming). The primary objective of this study was to develop an adaptive thermal comfort model for India.

This paper presents a part of the IMAC study, focusing on the role of air velocity in the thermal comfort sensation of building users. Adjusting local air velocity through the use of ceiling fans and/or windows is one of the most significant behavioral adaptation mechanisms. Studies show that the building occupants use this mechanism in warm or warm-humid conditions to achieve comfort. Nicol (1974) reported a reduction in thermal discomfort at 32-40 °C at air velocity >0.25 m/s in regional studies in India and Iran, supplemented by similar findings from Sharma and Ali (1986). Field studies in the sub-tropical climate of Hong Kong indicate that air velocity of 1.0-1.5 m/s would likely satisfy 80% of the occupants thermally in summer season and that with 1.5 m/s air velocity, the upper limit of comfort temperature reached 33.5 °C (Cheng & Ng, 2006).

Studies have also indicated the need for increase in air velocity even in air conditioned buildings to offset increase in temperature (Arens, Turner, Zhang, & Paliaga, 2009). Feriadi (Feriadi & Wong, 2004) reports the tendency of the occupants to modify the hot and humid living environment by turning on fans and opening the windows. Field studies in the warm and humid climate of Bangladesh show an increase in comfort temperature with air velocities greater than 0.3 m/s (Mallick, 1996).

METHODOLOGY

The analysis presented in this paper is based on the data collected over four campaigns of surveys in office buildings in India, spanning a period of one year. These surveys were administered in five Indian cities selected as representative locations for the five climate zones prevalent in India – warm & humid, hot & dry, composite, moderate and cold. In order to document a wide range of indoor environmental conditions, surveys were administered in naturally ventilated, mixed-mode and air conditioned buildings in these five cities during summer, winter and monsoon seasons. The instantaneous thermal comfort surveys (TCS), which were repeated every season, gathered responses related to thermal sensation, preference and acceptability, air movement satisfaction and preference, clothing and activity. These were accompanied by simultaneous measurement of the indoor climatic parameters – air temperature, globe temperature, relative humidity and air velocity. Building Use Studies (BUS) methodology (Building Use Studies Ltd., 2014) was also used as a post-occupancy evaluation tool to gather long-term responses (Leaman, 1995). It has questions framed to draw responses to the workspace environment on a seasonal basis from past experiences of the respondents. The questionnaire covers aspects such as thermal comfort, ventilation, lighting, noise, indoor air quality, personal control. A total of 6330 TCS and 2002 BUS responses were gathered from 16 buildings under the IMAC 2014 project. Of these, 2005 TCS and 652 BUS responses are from occupants in buildings that were naturally ventilated throughout the year and constitute the data set analyzed in this paper.

In the IMAC study, buildings that did not have any mechanical cooling or air-conditioning systems installed and had ceiling fans and operable windows, were classified as pure naturally ventilated (NV) buildings. Survey responses from NV buildings have been separated from those of the mixed-mode buildings working in naturally ventilated mode at the time of the survey (NVmm). Even though the indoor conditions follow the outdoor in both NV and NVmm, the premise for this distinction is that subjects in NVmm mode experience AC (air conditioned mode) for a part of the year and, therefore, may have different responses to, and expectations from, the thermal environment of the work space, as compared to those who never experience AC at work. This classification was done during the analysis of the study and it was found that none of the buildings in the composite climate zone could be categorized as NV.
The present paper focuses on the seven NV buildings, one each in the hot and dry zone (HD1) and warm and humid (WH1), two in moderate (MD1, 2), and three in cold (CD1-3) climate zone (Table 1).

<table>
<thead>
<tr>
<th>Building</th>
<th>TCS Responses</th>
<th>BUS Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD1</td>
<td>Ahmedabad</td>
<td>137 (May)</td>
</tr>
<tr>
<td>MD1</td>
<td>Bangalore</td>
<td>38 (May)</td>
</tr>
<tr>
<td>MD2</td>
<td>Chennai</td>
<td>132 (May)</td>
</tr>
<tr>
<td>WH1</td>
<td>Shimla</td>
<td>90 (Jun)</td>
</tr>
<tr>
<td>CD1</td>
<td>64 (Jun)</td>
<td>68 (Aug)</td>
</tr>
<tr>
<td>CD2</td>
<td>120 (Jun)</td>
<td>126 (Aug)</td>
</tr>
<tr>
<td>CD3</td>
<td>83 (Jun)</td>
<td>72 (Aug)</td>
</tr>
<tr>
<td>Total</td>
<td>664</td>
<td>669</td>
</tr>
</tbody>
</table>

Note: HD = hot and dry; MD = moderate; WH = warm and humid; CD = Cold

Table 2 Study parameters and scales used

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal sensation</td>
<td>Hot (+3)</td>
</tr>
<tr>
<td>Thermal acceptance</td>
<td>Unacceptable (1)</td>
</tr>
<tr>
<td>Thermal preference</td>
<td>To be warmer (1)</td>
</tr>
<tr>
<td>Air movement satisfaction</td>
<td>Unsatisfactory (1)</td>
</tr>
<tr>
<td>Air movement preference</td>
<td>More air movement (1)</td>
</tr>
<tr>
<td>Fan operation</td>
<td>OFF (0)</td>
</tr>
<tr>
<td>Window operation</td>
<td>Shut (0)</td>
</tr>
<tr>
<td>Air stillness</td>
<td>Still (1)</td>
</tr>
<tr>
<td>Air quality</td>
<td>Unsatisfactory (1)</td>
</tr>
</tbody>
</table>

Three responses related to thermal sensation, acceptance and preference, and two responses related to air movement satisfaction and preference from TCS were used for the analysis. From BUS, responses to the fields related to air stillness and satisfaction with the overall air quality were included. Status of fans and windows for each survey response was also recorded. The scales and values for each of these variables are given in Table 2.

RESULTS

Indoor Climate

Air velocity in naturally ventilated buildings is primarily a function of cross ventilation by opening of windows or the use of ceiling fans. In the NV dataset, the mean indoor air velocity observed was around 0.2 m/s (range = 0-1.96 m/s; SD = 0.4) across all seasons and climate zones. Figure 1 plots the mean, maximum and minimum air velocities for each climate zone-season aggregate for NV buildings. Of the four climate zones, the highest mean air velocity of 0.6 m/s was observed in warm and humid zone in monsoon and summer, and maximum air velocity of 1.96 m/s in monsoon, the highest of all other zones. This can be explained by greater use of ceiling fans or windows to reduce the discomfort resulting from high humidity and temperature. Hot and dry climate zone also presented trends of high values of mean and maximum air velocity. There was almost no variation in mean air velocity in cold climate zone. This is because ceiling fans were not available in any of the buildings surveyed and are not a common feature in buildings in cold climate. Across all climate zones, the highest mean air velocity occurred in summer (0.3 m/s) and the lowest in winter (0.1 m/s).
Comparing Figure 1 and Figure 2, it may be observed that the indoor operative temperature trends were followed closely by the mean air velocity trends – air velocities increased exponentially with increase in indoor operative temperature, till about 30 °C, beyond which there was no change. It was, however, difficult to relate mean air velocity with the variation in mean relative humidity. This may indicate that the increase in mean air velocity as an adaptive measure was, in most instances, related to adapting to high indoor temperature rather than high humidity levels.

Figure 3 plots the mean, maximum and minimum air velocities with respect to the mean indoor operative temperature. In the range of 21.5-29.5 °C, the relationship was best explained by expressing indoor air velocity as an exponential function of indoor operative temperature, explaining 80% of the variance in air velocity in NV buildings. Mean air velocities at indoor operative temperatures less than 21.5 °C were constant at 0.05 m/s and those at temperatures greater than 29.5 °C were constant at 0.6 m/s. This may be indicative of the limitations of changing the air velocity as an adaptive mechanism for very high or low indoor temperatures. Figure 4 examines the relationship between mean air velocity and outdoor 7-day weighted running mean air temperature. The exponential function explained 47% of the variance in air velocity with outdoor temperature. The relationship, however, was not as strong as in the case of indoor operative temperature in Figure 3.

Adaptive opportunities: status of fans and windows

For almost all survey responses, fans were observed to be ON during all three seasons in the warm and humid climate (Figure 5). This may be to alleviate discomfort due to high temperatures in summer and high humidity levels in monsoon and winter. In hot and dry zone, almost all fans were reported to be ON in summer and monsoon and almost all were OFF in winter.

A more mixed use was observed in the moderate climate zone where fans were ON in 80% instances in summer and almost 25% in monsoon and winter. Cold climate zone did not have any fans available, except for a small fraction of 4-10% owing to isolated cases of table/wall mounted fans. Window use was highest in hot and dry and warm and humid climate zones in monsoon with 71-78% responses indicating open windows (Figure 7). 45-60% of the responses reported open windows in
summer, across all climate zones. For monsoon and winter, however, the variation was greater.

Figure 5 Status of ceiling fan operation in NV buildings in different seasons and climate zones

Figure 6 Status of concurrent operation of ceiling fans and windows in NV buildings in different seasons and climate zones

Figure 7 Status of window operation in NV buildings in different seasons and climate zones

Figure 8 Proportion of fans and windows in use in NV buildings expressed as a function of indoor operative temperature

Figure 6 superimposes mean air velocity with fan and window operation. It clearly indicates that window use had little effect on mean indoor air velocity. When the fans were OFF or not available, opening or shutting the windows led to prevalent mean air velocities ranging from 0.06-0.13 m/s. On the other hand, when windows were shut or unavailable, operation of fans induced mean air velocities ranging from 0.36-0.46 m/s. In warm and humid zone, more than 90% fans were ON in all seasons. In hot and dry zone, almost 100% fans were ON in summer and monsoon.

In Figure 8, indoor operative temperatures were binned at 0.25 °C and percentage of fans and windows in operation was calculated for each temperature bin. A logit curve best explained fan operation with change in indoor operative temperature. It indicates that percentage of fans in ON mode increased exponentially with increase in indoor operative temperatures. When indoor operative temperatures were higher than 31 °C, all fans were ON and almost 90% of the fans were OFF below 25 °C. Figure 8 also shows window operation was used as an adaptive measure till the indoor operative temperatures reached 32 °C at which point all windows were open. Beyond 34 °C, occupants seemed to be shutting the windows, again as an adaptive measure to avoid excessive heat ingress from outdoors into their workspaces. A polynomial trend line (R²=0.66) was used to capture occupant behavior more closely with actual operation. The polynomial curve, however, was still not able to explain the instances where all windows were open. A linear trend line (R²=0.79) was then used which was able to explain window operation till 32 °C of indoor operative temperatures. Within this limit it indicated a significant relationship showing that with every 1 °C increase in indoor operative temperature, the proportion of open windows increased by 5%.  

Chi-square = 55.156
p = 0.034

y = 0.0517x + 0.8126
R² = 0.79

y = -0.0002x³ + 0.0114x² - 0.198x + 0.9683
R² = 0.66
The figure establishes the use of fans and windows to alleviate discomfort owing to high indoor temperatures. It also indicates the level of indoor thermal conditions at which these adaptive measures were used. This provides a critical piece of information regarding occupant behavior that is important for building energy simulation but has not been available for workspaces in India.

**Impact of air movement on thermal comfort**

It is evident from Figure 9 that 65% of the people who voted neutral for thermal sensation also voted for no change in air movement. Almost 70% of people who voted ‘hot’ (+3) on the sensation scale preferred more air movement. Percentage of responses voting for no change in air movement decreased towards both ends of the sensation scale (hot and cold). The preference for more air movement, however, increased as the sensation votes moved towards +3. 57% of the people feeling ‘slightly cool’ preferred no change but a staggering 40% wanted more air movement. In Figure 10, almost 70% of the respondents voting for no change in the thermal environment did not want any change in the air movement. 65% of the people who wanted to be cooler also preferred to have more air movement. This agrees with the general idea that in an uncomfortably warm environment, people tend to want high air velocity as an adaptive measure. It is interesting to note, however, that more than 40% of people who were feeling cooler than normal (wanted warmer) also wanted more air movement even though more air movement would make them cooler than they felt. Almost 60% of the people who found their thermal environment unacceptable voted for more air movement (Figure 11). About the same ratio wanted no change in air movement among those who voted the thermal conditions as acceptable. Almost 43% of the respondents in NV buildings wanted more air movement and 3% wanted less air movement.

![Figure 9 Distribution of air movement preference votes on the thermal sensation scale](image1)

![Figure 10 Distribution of air movement preference votes across thermal preference response categories](image2)

![Figure 11 Distribution of air movement preference votes across thermal acceptability response categories](image3)

![Figure 12 Distribution of air movement satisfaction votes on the thermal sensation scale](image4)

In order to assess air movement satisfaction, the 7-point scale from Table 2 was converted into a three-point scale by merging the responses in the first two categories into one ‘not satisfied’ category and merging the last two into ‘very satisfied’. The central three categories formed ‘moderately satisfied’. The number of votes (%) was then plotted against thermal sensation (Figure 12). Among the subjects who voted for neutral thermal sensation, 54% were very satisfied, 41% were moderately satisfied and 5% were dissatisfied with air movement. The percentage of dissatisfied respondents increases as the sensation moves towards ±3 vote. Almost 35% of the respondents voting ‘hot’ are dissatisfied with the air movement. Interestingly, this percentage increases to 45% for those voting ‘cold’. 60% subjects who did not want to change their thermal environment were moderately satisfied with the air movement.
Almost 85% of the people who were very satisfied with the air movement did not want any change but 15% wanted more air movement (Figure 13). This suggests a discrepancy between air movement satisfaction and preference. Of those who were moderately satisfied with the air movement, 60% wanted more air movement. It is important to note, however, that 95% of the subjects not satisfied with air movement wanted more air movement in the work space.

Reponses related to overall air quality and draught from the BUS questionnaire were compared with air movement satisfaction (Figure 14). It is important to note here that the BUS survey was administered in the seven NV buildings in the monsoon season. So, the responses to air quality and draught for summer and winter seasons were based on respondents’ memory of their experiences related to these aspects of the work space. Draught does not seem to be a problem in the NV buildings, with only 10-20% of the subjects interviewed reporting draught across three seasons. Almost 60-70% responses indicated that the workspaces were moderately draughty. Reponses to the question of air quality satisfaction indicate 30-45% subjects being very satisfied and 45-65% being moderately satisfied. Maximum dissatisfaction responses of 10% occur in summer season.

CONCLUSION

The results from the study revealed the range of air velocities prevalent in NV office buildings in India, reaching as high as 2.0m/s. Indoor air was nearly still (average air velocity < 0.1 m/s) in cold climate zones across all seasons. Mean air velocities in all seasons in warm and humid zone were highest (0.4-0.6 m/s) as compared to other climate zones. They were closely related to the indoor operative temperatures and increased exponentially from 22-30 °C. Below 22 °C, mean air velocities were less than 0.1m/s and above 30 °C indoor operative temperatures, they were constant at 0.6 m/s. This indicated that high air velocity was used as an adaptive measure to address discomfort due to indoor warmth rather than humidity. There was a strong relationship between mean indoor air velocities and indoor operative temperatures. The dependence of mean air velocities on outdoor warmth, however, was not very robust.

Fans and windows are very important adaptive measures for subjects working in naturally ventilated spaces. That said, higher air speeds were primarily a contribution of fans (0.3-0.4m/s) and windows had a limited role (<0.06 m/s) to play. One may suggest that more than the need for higher air movement, windows were opened for other reasons such as cooling the indoors (when outdoor is pleasant), fresh air, daylight and view.

Window use also showed a very robust correlation with indoor operative temperature explained by a linear trend till 32°C indoor operative temperature. Occupants started operating windows when the indoor operative temperatures reached 15 °C. All windows were open between 32-34 °C and closed again when temperatures approached 34 °C. The logit regression predicted that ceilings fans started operating at 23 °C and 100% of the fans were in use at 31°C and higher indoor operative temperatures.

The study also shows that the office workers in India tend to prefer more air movement, or higher air velocities. Even when they found the thermal environment acceptable, almost 40% wanted more air movement. Respondents’ dissatisfaction with air movement was primarily due to the lack of it. Air movement preference and satisfaction were closely related to thermal sensation. Subjects preferred more
air movement as the sensation moved towards the either end (+3 and -3) of the 7-point sensation scale. At +3, 70% respondents wanted more air movement and at -3 the percentage of respondents wanting more air movement was 45%. Even when subjects were cooler than they would like, they wanted higher air movement.

Most importantly, the study provided valuable insights into occupant behavior in office buildings. Some of the results from this study could be used to better inform the simulation models that are usually very different from the real buildings. The results give very clear indications of how fans and windows are operated in naturally ventilated office buildings and could help build operation schedules for building energy simulation.

ACKNOWLEDGEMENTS

The authors would like to thank the Ministry of New and Renewable Energy, Government of India, and Shakti Sustainable Energy Foundation for funding this study. They are grateful to all the survey respondents and managers/owners of the buildings that were surveyed. The authors would also like to acknowledge all the field researchers for their extensive work at data collection.

NOMENCLATURE

TCS = Thermal Comfort instantaneous survey
BUS = Building Use Survey
HD = hot and dry climate zone
MD = moderate climate zone
WH = warm and humid climate zone
CD = cold climate zone
S = summer
M = monsoon
W = winter
NV = fully naturally ventilated buildings

REFERENCES

LEARNING ENERGY SYSTEMS: An holistic approach to low energy behaviour in schools

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ABSTRACT
Existing buildings are aligned with substantial energy use. Energy modelling is failing to produce an accurate prediction of the energy needed to operate buildings, particularly in the education sector. Schools and higher education estates often use 50% more electrical energy than the design models show. Much of this is associated with what is termed ‘unregulated’ energy, in other words, energy associated with unpredicted use of the building.

Working with sets of energy data, school pupils, teachers and building managers were involved in an action research project around the theme of lighting energy. This led to a reduction in energy use by lighting of 15%. Lighting control systems and education and awareness of energy use both contributed to this reduction. The study considers the benefits in financial terms. The relatively small gains offer significant potential over the lifespan of a school building. The wider benefit is in the involvement of building users in the management of their energy use.

INTRODUCTION
Understanding the way people use energy is seen as the key to improving energy performance in buildings. This paper presents a pilot study examining an interactive response by school children to the management of lighting in their school. It is part of a wider research project exploring the integration of the ‘human’ into the energy management of school buildings. The pilot study combined the use of energy data, and lux level measurement with action research in the school building.

It is estimated that lighting for buildings consumes 19% of global electricity generation (Grinfeld and Grinfeld 2009). Improved energy efficiency of lighting has resulted in an overall reduction in this load. UCD-OPET (1994) identifies 12% of energy use for lighting in typical UK schools in the 1990s. This had reduced to 8% in 2012 (Carbon Trust, 2012) due to improved lighting efficiency, however this equates to 20% of the energy costs of the building. This is why it is so important to reduce the amount of energy we use in for lighting (Ryckaert, Lootens, Geldof, & Hanselaer, 2010). Artificial lighting is dependent on electricity and has the highest CO₂ emission factor of energy sources (compared to gas oil and coal) at 0.422 kgCO₂/kWh which further emphasises the need for reducing the energy used for illuminating our buildings (Lee & Guerin, 2010). As well as the cost to the environment, is the cost to society in energy bills. Reducing the energy use of public buildings will reduce the financial burden on local government (Di Stefano 2000).

The amount of energy used for lighting in public buildings is affected by two primary factors: the design of lighting system; and the users of the building and their attitude towards the energy. This study focuses on a primary school building in Scotland, and encompasses an overview of the types of lighting control currently used in existing school buildings. By involving building occupants, the study examines
how these lighting controls can be better used and managed by building occupants to reduce their consumption of electricity, and if modification of building users' behaviour and attitudes towards energy use can reduce the overall energy consumption of the building.

LIGHTING CONTROL

Well designed and controlled lighting systems can reduce the energy use of artificial lighting by up to 40% (Grinfeld and Grinfeld 2009). For optimum energy efficiency a lighting control system must be designed so that it generates the required lux levels, delivering lighting using the least amount of energy (Karlen, Benya, & Spangler, 2012). Control systems have become more sophisticated and range from individual control, to highly sensitive computer operated building systems. This range of systems is found in the school being used for this study.

Local manual switching usually comes in the form of wall switches that can be controlled by building users with on/off or dimming switches (Simpson 2003). Relying on manual switching can lead to a high amount of wasted energy if occupants do not control them efficiently (Rawlinson 2008). Local manual switching is used in the classrooms in the school being studied. Centralised switching can be operated automatically at certain times in the day relating to the operating hours of the building (Wall and Everest 2003). Manual switching is still possible with this system to override automatic settings. If the system is well designed, studies show that few occupants will use the manual override (Grinfeld and Grinfeld 2009). This type of control is used in the corridors and assembly halls of the school but the manual override function is kept locked and can only be operated by the janitors.

Occupancy sensors are used to automatically: turn lights on when a space is occupied; keep lights on while the space is occupied; and turn off the lights once the space is no longer in use (Simpson 2003). The lights will be automatically turned off again after a definable period of inactivity. A Post Occupancy Evaluation (POE) carried out by Buro Happold (engineering consultancy company) on five schools built in the UK between 2002-2005 revealed that the use of PIR sensors saved 30-40% compared to manual switching (Pegg 2009). This study found that general circulation lighting was the worst managed, especially in areas such as atriums. This is due to the space not being 'owned' by anyone, therefore responsibility for the operation of these lights needs to be addressed (Pegg 2009). It is very important for building designers to think about maximising the use of daylighting when designing a building (Loe 2009). Photoelectric lighting controls (daylight linking) can either be an on-off system or a dimming system (Grinfeld and Grinfeld 2009). This type of control is present in the classrooms of the school.

Programme Logic Controllers (PLC) are centralised lighting management systems that control a whole building e.g. a school (Grinfeld and Grinfeld 2009). They consist of a computer based system that can control a combination of presence detection, daylight linking, timed and manually operated lighting systems to provide optimum control, tailored to a specific building and its users needs (Rawlinson 2008). PLCs in conjunction with a mixed manual and automatic control system will use energy most efficiently as long as they are designed to be user friendly (Loe 2009). They are also used in lumen maintenance as a new lighting system may be over specified, therefore it can be dimmed initially and power can be increased over time as the lamps lose light (Grinfeld and Grinfeld 2009) to prolong their life. The school studied has a computerised PLC system (Philips Light Manager) which allows alterations to be made to lights in the school that are controlled by automated PIR, daylight linking and timed systems.

BUILDING OCCUPANT BEHAVIOUR

The behaviour of building users can have a large effect on the amount of energy that the building consumes (Hori, Kondo, Nogata, & Ben, 2013; Masoso & Grobler, 2010). Newborough and Probert (1994) take the strong view that a lack of awareness in how energy is consumed is illiterate and apathetic. AI-Mumin et al.(2003) makes a statement that concurs with these views saying that 'energy-unconscious' behaviour of building occupants can lead to an excess in energy consumption. Zografakis (2008) holds the view that young people need to be properly educated on energy saving matters so that our future energy use will bereduced and that the way to do this is the education of students throughout
their school life to instil an 'energy saving culture' (Faiers, Cook, & Neame, 2007; Zografakis, Menegaki, & Tsagarakis, 2008), thus creating a more energy literate society (Newborough & Probert, 1994).

![Figure 1: The effects of energy related education in society (Zografakis et al. 2008)](image)

Figure 1 demonstrates how energy education leads to a higher understanding of the need to save energy and encouraging energy efficient behaviour. Although buildings consume the most energy during the day, often the most energy is wasted when the building is unoccupied. This is due to users leaving lights on overnight when they are not needed (Masoso & Grobler, 2010). There is a great need for building occupants to be more energy aware and learn to switch off lights and appliances when they are not being used, to reduce energy wastage (Al-Mumin, Khattab, & Sridhar, 2003; Masoso & Grobler, 2010).

The attitudes and behaviour of building occupants can undermine energy efficient building systems and technology and the two must work in harmony for significant reductions in energy use to be realized (Hori et al., 2013; Masoso & Grobler, 2010). At the same time building designers must gain accurate knowledge of how a building will be used to tailor the design to the users to achieve maximum energy efficiency (Carbon Trust, 2012).

The advantages of behavioural change through education are numerous (Dias, Mattos, & Balestieri, 2004). The potential energy saving could be more than is possible with just energy efficient equipment and systems. It is relatively very cheap and can be applied to any building new or existing (Masoso & Grobler, 2010). They make the argument that to improve energy efficiency; we should concentrate more on improving occupant behaviour and attitudes through education in energy awareness, rather than solely focusing on energy efficient technologies. Many lighting systems in public buildings, such as schools are very complicated. Even with a well designed system, for a building to reach its maximum energy efficiency it is necessary to have energy aware building users (Winterbottom & Wilkins, 2009).

**ACTION RESEARCH IN LIGHTING USE**

The study involved a group of school children in an action research project associated with lighting in their school. Involving school children in the study helps us see energy use from the eyes of the child. This user group offers a perspective that is often omitted from building management strategies in schools. The opportunity to engage children in the active management of energy use in their schools presents a novel response to the need to reduce energy, and fundamentally, it increases the pool of participants with responsibility for energy use.

**Methodology**
The research was designed to test two propositions: the behavior and attitudes of staff and pupils at the school will change in response to learning about how lighting uses energy; and that involving building users in the control of the lighting system will lead to a reduction in energy use. Recognition that this was about problem solving, led to an action research approach. This involves interaction to improve the situation, and this pro-active approach offered efficient empirical data collection, vital to the evaluation of the study (Costello, 2011).

The first visit to the school, led by the Facilities Manager, involved quantitative data collection on the lighting system of the school. This included lamps, luminaries and control systems to allow assessment of the energy efficiency of the current lighting system and to see if the hardware and technology could be improved. This was followed by the first phase of the ‘lighting use survey’. Another visit to the school, led by the deputy head teacher, enabled qualitative data to be gathered relating to the energy saving attitudes and practices of the school, and an ‘energy awareness presentation’ to inform the whole school about the lighting study. This was followed by the second phase of the ‘lighting use survey’. Figure 2 illustrates the action research process.

Figure 2: Action Research Process

The action research involved pupil members of the Eco-Committee undertaking the ‘lighting use survey’ over two separate weeks. Four areas of the school were chosen for the study to capture a range of lighting systems: a general classroom; a science room; the dinner hall; and a shared seating/circulation area. The study was carried out before and after the ‘energy awareness presentation’ to enable the impact of this session on energy behavior to be gauged. The survey was set up to record three sets of quantitative data:

1. If the lights were on or off at hourly intervals throughout the school day from 9am until 4pm Monday to Friday.
2. If the room was in use during these times.
3. The lux level. (meter placed on table in centre of room, for every reading)

Data from the first phase was used in the ‘energy awareness presentation’, delivered at a school assembly to all pupils and staff at the school. This provided pupils with information about energy sources both renewable and non-renewable and how we consume this energy. The presentation was designed for primary school children in accordance with advice in the paper 'EnergyEducation' by Kandpal & Garg, (1999). Repeating the ‘lighting use survey’ following the presentation meant that changes in awareness and attitudes to lighting use could be evaluated in terms of actual decreases in lighting use.

**Action Research results**

Two sets of quantitative data were produced. The first week shows normal lighting usage in the selected areas of the school. The second week demonstrates lighting use after problem solving action in the form of an educational presentation. This allows simple measurement to determine if the change in behaviour of the occupants could have a significant effect on reducing the energy use of the school from...
lighting. The four rooms used in the study offer distinct use patterns. The Dinner Hall and Shared Area are used occasionally by large numbers of pupils and are not associated with any particular class group. The Classroom is occupied by the same group of children for the majority of the school week. The Science Room is used occasionally for specific class activities by small groups of pupils led by a teacher.

The action research led to a reduction in energy use from lighting in all areas apart from the Dinner Hall (Figure 3). The graphs show the number of hours that the lights were on and the number of hours that each space was occupied. The significant reduction in energy use is seen in the rooms that are occupied by defined groups (classes). The two large areas with occasional use showed small improvements in redundant use of lighting, and demonstrate the difficulty faced in managing energy consumption in spaces that are not ‘owned’ by their occupiers.

![Figure 3: (a) Light and Room Use in Phase 1 (b) Light and Room Use in Phase 2 (numbers represent hours that light is on or room is occupied)](image)

**Room Area analysis**

The dining area is controlled by a key operated switch box that is kept by the janitors. This meant the energy use could not be directly controlled by the room users. This seems to be linked to energy waste (lighting on in an empty room) at 36% in the first week's study. Redundant light use decreased by 15%. The lighting use was identical over the two weeks but the physical use of the room increased corresponding to an increase in the lighting efficiency (lighting on in a room that is being used) from 64% to 79%, however this cannot be correlated with energy saving behaviour. The lux level was above the recommended 500lux for dining halls in CIBSE (2002) at an average of 770lux during the both weeks of the study. Therefore daylight linking would provide a direct reduction in energy use.

The control system in the classroom is quite advanced as there are three sets of lights. The sets of lights at the window and the corridor side of the classroom are controlled by two daylight sensors at either side of the room. If there is the required lux level of 500lux (CIBSE) then the lights will switch off in that area to save energy. The main on/off switch is located in the classroom and is therefore user controlled. The energy use in this room was very good in the first week's study, 97% of the light was being used and only 3% was being wasted. However in the second week an improvement was made as there was no wastage of light and the room was in use for three hours when the lights were turned off, as daylight would supply the required lux level. The room also used 3 hours less energy in the second week with the similar amount of use. The lighting system is quite advanced. The luminaries are energy saving models with high frequency ballast. However the control system could be improved by the daylight linked lights being dimmed rather than turned completely off. This will save more energy, extend the life of the lamps and be less distracting to room users (Roisin et al. 2008, Li et al. 2010). The average lux level over the two weeks was 510 lux which is very close to the recommended 500lux for classrooms.

The control system in the science classroom is very similar to the P2/3 Classroom as there are three sets of lights. The main lighting switch is user controlled. The lighting wastage from this area in the first week was a relatively high at 67%. In the second week 4 hours less lighting the lights were only used when the room was occupied. As with the P2/3 classroom, the lighting system in the science room is
The lighting system is quite advanced. The luminaries are energy saving models with high frequency ballast. However, the control system could be improved by the daylight linked lights as the shared area is located beside two large windows. The average lux level over the two weeks was 554 lux which is much higher than the recommended 200 lux for shared circulation space. This means that the lights could be dimmed to save energy (Li et al. 2009).

Overall in week 1 of the study the four rooms in the study had lights on and the room not occupied for 32% of the time. The use of lighting when not required (i.e. day lighting adequate or room not occupied) reduced by 15% in week 2 of the study.

Cost Analysis

Table 1 shows the savings per week which were calculated by multiplying the power load for the room in watts (electricity use when lights are on) by the by the number of hours the lights were used. This gives an amount of power used in watts which is then divided by 1000 to give an amount in kilowatts. This is a necessary step as a building's electricity use is measured in kilowatt hours (kWh). The amount of kWh is then multiplied by the unit rate for the school which was at £0.0671 at the time of the study.

<table>
<thead>
<tr>
<th>Area</th>
<th>Saving from energy education/week</th>
<th>Saving from dimming lights/week (-20%)</th>
<th>Estimated saving from daylight linking (-15%)</th>
<th>Total combined saving/week</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dining Hall</td>
<td>£0.00</td>
<td>£0.55</td>
<td>£0.41</td>
<td>£0.96</td>
</tr>
<tr>
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<tr>
<td>Science Room</td>
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<td>N/A</td>
<td>£0.08</td>
</tr>
<tr>
<td>Shared Area</td>
<td>£0.10</td>
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<td>£0.17</td>
<td>£0.49</td>
</tr>
<tr>
<td>Actual Savings</td>
<td>£0.39</td>
<td>£0.77</td>
<td>£0.58</td>
<td>£1.74</td>
</tr>
<tr>
<td>Total across school/week</td>
<td>£19.45</td>
<td>£15.40</td>
<td>£11.55</td>
<td>£46.39</td>
</tr>
<tr>
<td>Total across school/year</td>
<td>£719.49</td>
<td>£569.63</td>
<td>£427.22</td>
<td>£1,716.34</td>
</tr>
</tbody>
</table>

Table 1: Potential cost savings from lighting efficiencies

The lighting cost was then multiplied by the number of similar rooms or spaces to give a total saving across the whole school campus. This figure was then multiplied by the number of operational school weeks in the year to generate an estimated figure of yearly energy savings. Firstly, the estimated yearly energy saving from regular energy awareness presentations is £719.49. This is therefore an effective energy saving measure with a low implementation cost. The lighting system is controlled by Philips Light Manager system which could dim the lights in the appropriate rooms via the computer control system. The lighting savings from dimming the lighting by 20% came in at a lower yearly saving of £569.63 which is possible with the existing lighting infrastructure and is therefore an affordable and feasible energy saving measure. Two out of the four rooms studied could benefit from daylight linking systems as they are located near windows. Although this indicates a decent saving of £427.22, this does not take into account the cost of installation. Therefore with only a small expenditure for energy awareness presentations combined with dimming lights, there is a potential saving of over £1,200 per
year to be made. On top of this, if the daylight linking systems were found to be financially then even more money could be saved on lighting. The cost analysis offers realistic scenarios with commonly used equipment and control systems found in many modern buildings. The installation has a sophistication that offers the ability to respond to the lived experience and feedback on the people using the buildings with small cost implications.

**CONCLUSION**

Active involvement of building users in the management of buildings is shown to lead to better performing buildings (Bordass & Leaman, 2005). This study has shown engagement with quantitative monitoring, and qualitative education, that direct gains can be made in energy reduction. The focus on lighting provided a tangible and visible energy stream that was measureable and controllable by the project participants. Involvement of school children in this action research is important to embrace the idea of energy communities and their ability to manage energy demand (Fazeli, Christopher, Johnson, Gillott, & Sumner, 2011). The reduction in lighting use experienced in this study, seems to be linked to feedback data on lighting use, combined with an educational presentation on energy.

These results show that there is a large scope for energy saving through different aspects of lighting control. This can be done by either changing how the lighting operates using the PLC or changing how the lighting is operated by changing the behaviour and attitudes of the building occupants. It also highlights that there is little or no energy savings to be made by upgrading lamps and ballasts at the moment as the school has very up to date technology.

The study provides useful insights into the effectiveness of including people in the management of complex energy systems. Modern energy infrastructure is increasingly relying on complex building management systems (BMS) to monitor and control systems. In the study building a sophisticated lighting control system is installed. The way in which it has been set up does not relate to the way in which the building is being used. The involvement of building occupants in their environment offers potential for improving the way that complex systems can operate and respond to the lived experience of these people.

This study is part of a larger project, Learning Energy Systems at the University of Edinburgh, currently exploring methods to better integrate building occupants into the management of energy in their school buildings. This study demonstrates that with small interventions, significant energy reduction is possible over the life span of a building by addressing user behavior. In this case 15% reduction in lighting use was achieved with minimal intervention or alteration to the lighting control system. This potential this offers to a wider range of energy use beyond lighting in school buildings is considerable, and this provides interesting context for further work in this area.

**REFERENCES**


Session 7D : Tools and methods/ framework

PLEA2014: Day 3, Thursday, December 18
10:25 - 12:05, Trust - Knowledge Consortium of Gujarat
The Study of Sky View Factor in Urban Morphologies: Computational Tools and Methods of Analysis

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ABSTRACT

Regarding density, many studies confirm that a crowded space cannot be described easily by one single number. Its perception differs from individual to individual, leading to the concept of perceived density. Among the aspects that can influence such perception, the sky view factor (svf) can be highlighted. This paper focuses on the sky view factor and investigates different methods to calculate such parameter in urban design. Several procedures and computational tools were listed and three of them were selected for practical investigation: I) MapInfo and II) Sky View Factor Calculator, both for the analysis of fish eye lens images; and III) DEM (Digital Elevation Model). Three neighbourhoods in São Paulo, Brazil, were chosen as case studies for investigation with the selected methods: Cambuci, Bela Vista and República. The results of the case studies and the application of each tool are discussed. As part of the results, unexpectedly lower values of svf were obtained with the DEM analysis in comparison with the fish eye lens methods. DEM allowed for a quick view of the distribution of svf in urban area; nevertheless, it showed lack of accuracy on the representation of irregular surfaces and other obstructions at the pedestrian level such as trees and urban equipment. The fish eye lens methods were more efficient for the analysis of smaller areas with more details; however, its results also depend on the procedure used to calculate the svf. Finally, it was concluded that the efficiency of each method of sky view factor prediction depends on the aim of the specific research; and that the svf is a valid parameter to inform sustainable urban design. Further investigation on the subject is recommended.

1. INTRODUCTION

Many studies confirm that density in urban spaces cannot be described only as a single number (quantity of individuals or buildings divided by area) (Churchman, 1999; Rapoport, 1978). The definition of what is a crowded place can vary from individual to individual, according to their culture, background, location and function. In urban morphologies, additionally to all these aspects, the sky view factor (svf) can be highlighted (Cheng, 2010).

Sky view factor indicates the percentage of visible sky for a specific observer, or, in other words, it indicates the openness of an area (Holmer, Postgard & Eriksson, 2000). The factor varies from 1 to 0, being 1 a completely unobstructed view of the sky and 0 an obstructed view. It is a dimensionless parameter related to two planes: horizontal and vertical. In analyses of urban morphologies, the svf is closely related to the streets’ width and the height of obstructions (such as buildings, monuments, objects, trees).

The sky view factor has already shown its importance in solar availability and natural lighting studies. Many researches were developed to facilitate its identification and analysis through
computational tools, mathematics, diagrams and graphics, fish eye lens images and image processing tools (Souza, Rodrigues & Mendes, 2003; Ratti & Richens, 2004; Zaksek, Ostir & Kokalj, 2011; Santos, Lima & Assis, 2003).

Aiming to test some of those methods, three case studies were developed in Sao Paulo, Brazil, as part of a major research on building typologies and urban morphology in the city. In the first case, Cambuci, new buildings were proposed and their orientation was analysed for a fixed population density. For the second and third neighbourhoods, Bela Vista and Republica, existing building typologies were studied.

2. COMPUTATIONAL TOOLS FOR SKY VIEW FACTOR ANALYSIS

Three methods involving computational tools were selected for practical investigation regarding the svf: I. DEM (digital elevation model) which was generated by Image J or NIH Image; II. MapInfo; and III. Analysis of fish eye lens images.

2.1. DEM (Digital Elevation Model)

According to Ratti & Richens (2004), DEM is a simplified way to represent urban morphologies. It is visualized in a grayscale plan where each colour determines the height of the pixel. In simple image software such as ImageJ and NIH Image (Ratti & Richens, 2004), it is possible to create a plan and apply different colours to each pixel. The same programs are capable of reading and translating those colours into their corresponding height, turning the 2D plan into a 3D model.

The DEM is an 8-bit .TIFF image in grayscale, with colours varying from 0 to 256. Each plan is created with a lock-up table (LUT) which is similar to a template. It allows the user to attribute a height to each colour. Normally, the grey number 0 is defined as 0m height, grey number 1 equals 1m height, and so on. This makes it easier to change the images’ height without recoloring the entire plan.

It is possible to import images into ImageJ and NIH Image, however, inevitably some colour fixing will be necessary. Both software are able to create macros which allow other types of analysis. Nonetheless, it is also possible to calculate built area through histograms, to create sections of the site and axonometric representations, as well as to visualize the 3D model.

There were found two macros for DEM analyses. The first one was developed by Ratti & Richens (2004) based on a study on building’s shadows. Their aim was to determine the sky view factor by the shadows created by the obstructions. This macro was written for NIH Image, which only runs on iOS system; due to this fact, and because the only system available for the present research was a Windows, it was adopted the second macro developed by Zaksek, Ostir & Kokalj (2011). The latter was developed in ENVI+IDL in a partnership between the Universities of Hamburgo (Germany) and Ljubljana (Slovenia) with the objective of identifying surfaces’ imperfections in geomorphological studies.

2.2 Fish Eye Lens Images

Fish eye lens allow a physical camera to register a field of view wider than regular lens, close to 180° wide. The resulting image is created in a complex process. Firstly, the obstructions (pedestrians, buildings, objects) are projected in a half-hemisphere, or sky vault, which defines the field of view around the lens. Then, such images are projected again in a horizontal plane (Souza, Rodrigues & Mendes, 2003). For the analysis of the first case study, Cambuci, as the model was already built in Google SketchUp, two digital cameras were adopted to generate the fish eye lens images: VRay for SketchUp and Autodesk Ecotect Analysis. For the latter tool, it was necessary to import the model from SketchUp and rebuild it. In the second and third cases studied (Bela Vista and Republica) the focus was the existing morphology, and thus images were shot with a physical camera.

Computational tools were then used to analyse the obtained images. Generally, such tools divide the sky vault into several parts which are later projected in the horizontal plane. Following, each part is identified as being and obstruction or a part of the sky. The software differ from each other by the way they divide the vault.
Two computational tools were adopted for this phase of the research. The first one was developed by Santos, Lima & Assis (2003) at the Universidade Federal de Minas Gerais and was analysed by MapInfo. The second one, Sky View Factor Calculator, was developed by Lindberg & Holmer (2010).

Other methods were listed; however, due to limitations on time and software availability, it was not possible to assess them all. Among those, it is worth mentioning Souza, Rodrigues & Mendes (2003), which developed a SIG based model created in ArcView. As part of such method, the sky view factor is calculated by an extension called 3DSkyView, which runs together with 3d Analyst, from ArcViewGIS. Once the observer is located, it is possible to generate stereographic and orthographic projections. The obstructions and the visible sky are automatically detected by the extension, which additionally compares the generated image with a stereographic grid of the sky vault, enabling the calculation of the sky view factor. The main reason for not including that method on the present study was the unavailability of a former version of ArcViewGIS, which is required for the 3DSkyView extension to run.

Another tool listed, although not adopted, was CityZoom, developed by SimLab from Universidade Federal do Rio Grande do Sul, in Brazil. This tool is intended for urban design applications (Ely, Lins & Sonza, 2009). As part of the main features, regarding the geometry to be studied, a 3D volume can be drawn directly in the software or a .DXF file can be imported from Autocad. The software can calculate sky view factor by itself without any extensions. It seems to be a fast and friendly tool, but unfortunately it was not available for download by the time this research was ongoing.

2.2.1. Fish Eye Lens Image and MapInfo

Following Santos, Lima & Assis (2003), a fish eye lens image of the area of interest is compared to a template: a grid divided in cells developed by Souza, Rodrigues & Mendes (2003). A number corresponding to a portion of the sky vault is attributed to each cell, as indicated in Fig. 1. The sum of numbers equals 10,000, representing 100% of the visible sky.

![Figure 1. Grid for MapInfo analysis, developed by Souza, Rodrigues & Mendes (2003).](image)

The grid was vectored in Autocad, as well as the fish eye lens image; in the latter case, the obstructed area was separated from the unobstructed one. Using MapInfo (Santos, Lima & Assis, 2003), it was possible to compare the fish eye lens image and the template, resulting in the sky view factor.

2.2.2. Sky View Factor Calculator (Lindberg & Holmer, 2010)

This computational tool was developed in MATLAB, and runs on MATLAB Compiler Runtime (MCR). It can analyse any image file and detect the portion of sky and obstruction automatically. This tool is easier and simpler than the method developed by Santos, Lima & Assis (2003). Once the fish eye lens image is uploaded, the program turns it into a black and white image, where black represents the obstructions and white, the visible sky. Subsequently, the tool can calculate the sky view factor according to two methods.

The first method (Johnson & Watson, 1984) analyses the wall view factor, which is the area...
occupied by the walls that contour the urban canyons. It was originally used for evaluation of long wave radiation exchange within urban canopies.

The second calculation method (Holmer, Postgard & Eriksson, 2000) analyses each pixel of the image and assigns, to each one, a value representing its percentage in the sky vault. Such portion is related to the angular distance from the centre of the vault. In the present study, the results obtained with this calculation method were discharged due to a great discrepancy in comparison with the results of the other methods.

3. CASE STUDIES: ANALYSIS OF THREE NEIGHBOURHOODS IN SAO PAULO

Sky view factor was predicted and analysed for three neighbourhoods in Sao Paulo: Cambuci, Bela Vista and República. All areas are located in the city centre, have mixed occupation (commercial and residential), urban infrastructure and demonstrate to have potential for an increase in population density.

3.1. Cambuci

The first neighbourhood analysed was Cambuci. A target density was adopted and 16m x 50m buildings were proposed and located in a chosen plot with a minimum distance of 25m between them, according to solar access criteria. For this first essay, the existing buildings, trees and street furniture were discarded. Three scenarios were created and analysed with DEM and fish eye lens images processed with MapInfo method.

For the DEM analysis, the macro was calibrated for a 350 and 250 radius and 180 directions. Each pixel represents 1m distance (Fig. 2).

![Figure 2. Cambuci neighbourhood, scenarios 1 to 3 analysed with DEM (radius=350 / 180 directions).](image)

Since the scenarios were created in Google SketchUp, firstly fish eye lens images were generated by VRay for SketchUp and by Autodesk Ecotect for comparison between the two results, and latter the images were analysed with MapInfo.

![Figure 3. Cambuci neighbourhood: scenarios 1 to 3 with their points of analysis.](image)
Four points located in the centre of each street around the plot were selected for evaluation (Fig. 3). The results of sky view factor can be seen in Table 1.

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>1</td>
<td>0.35</td>
<td>0.32</td>
<td>0.22</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.41</td>
<td>0.29</td>
<td>0.20</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.34</td>
<td>0.32</td>
<td>0.21</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.34</td>
<td>0.25</td>
<td>0.22</td>
<td>0.26</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>1</td>
<td>0.42</td>
<td>0.34</td>
<td>0.25</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.33</td>
<td>0.27</td>
<td>0.22</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.29</td>
<td>0.20</td>
<td>0.18</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.32</td>
<td>0.30</td>
<td>0.22</td>
<td>0.26</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>1</td>
<td>0.34</td>
<td>0.29</td>
<td>0.24</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.21</td>
<td>0.24</td>
<td>0.21</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.18</td>
<td>0.25</td>
<td>0.17</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.20</td>
<td>0.28</td>
<td>0.20</td>
<td>0.26</td>
</tr>
</tbody>
</table>

It is possible to see that, in general, the VRAY image indicated more visible sky than the DEM analyses. However, such lens is more esthetical than technical, and no precise information was found about the type of image generated by this plugin. The results of the fish eye lens images varied from 0.02 to 0.12 in comparison with the DEM evaluation. Despite the different radius adopted for the DEM analysis, the svf results showed some consistency between them and were very similar to the ones obtained with Ecotect + MapInfo.

3.2. Bela Vista

Aiming to study the existing urban morphology, the second neighbourhood analysed was Bela Vista. A block was selected for the investigation and its buildings were catalogued. Fish eye lens pictures were taken directly on site with a camera. Ten points of analysis were selected, comprising all corners of the block and the centre of each surrounding street (Fig. 4). Due to the existence of many trees in the area, it was not possible to determine the svf with the MapInfo method. For this case, it was adopted the Sky View Factor Calculator (Lindberg & Holmer, 2010).

In order to compare results, a DEM was developed for the area (Fig. 5). Since the fish eye lens pictures were taken in pedestrian level (2m from the ground), to build the DEM, the height of the buildings were reduced in 2m. Additionally, the topography in Bela Vista is uneven, and thus its surface was reproduced considering 10cm for each pixel, aiming to improve precision. As a limitation, it was not possible to reproduce trees and other street furniture which are required to accurately represent the area.

![Figure 4. Points of analysis in Bela Vista with fish eye lens pictures.](image-url)
Regarding the fact that the DEM did not consider the obstruction caused by trees, it was expected to present higher svf results than the ones from the fish eye lens images (Table 2). Nevertheless, some of the results were similar (see points 4, 5 and 8) and can be justified by: I. The difficulty to calibrate the Sky View Factor Calculator for the representation of the transparency of the trees; II. The lack of precision in DEM, as the 3D model was generated by a city plan provided by the City Hall website; and III. The difficulty to precisely identify in DEM the same points analysed with the fish eye lens.

3.3. República

The method of analysis adopted for the República neighbourhood is similar to the one adopted in Bela Vista. An urban block was selected and eight points of analysis were chosen (Fig. 5). The buildings were catalogued and fish eye lens pictures were taken in loco at pedestrian level with a physical camera. Those pictures were analysed with Sky View Factor Calculator (Lindberg & Holmer, 2010).

Regarding the fact that the DEM did not consider the obstruction caused by trees, it was expected to present higher svf results than the ones from the fish eye lens images (Table 2). Nevertheless, some of the results were similar (see points 4, 5 and 8) and can be justified by: I. The difficulty to calibrate the Sky View Factor Calculator for the representation of the transparency of the trees; II. The lack of precision in DEM, as the 3D model was generated by a city plan provided by the City Hall website; and III. The difficulty to precisely identify in DEM the same points analysed with the fish eye lens.

3.3. República

The method of analysis adopted for the República neighbourhood is similar to the one adopted in Bela Vista. An urban block was selected and eight points of analysis were chosen (Fig. 5). The buildings were catalogued and fish eye lens pictures were taken in loco at pedestrian level with a physical camera. Those pictures were analysed with Sky View Factor Calculator (Lindberg & Holmer, 2010).

The urban surface in República is more even than the one in Bela Vista, thus the terrain did not need to be reproduced. A DEM at pedestrian level was also generated for that case and compared to the fish eye lens pictures (Fig. 5 and Table 3).
Once again, there was a considerable difference between the results obtained by fish eye lens pictures + Sky View Factor Calculator method and DEM. One should expect DEM to show higher levels of visible sky than the former method, since it does not consider street furniture and vegetation, although this theory proved not to be true in both neighbourhoods.

4. CONCLUSION

During the development of this study, the fish eye lens pictures and the Ecotect lens showed svf with more visible sky than the DEM method. It was unexpected due to the fact that DEM ignores vegetation and street furniture as obstructions, and therefore higher results of svf were expected.

Despite the differences among the results, one advantage of the DEM method for svf analysis is the possibility to obtain a general view of an urban area in opposition to a punctual analysis.

Regarding the results of this research, by analysing the existing morphologies in Bela Vista and República, the average sky view factors were:

- Bela Vista: 0.39
- República: 0.25

Thus, based on the perceived density concept (CHENG, 2010), the República neighbourhood can be said to be perceived by its users as a denser area than Bela Vista. Such result was already expected and it is probably due to the fact that the buildings in the first neighbourhood are placed directly on the front part of the lot, aligned with the street and close to each other. On the other hand, the buildings in the second neighbourhood are placed in the middle of the plot and most of them have gardens in the front part. The streets in Bela Vista were also wider and had plenty of trees, which according to Cheng (2010), helps reducing the perceived density.

Regarding this research, the method used to analyse sky view factor in areas with considerable amount of trees needs to be improved.

In the Cambuci area, the average sky view factor was:

- Scenarios 1 to 3, fish eye lens image from VRay: 0.30
- Scenarios 1 to 3, fish eye lens image from Ecotect: 0.28
• Scenarios 1 to 3, DEM analysis: 0.21

For that neighbourhood, the DEM method showed the lower results. However, for this specific research, related to the analysis of the perceived density, a simplification is suitable and thus the results could be considered as similar, leading to the conclusion that the perceived density in that area is higher than in Bela Vista, but lower than the density perceived in República.

Regarding limitations of the study, glare occurred in the fish eye lens pictures taken with physical camera in Bela Vista and República, which led the software to consider some parts of buildings and trees as part of the sky. The same issue occurred in the buildings covered by glass façades, which reflected solar radiation. How does this fact effectively affect the perception of density?

Some unsolved questions remain for a future research, such as the reasons why there were differences between the results obtained in the different methods and aspects of the DEM calibration. Another important issue is the search for methods to analyse the sky view factor in areas covered with vegetation. It was not possible to include trees in the DEM analysis, and the fish eye lens study demonstrated lack of precision.

The sky view factor is a parameter that influences many analyses, such as acoustics, thermic, ventilation and solar radiation (Cheng, 2010). For this reason, it can be emphasised the relevance of understanding the theoretical concepts and relationships among the variables involved in the subject of svf in order to analyse it with more precisely, combining both hypothetical models and existing areas which present multiple types of obstruction.

ACKNOWLEDGEMENTS

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REFERENCES

Investigation of methodologies for artificial lighting performance simulations with the presence of shading devices in residential buildings

Patrícia Soares, M.Arch. [UFMG]  Raquel Lemos, B.Arch. [UFMG]  Roberta Souza, PhD [UFMG]

ABSTRACT

In tropical countries, such as Brazil, daylight is an important feature used to reduce energy consumption in buildings. However, its indiscriminate use may result in situations such as glare and excessive heating of the room. To prevent such unwanted situations and allow natural light in the room, shading devices appear as an important strategy. The Brazilian Regulation for Energy Efficiency of Residential Buildings (RTQ-R) considers shading devices by their effect on the thermal behavior of buildings, not taking into account the artificial lighting energy consumption caused by their presence. In order to study this issue, a thermo energetic behavior investigation was conducted for rooms with different shading devices. Simulations were performed in Daysim and EnergyPlus to get quantitative data about artificial lighting activation and the room’s energy consumption and thermal performance.

This article shows the choosing process between the artificial lighting activation systems available in Daysim 3.1, to determine the best one to evaluate artificial lighting activation in residential rooms with shading devices. The studied systems are "switch off occupancy sensor" and "combination on/off occupancy and dimming system" which were named in this study "user-sensor" and "automatic-sensor", respectively. The automatic-sensor is controlled only by occupancy and illuminance sensors while the user-sensor is activated by the user. The results showed that, although the user-sensor demonstrates a situation closer to a real user, the automated-sensor allows a more accurate view of the need of artificial lighting activation. This was evidenced by the greater variance between the increase in energy consumption of rooms with shading devices, in comparison with the model without solar shading, for the automatic-sensor in regard to the user-sensor.

INTRODUCTION

The development of this article was supported by CIE research project (agreement number ECV DTP 002/2011). This project intends to stimulate research development in the field of natural light to collaborate with buildings energy efficiency labelling.

After years of intense and indiscriminate use of energy by man crisis were generated due to resources scarcity. An example is the 1970’s oil crisis which affected the world economy and draw attention for other sources of energy. In Brazil, the 2001 energy crisis caused energy rationing and affected the country’s economy and culture of consumption (BRASIL, 2012). As an important measure
for energy efficiency, Brazilian government launched in 2009 the Regulation for Energy Efficiency of Commercial, Services and Public Buildings (RTQ-C) and in 2010 the one for Residential Buildings, the RTQ-R (BRASIL, 2010; BRASIL, 2012). These regulations stipulate references for the building’s energy performance based on comparative methods and values to classify it as most efficient (level A) or less efficient (level E).

This recent interest in energy efficiency and environmental quality and comfort in buildings has stimulated a return to the use of natural light (ROAF, 2009). Besides the availability during great part of the day, the excellent color rendering index and the possibility of high illuminance levels in the room, natural lighting may be used to reduce energy consumption (CORBELLA E YANNAS, 2003). However, its indiscriminate admission in hot weather buildings may result in unpleasant situations such as glare and excessive heating. These situations lead to immediate solutions which block natural lighting (BOGO, 2009). In this context, shading devices are an important feature to avoid these uncomfortable situations and allow natural lighting integration to the room. However, they need to be designed considering the room’s thermal comfort and natural lighting availability.

The importance of using shading devices for thermal comfort improvement has been demonstrated in recent researches such as Sorgato, Versage and Lamberts one (2011). They run computer simulations for a bedroom with shutter and another one without them in a residential building, for four different solar orientations and for the Brazilian Bioclimatic Zone 3 and Zone 8\(^1\). The results showed that for north and south façades the bedroom without shutters had an average of 32% more degree-hours summation than the bedroom with shutters. For west and east façades the average increase was 82% and 47%, respectively.

A study by Didoné and Bittencourt (2008) on the impact caused by the absence and the use of shading devices in the energy consumption of hotels adopted existing buildings which were not suitable for the investigated climate. The results showed that shading devices blocked the direct radiation and achieved an air conditioning energy saving from 2% to 6%. Besides, this change on the building façade promoted an efficiency natural lighting performance inside the rooms.

Cintra (2011) investigated the influence of the room depth on its daylight autonomy, for openings with and without shading devices. The study was performed through computer simulation in the software Daysim 3.1, for residential buildings, four solar orientations and 11 Brazilian cities. The author concluded that, for the conditions of her study, the maximum depth for a room without shading devices should be 2.6 times the window height, while for a room with shading devices this value should be 2.1 max, i.e., a reduction of 17.9%. Therefore, the presence of shading devices reduces the daylight autonomy of rooms.

In the RTQ-R the presence of shading devices in openings is defined by the somb variable and considered in the building envelope evaluation. Somb score ranges from 0 (zero) to 1 (one), being 0 for openings without shading devices and 1 only when used shutters (BRAZIL, 2012). Other shading devices, such as brise soleil, overhangs and balconies are scored based on two other methods and may receive up to 0.5 points. Thus, shading devices other than shutters cannot reach the maximum score, even though they can perform effective shading during daytime. This happens because the RTQ-R considers shading devices only by their effect in the room’s thermal behavior, not considering the darkening of the room caused by their use.

In this context, Soares (2014) developed a study which aimed to improve shading devices evaluation in the RTQ-R. This study is part of a major project from CIE-BRASIL which intends to improve natural lighting issues in energy efficiency regulations in Brazil. Soares (2014) investigated the influence of different shading devices on thermal, luminic and energetic performance of residential rooms, considering Brazilian climate context, through computer simulations. In order to define the influence of shading devices on the room’s natural lighting performance, computer simulations were

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1 The geographic limits of Brazilian Bioclimatic Zones (ZB) were delimited according to the bioclimatic strategies recommended for each point on the map of Brazil, based on Givoni Bioclimatic Chart and Mohoney Table criteria. The points with similar strategies were grouped in the same Zone, resulting in a total of eight Bioclimatic Zone, being ZB1 the coldest and ZB8 the hottest.
performed in the software Daysim 3.1.

In this software, user behavior in what concerns artificial lighting and blinds activation is defined by the Lightswitch algorithm. This algorithm was published by Reinhart (2004) and developed based on user behavior observations through field research in private and two-person offices. Based on these observations and in probabilistic analyses, Reinhart defined six artificial lighting activation models, which vary according to the activation (manually or automatically controlled) and the operation mode (on/off or dimmed). Therefore, a deeper investigation about these different Daysim 3.1 artificial lighting models was needed to determine which one would be the best fit for the CIE research. This article presents a discussion about the choosing process of the artificial lighting model to be used for the simulations for Soares’ study (2014) about the impact of using shading devices in residential buildings.

**METHODS**

This study was developed in four steps. First, the artificial lighting activation models to be simulated were chosen. Then, the rooms were defined and at last, the lighting and energy consumption simulations were performed.

The system on/off was the most commonly found in residential buildings, therefore this kind of system was sought among Daysim 3.1 possibilities. It was needed special attention in this part as the Daysim artificial lighting models were idealized based on field researches in offices. First, the Daysim models were divided in two groups: the ones manually controlled and the ones automatically controlled. Then, a system from each group was chosen to be analyzed by simulation, according to their main characteristics. Finally, the simulations were performed in order to determine which activation mode, manual or automatic, and which Daysim model would be the best one to verify the artificial lighting activation necessity in residential rooms with shading devices.

The models defined by Soares (2014) were used for the simulations and are described as follows. The simulated rooms were the living room and the bedroom of an intermediate apartment of a condo building. They were tested for four solar orientations (north, south, east and west) and for the city of Florianópolis, representative of the Bioclimatic Zone 3 and classified as Cfa climate by Köppen-Geiger.

A constant occupation was required to evaluate the shading devices performance in what concerns direct insolation control and daylight availability. The artificial lighting system was determined by a luminotecnic project. The opening area was defined according to the standard set by Guedes (2012) as recurring in residential buildings (15% of the floor area for the bedroom and 25% of the floor area for the living room). At last, different shading devices were selected to be compared to the ones referenced in RTQ-R, as showed in Table 1.

<table>
<thead>
<tr>
<th>Model</th>
<th>Typology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>No shading device (SP)</td>
<td>Model without shading device (score 0 in RTQ-R), basis for comparison of shading devices performance</td>
<td></td>
</tr>
<tr>
<td>Shutters defined by RTQ-R model (VRTQR)</td>
<td>Shutters defined according to RTQ-R model: always closed for ZB 6 to 8 and closed during spring/summer and opened during autumn/winter for ZB 1 to 4</td>
<td></td>
</tr>
<tr>
<td>Shutters with full opening (V90)</td>
<td>Operable window with two shutters and two glass panes. The full opening of the shutters allows 100% of natural lighting area</td>
<td></td>
</tr>
<tr>
<td>Shutters with opening up to 45% of the total area</td>
<td>Sliding window with one fixed shutter pane, one movable shutter pane and one glass pane. Therefore, the opening for lighting is reduced to 45% of the total opening area</td>
<td></td>
</tr>
</tbody>
</table>
After defining the models the simulations were performed in Daysim. This software produces a report with metric values for each point of the sensors mesh previously defined. For this study it was used Daylight Autonomy metric to verify when the artificial lighting would be activated, based on the minimum illuminance level demanded by Brazilian regulation NBR 5413 (ABNT, 2013) – 100 lux for both living room and bedroom. The sensor mesh was located together with the lamps in order to verify weather they would be on or off. Therefore, for the bedroom it was used only one sensor, located in the center of the room and 75 centimeters above the floor, while for the living room there were two sensor located in the longitudinal central axis, at the same height (Figure 1).

The V90 and V45 shutters schedule was defined by Daysim dynamic shading model, which predicts that blinds will be lowered when there is excessive glare on the workplane or when direct solar radiation is above 50W/m². The sensors used for this purpose were located together with the artificial lighting sensors. For the RTQ-R shutter (VRTQR) the schedule was defined seasonally, as exposed in Table 1. The static shading devices were drawn as part of the building, within the 3D model. The artificial lighting and shutters activation schedules were used as input data in EnergyPlus to get energy consumption results.

![Location of sensors](Figure 1. Location of sensors)

**ANALYSIS AND DISCUSSION**

**Selection of the systems for simulation**

Based on Reinhart study (2004) concerning the comparison of artificial lighting energy consumption between different types of users and activation modes, the main characteristics of each Daysim 3.1 Lightswitch activation models were identified. This is presented in Table 2.

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2 Guedes (2012) defined the useful daylight availability period according to RTQ-R requirement which demands proof of a minimum illuminance level of 100 lux in a room for 70% of a year’s daytime. The author considered an average daytime period from 6 AM to 6 PM and selected 70% of this time resulting in the period from 7h45 AM to 16h15.
Table 2 – Daysim 3.1 artificial lighting activation models

<table>
<thead>
<tr>
<th>Models</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual on/off near the door</td>
<td>Typical on/off switch system near the door. The user activates the system once a day, when the illuminance level is insufficient. The system remains on for the rest of the occupation hours and the user turns the system off when leaving the office.</td>
</tr>
<tr>
<td>Switch off occupancy sensor</td>
<td>The system is activated by the user, as the manual system above, but it is turned off automatically by an occupancy sensor.</td>
</tr>
<tr>
<td>Switch on/off occupancy sensor</td>
<td>Automated model. The system is turned on and off automatically by an occupancy sensor.</td>
</tr>
<tr>
<td>Photosensor controlled dimming system</td>
<td>The system is activated as in the manual model, but it is dimmed. Therefore, it complements the natural lighting illuminance. However, this model foresees that sometimes the user forget to turn off the system. It happens because is considered that depending on the natural lighting intensity the user might not see that the artificial lighting system is on when leaving the office so the system stays on during the night.</td>
</tr>
<tr>
<td>Combination switch off occupancy and dimming sensor</td>
<td>Considers an initial manual activation by the user (switch) when one arrives at the office, but with a dimming activation by photosensor. The system is turned off automatically by an occupancy sensor. Therefore, the system is available only when the switch is on.</td>
</tr>
<tr>
<td>Combination on/off occupancy and dimming system</td>
<td>Automated model which turns the system on and off by an occupancy sensor, but with a dimming activation by photosensor. Therefore, the system is available during the whole time the office is occupied.</td>
</tr>
</tbody>
</table>

Later, the activating models were divided in two groups: the systems manually controlled and the ones automatically controlled (Table 2). One system from each group was chosen to be conducted to simulations, aiming to identify which type of control would be the most adequate for the investigation about shading devices impact on the room’s lighting.

For the manually controlled group, the **manual on/off near the door** model is activated according to the user’s behavior, which, many times, does not take into account the illuminance level. Therefore, it is not indicated for the proposed simulation.

Table 3 – System control modes

<table>
<thead>
<tr>
<th>Activation mode</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manually controlled systems</td>
<td>Manual on/off near the door&lt;br&gt;Switch off occupancy sensor&lt;br&gt;Photosensor controlled dimming system&lt;br&gt;Combination switch off occupancy and dimming system</td>
</tr>
<tr>
<td>Automatically controlled systems</td>
<td>Switch on/off occupancy sensor&lt;br&gt;Combination switch on/off occupancy and dimming system</td>
</tr>
</tbody>
</table>

The **photosensor controlled dimming system** is not adequate for the proposal because considers an eventual user forgetfulness, as showed in Table 2. Therefore, this activating model does not allow an accurate investigation of the artificial lighting activation. The **combination switch off occupancy and dimming system** was dismissed because even though it considers that the user activates the system by a switch, the lighting is turned on by dimmer. Therefore, it does not represent an on/off system, as highlighted before as the object of study. Thus, the **switch off occupancy sensor** was chosen to represents the manually controlled group, being called in this article user-sensor. This activation model takes into account user behavior and an on/off model.

For the automatically controlled systems, the **switch on/off occupancy sensor** was dismissed.
because it is activated only according to the occupation, not taking into account the room’s illuminance level. Therefore, the **combination switch on/off occupancy and dimming system** was chosen for the automatically controlled group. In this article, it was denominated automated-sensor. Although this model has a dimming reactor, it was chosen once considers the illuminance level, while the other model considers only occupation. The automated-sensor has automation by photosensor and by occupation, i.e., artificial lighting is activated only when the room is occupied and illuminance level is lower than the pre-determined.

In order to approximate this activation mode to the residential buildings reality, it was estimated on/off activation based on the dimming system results. Thus when the dimming system presented any indicative of activation it was considered the complete activation of the system (100%).

### Shading devices sizing

Table 3 shows the sizing of *brise soleil* type shading devices. In general, PTI/PTF was the larger device, followed by TN model. The model L23 was the smallest device.

**Tabela 3 – Sizing of shading devices (*brise soleil* type)**

<table>
<thead>
<tr>
<th></th>
<th>North</th>
<th>South</th>
<th>East</th>
<th>West</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTF/PTI</td>
<td>L23</td>
<td>TN</td>
<td>PTF/PTI</td>
<td>L23</td>
</tr>
<tr>
<td>α</td>
<td>59.9°</td>
<td>51.1°</td>
<td>16.1°</td>
<td>78.7°</td>
</tr>
<tr>
<td>βd</td>
<td>44.1°</td>
<td>-</td>
<td>9.2°</td>
<td>-</td>
</tr>
<tr>
<td>βe</td>
<td>44.1°</td>
<td>-</td>
<td>9.2°</td>
<td>-</td>
</tr>
<tr>
<td>γd</td>
<td>-</td>
<td>45.0°</td>
<td>-</td>
<td>45.0°</td>
</tr>
<tr>
<td>γe</td>
<td>-</td>
<td>45.0°</td>
<td>-</td>
<td>45.0°</td>
</tr>
</tbody>
</table>

Figure 3 shows shutters sizing, represented by the percentage of activation hours in relation to the room’s occupancy hours. It can be noticed that the device with the most activation hours is VRTQR. The other shutters, V90 and V45, presented few activation hours. These results can be explained by the sensor positioning. The shutter sensors were located in the same place as the lighting sensors; therefore it was far from the opening, so the sensor was little affected by direct insolation and excessive glare.

**Figure 3 – Shutters sizing**

![Shutters sizing graph]

### Simulations results

Table 4 shows the activation hours percentage and energy consumption variation for each shading device and activation mode, for the north oriented façade. The other façades had the same characteristics. The graphics below are a compilation of living room and bedroom results.

Observing the shading devices performance it can be noticed that larger devices, as PTI, PTF and VRTQR, cause greater darkening of the room and, consequently, more artificial lighting activation hours. V45 showed great activation hours because it has a fixed shutter pane which contributes to a greater darkening of the room. Also according to Table 4, it can be noticed that user-sensor caused more activation hours and energy consumption than automated-sensor. However the raise in energy consumption when used different shading devices, when compared to the model without shading devices, was not always higher for the user-sensor. This can be seen in Table 5.
Besides that, it can be noticed a smaller variation in energy consumption raise for the different shading devices when the artificial lighting is activated by the user-sensor than when it is activated by the automated-sensor.

**CONCLUSIONS AND FINAL CONSIDERATIONS**

In this study two artificial lighting activation modes were investigated and compared in what concerns energy consumption performance: manually controlled systems (user-sensor) and automatically controlled systems (automated-sensor). Based on the systems analyses it was concluded that the automated-sensor represents an idealized user who activates artificial lighting only when necessary to
complements natural lighting illuminance, while the user-sensor is closely to a real user behavior.

The results showed that the user-sensor consumes more energy than the automated model. However, when comparing the energy consumption raise when used different shading devices in relation to the base model (without shading device), for each activation model, it was noticed that there was a larger variation for the automated-sensor than for the user-sensor. This can be explained by the fact that the automated-sensor has a variable activation during the day, due to the photosensor. This irregularity in activation results in a higher energy consumption than the user-sensor, as it is needed more energy to activate the artificial lighting system than to maintain it on. In addition, the user role in the user-sensor model tends to reduce shading devices influence on the room’s lighting, as the user makes artificial lighting activation more homogeneous, turning the artificial lighting on even when it is not necessary.

Therefore, the automated-sensor was chosen to be used on the shading devices lighting performance analyses, once this activation mode allows a more accurate view of the need of artificial lighting activation. It is understood that this article meet the goal of understanding how Daysim 3.1 artificial lighting activation models work and also showed the influence of this choice on the simulation results.

ACKNOWLEDGEMENTS

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Session 8A : Material technology

PLEA2014: Day 3, Thursday, December 18, 2014
14:10 - 15:50, Auditorium - Knowledge Consortium of Gujarat
Possible Application of Seaweed as Building Material in the Modern Seaweed House on Læsø

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ABSTRACT
The aim of the paper is to present the possible application of seaweed in the contemporary environmentally friendly and affordable architecture. Properly used, seaweed can be an ultimate sustainable material, which is not only available in many areas of the world, but also reproduces itself in the sea and is very easy to gain on the seashore. In some regions, where the quantity of building materials is limited (e.g. Danish islands), seaweed was traditionally used in vernacular architecture. Today, when many countries are threatened with deforestation, we are looking for cheap materials alternative to wood. Seaweed has some important advantages: it is non-toxic and fireproof, provides good insulation, reduces CO₂ emission, has a life expectancy of more than 150 years and, what is also valuable, can be visually attractive. To the top of that, using seaweed can promote the respect for the uniqueness of regional architecture. Some examples of creative and contemporary dwellings made of seaweed as well as the brand new construction methods are presented and discussed in purpose to assess the promising possibilities of rediscovering this forgotten material.

Keywords: vernacular architecture, zero emission, building conservation, low energy materials

INTRODUCTION: ORGANIC MATERIALS IN VERNACULAR ARCHITECTURE.
Gaining building materials from the environment has been one of the most natural architectural concepts from the beginnings of humanity. As pointed by Torben Dahl “Throughout the world, the expressions of traditional architecture are based on and adapted to local conditions. This applies primarily to the local availability of materials and the response to the climatic conditions” (Dahl, 2008, p.8). Locally available, organic or non-organic substance, could be found not only in low-tech constructions but also in very advanced projects, based on the most contemporary technologies. In both cases such material choices increase the connection with local culture, create harmonious composition with the landscape and help reducing transportation. Organic materials deriving from the same climate zone are also well adapted to the climatic conditions.

In vernacular architecture natural materials were used almost exclusively. Today many architects combine them with concrete and steel to achieve modern appearance. In some cases the reason for abstention from the use of natural materials is the awareness of the threat of over-exploitation of the environment. For example the usage of wood needs to be carefully considered to avoid cutting valuable tree species and to maintain a balance of wooded areas, both on the local and the global scale. In some other circumstances the construction system, the functional requirements or even the artistic vision may entail the specific materials, not necessarily natural. Still, it is worth to remember that organic elements of the building also can have a contemporary appearance. Amazing wealth of materials found in nature endows architecture with the unique character. While timber and stone are highlighted in many projects, there is a lot of interesting but almost totally unknown (or forgotten) materials, that may be applied in modern, ecological and affordable architecture. One of such promising examples is seaweed.

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SEAWEED CLADDING TRADITION

Nowadays the usage of seaweed in the building industry is observed in very few places in the world. However, it is worth to note that properly used seaweed can be an ultimate sustainable material, which is not only available in many regions, but also, as Jørgen Søndermark noticed "reproduces itself every year in the sea, (...) comes ashore without any effort from humans, and it is dried on nearby fields by sun and wind" (Søndermark, 2013). As a building material it seems to have a great potential since it provides good insulation (which is typical for mineral materials), it is non-toxic and fireproof, and it has a life expectancy of more than 150 years.

In some coastal areas, where the quantity of timber (or even straw) was limited (e.g. on small Danish islands like Læsø), while a lot of seaweed was thrown out by the sea, the eelgrass was used in vernacular architecture, mainly for the house cladding. According to Realdania Byg, the non-profit organization who initiated a preservation project “Seaweed Houses on Læsø”, there were hundreds of seaweed cladded houses on the island. Unfortunately today there are only 36 of such homes left.

![Image](image1.png)

**Figure 1** The Kaline’s House (dated 1865) on Læsø with traditionally thatched seaweed roof, restored in 2012 by Realdania Byg. Photographer: Helene Hoeyer Mikkelsen/Realdania Byg (2012).

PRESERVATION PROJECT ON LÆSØ

In the continuation of efforts for preserving the cultural heritage of the small region of Læsø, in 2012 Realdania Byg organized the restoration of 150-year-old Kaline’s House on Læsø, with traditionally thatched seaweed roof. Simultaneously the same group launched the architectural competition with a goal to design the modern house on Læsø, referring to the local tradition but offering the contemporary standard. The Vandkunsten architectural studio, who won the competition, developed a very creative and contemporary dwelling made of seaweed. As a consequence the Modern Seaweed House on Læsø was built in 2012-2013, according to the project of Vandkunsten studio in cooperation with Realdania Byg. The designers decided to use the seaweed as a traditional material but they also proposed the new technology and the brand new construction method.

In vernacular structures the seaweed was placed directly on the roof, one layer after another, to provide the demanded thermal insulation and impermeability. Within years new layers were added and some roofs became very thick, they would even reach the thickness of 1,5 meter. The drawback of that
system was not only the size, but also the weight of the roof, with the increased risk of collapsing. Although some of the houses could be perceived as beautiful from outside, the visual comfort of the user was often disturbed by small windows, additionally shaded by many layers of seaweed, that would block the sunlight penetration into the living areas of the house as shown in Figure 1.

THE CONTEMPORARY DWELLING MADE OF SEAWEED

The authors of the Modern Seaweed House on Læsø carried out Environment Behavior Studies (EBS) in purpose to use vernacular architecture as a model, as suggested by Rapoport, and consequently to improve the solutions observed in vernacular buildings instead of copying it directly (Rapoport, 2006). To provide the functional and comfortable dwelling the architects focused on the value of natural light and space. They developed the summer holiday residence with a big common space in the center and some smaller rooms on both sides of the building. The house is heated with a highly efficient heat pump, placed in an adjacent shed that can also be used as a storage (e.g. for bikes and kayaks). The building is tight, well insulated and fitted with an effective mechanical ventilation system with heat recovery. Due to the proper insulation it is possible to maintain constant temperature of minimum 10°C throughout the winter, so that the house is frost-free.

![Figure 1](image1.png)

**Figure 1** The Modern Seaweed House (2012-2013) on Læsø, designed by Vandkunsten in cooperation with Realdania Byg. Photographer: Helene Hoeyer Mikkelsen/Realdania Byg (July 2013).

The light construction was designed without steel nor concrete. Instead, to emphasize the unique spirit of the island, the sea plant from the family Zostera marina was used as a building material i.e. as an insulation for ceilings, roofs and walls. As shown in Figure 2, in some elements it was introduced in the clearly visible form, while in others it is slightly hidden, both for functional and esthetic reasons.

The most obvious application of seaweed was the roof cladding shown in Figure 3a. Nevertheless, it was necessary to propose the brand new technology to achieve the lightweight and contemporary looking roof. On the other hand it was equally important not to lose the ambience of simplicity, connection with the environment and the obvious utilitarianism, that stood behind the usage of the natural material that could be found on the beach. Therefore the seaweed was stuffed into the nets knitted from a woolen yarn as shown in Figure 3b. Each element is 6-8 meters long and closed at both ends. These nets were attached to the façade and to the roof, where they formed the original and expressive finishing. At the same time, the seaweed filling was placed inside the wooden cassettes made of low processed timber.
and divided into smaller inner sections. These prefabricated building modules formed the house framework and provided an excellent insulation of floors, walls and ceilings with the $\lambda$ value 0.0376 W/mK (Pedersen, Ransby 2005, p.4). Another innovative application of seaweed was inspired by traditional mattresses. The dried seaweed was used for internal finishing elements, which are stuffed with eelgrass and covered with natural colored linen so that they slightly resemble the mattresses as shown in **Figure 4a**. These elements were used for internal wall cladding. The bright linen corresponds well to the timber color and gives the interiors light and natural appearance as shown in **Figure 4b**. Furthermore such used seaweed has exceptionally good acoustic properties.

Another seaweed feature, which is very useful in building, is the ability to absorb and give off moisture. That contributes to the regulation of indoor air humidity parameters. Various solutions, based on the seaweed application, created truly comfortable interiors with high-quality indoor microclimate. The list of possible variants of seaweed implementation can be developed further, in purpose to expand

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**Figure 3**  
(a) The seaweed roof cladding and (b) the detail of seaweed placed in the knitted nets. The Modern Seaweed House (2012-2013) on Læsø, designed by Vandkunsten in cooperation with Realdania Byg. Photographer: Helene Hoeyer Mikkelsen/Realdania Byg (July 2013)

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**Figure 4**  
(a) Dried seaweed inside white linen finishing elements and (b) natural bright interiors. The interiors of the Modern Seaweed House (2012-2013) on Læsø, designed by Vandkunsten in cooperation with Realdania Byg. Photographer: Helene Hoeyer Mikkelsen/Realdania Byg (July 2013).
the prospective options for affordable sustainable building. The Modern Seaweed House has a very low energy consumption and due to the fact that the organic materials were used almost exclusively, the house accumulates more CO$_2$ than it was emitted within the whole process of production and transportation of the building materials (Realdania Byg, Walther, 2013).

THE LIFE CYCLE ASSESSEMENT FOR THE MODERN SEAWEED HOUSE ON LÆSØ

In purpose to assess the potential for the application of seaweed as a sustainable material for the contemporary, ecological and affordable architecture the Life Cycle Assessment (LCA) was carried out by Kauschen (Kauschen, 2013).

In general LCA is a technique that allows to assess the environmental aspects and potential impacts associated with products and processes by:

1. Compiling relevant energy and material inputs and environmental releases
2. Evaluating potential environmental impacts connected with identified inputs and releases
3. Interpreting the results for making more conscious decisions (EPA, 2006, p.2).

LCA method evaluates all stages of product’s life and includes all phases necessary to produce, operate and dispose a building (“cradle to grave”). The phases are divided into raw material acquisition, building materials and/or component production, use and maintenance, waste management (“End-of-Life”). The applied “End-of-Life” method includes also the possibility of recycling. In accordance to ISO14040 standard, the research involved:

1. Goal and Scope defining (at this stage the assessment context was established, the boundaries and potential environmental effects were identified, a functional unit as a reference value for the assessment was defined);
2. Life Cycle Inventory (LCI, i.e. the inventory analysis which identifies and quantifies energy, water and materials usage and environmental releases) with the model based on building description, drawings and data extraction from BIModel (Revit).
3. Life Cycle Impact Assessment (LCIA) that allows to assess the potential ecological effects and refers to all inputs and outputs defined in the inventory analysis.
4. Interpretation of the inventory analysis and impact assessment in purpose to select the products and processes “with a clear understanding of the uncertainty and the assumptions used to generate the results” (EPA, 2006, p.2). In this stage the results were interpreted and validated.

The categories and calculation methods used in LCIA match DGNB standard (DGNB, 2010), as a DGNB Denmark (Danish adaptation of German standard DGNB, Deutsche Gesellschaft für Nachhaltiges Bauen), is a standard certification system for sustainable building in Denmark (Green Building Council Denmark, 2012). The impact categories and characterization factors are based on CML 2001 method, developed by the University of Leiden (Guinée, 2002). The environmental data was taken from ökobau.dat database (2011). For new processes (already not existing in ökobaut.dat), the assumptions were based on similar processes from Ecoinvent database (2.2), information from experts and producers Environmental Product Declarations (EPD). The Excel tool developed for the calculation of the product system was based on the method described in DGNB manual (DNGB, 2010). It should be mentioned that this LCA was carried out to identify potential environmental impacts with a goal to optimize the project in these terms and no critical review was undertaken. Thus the assessment can be classified as the life cycle screening (hot-spot analysis) instead a full LCA according to ISO standard 14040. The following impact categories of the seaweed building were analyzed: global warming potential (GWP100) [kg eq. CO$_2$], ozone depletion potential (ODP) [kg eq. R11], photochemical ozone creation potential (POCP) [kg eq. C$_3$H$_8$], acidification potential (AP) [kg eq. SO$_2$], eutrophication potential (EP) [kg eq. PO$_4$], non-renewable primary energy demand (NPED) [MJ], renewable primary energy demand (RPED) [MJ], total primary energy demand (TPED) [MJ], water usage [t], waste production [t], hazardous waste production [t], abiotic resource depletion [t], excavation residues [t]. For the LCA calculations the functional equivalent of a holiday property was set at 86m$^2$ gross floor area, 30m$^2$ loft and 124m$^2$ terrace. The house has up to 10 beds and is used 168 hours a week, whole year, for
50 years (Kauschen, 2013, p.7). The building includes about 200 components and 38 different materials, which are divided into different building elements shown in Table 1 and 2. Electric air-water heat pump is used for heating and hot water preparation. The BE10-calculation shows a total energy requirement of 64,4kWh/m²a, while the total electrical energy need is 54,4kWh/m²a. BE10 is the software developed by the Danish Building Research Center (SBI), mandatory to be used in Denmark for energy calculations for reference purposes.

Table 1. Compiled Results of LCA, part 1. Based on Kauschen (Kauschen 2013).

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Façade</td>
<td></td>
<td>15681,27</td>
<td>-2820,77</td>
<td>0,00</td>
<td>1,27</td>
<td>19,09</td>
<td>-30,23</td>
</tr>
<tr>
<td>Roof</td>
<td></td>
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<td>8,64E-05</td>
<td>2,11</td>
<td>31,63</td>
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<tr>
<td>Structure</td>
<td></td>
<td>9328,74</td>
<td>-2012,86</td>
<td>2,38E-05</td>
<td>0,24</td>
<td>3,23</td>
<td>-5,97</td>
</tr>
<tr>
<td>Interior</td>
<td></td>
<td>9223,66</td>
<td>-1480,38</td>
<td>9,06E-06</td>
<td>0,96</td>
<td>11,49</td>
<td>-3,54</td>
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<tr>
<td>Bathroom</td>
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<td>813,81</td>
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<tr>
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<td></td>
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<td>3,42</td>
<td>0,56</td>
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<td>429,00</td>
<td>124109,06</td>
<td>5,52E-04</td>
<td>18,28</td>
<td>231,94</td>
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</tr>
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</table>

Table 2. Compiled Results of LCA, part 2. Based on Kauschen (Kauschen 2013).

<table>
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<tbody>
<tr>
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<td></td>
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<td>247945,06</td>
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<td>Structure</td>
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<td>-18287,4</td>
<td>102619,32</td>
<td>84783,86</td>
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<td>Interior</td>
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<td>2,43</td>
<td>4,29E-04</td>
<td>237,91</td>
<td>0,01</td>
</tr>
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</table>

To check the environmental impact of the holiday house three energy scenarios were proposed: without operational energy; operating with energy from DK wind power; operating with energy from DK Grid Mix (Tables 3,4,5). The option to use wind power was the most interesting since there is no need to produce renewable energy in the holiday house itself. Solar energy was not taken into account as the house is situated in the shadow of the forest and also because the photovoltaic panels would not fit to the concept of the seaweed roof that should preserve the unique spirit and heritage of the place.
Table 3. Environmental Impact. Based on Kauschen (Kauschen 2013, p.14)

<table>
<thead>
<tr>
<th>Category of influences</th>
<th>GWP</th>
<th>ODP</th>
<th>POCP</th>
<th>AP</th>
<th>EP</th>
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<td></td>
<td>Unit</td>
<td>kg eq. CO₂</td>
<td>kg eq. R11</td>
<td>kg eq. C₂H₄ (ethene)</td>
<td>kg eq. SO₂</td>
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<td>Scenario 1 without operational energy</td>
<td>Total /50 years</td>
<td>-8.830,61</td>
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<td>70,59</td>
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<tr>
<td></td>
<td>Per m²/year</td>
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<td>3,18E-08</td>
<td>0,00112</td>
<td>0,01600</td>
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<tr>
<td>Scenario 2 energy from DK wind power</td>
<td>Total /50 years</td>
<td>-5.827,05</td>
<td>0,00066</td>
<td>5,92</td>
<td>79,35</td>
</tr>
<tr>
<td></td>
<td>Per m²/year</td>
<td>-1,32</td>
<td>1,51E-07</td>
<td>0,00134</td>
<td>0,01799</td>
</tr>
<tr>
<td>Scenario 3 energy from DK Grid Mix</td>
<td>Total/50 years</td>
<td>115.278,45</td>
<td>0,00069</td>
<td>23,21</td>
<td>302,54</td>
</tr>
<tr>
<td></td>
<td>Per m²/year</td>
<td>26,13</td>
<td>1,57E-07</td>
<td>0,00526</td>
<td>0,06858</td>
</tr>
</tbody>
</table>

Table 4. Energy Resources. Based on Kauschen (Kauschen 2013, p.14)

<table>
<thead>
<tr>
<th>Category of influences</th>
<th>NPED non-renewable primary energy demand</th>
<th>RDEP renewable primary energy demand</th>
<th>TPED total primary energy demand</th>
<th>TPED/share of RPED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit</td>
<td>MJ</td>
<td>MJ</td>
<td>MJ</td>
</tr>
<tr>
<td>Scenario 1 without operational energy</td>
<td>Total/50 years</td>
<td>-24.255,84</td>
<td>913.136,76</td>
<td>889.013,38</td>
</tr>
<tr>
<td></td>
<td>Per m²/year</td>
<td>-5,50</td>
<td>206,99</td>
<td>201,52</td>
</tr>
<tr>
<td>Scenario 2 energy from DK wind power</td>
<td>Total/50 years</td>
<td>24.537,32</td>
<td>3.045.474,74</td>
<td>3.070.062,41</td>
</tr>
<tr>
<td></td>
<td>Per m²/year</td>
<td>5,56</td>
<td>690,35</td>
<td>695,92</td>
</tr>
<tr>
<td>Scenario 3 energy from DK Grid Mix</td>
<td>Total/50 years</td>
<td>1.465.601,11</td>
<td>1.500.731,80</td>
<td>2.966.383,25</td>
</tr>
<tr>
<td></td>
<td>Per m²/year</td>
<td>332,22</td>
<td>340,19</td>
<td>672,42</td>
</tr>
</tbody>
</table>

Table 5. Other Selected Resources (Inputs And Outputs). Based on Kauschen (Kauschen 2013, p. 14)

<table>
<thead>
<tr>
<th>Category of influences</th>
<th>Water usage</th>
<th>Waste</th>
<th>Hazardous waste</th>
<th>Excavation residues</th>
<th>Abiotic resource depletion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit</td>
<td>T</td>
<td>t</td>
<td>T</td>
<td>t</td>
</tr>
<tr>
<td>Scenario 1 without operational energy</td>
<td>Total/50 years</td>
<td>-6.098,20</td>
<td>-11,81</td>
<td>0,12</td>
<td>0,34</td>
</tr>
<tr>
<td></td>
<td>Per m²/year</td>
<td>-1,38</td>
<td>-0,00268</td>
<td>2,77E-05</td>
<td>0,00008</td>
</tr>
<tr>
<td>Scenario 2 energy from DK wind power</td>
<td>Total/50 years</td>
<td>-2.658,51</td>
<td>-11,50</td>
<td>0,12</td>
<td>16,84</td>
</tr>
<tr>
<td></td>
<td>Per m²/year</td>
<td>-0,60</td>
<td>-0,00261</td>
<td>2,78E-05</td>
<td>0,00382</td>
</tr>
<tr>
<td>Scenario 3 energy from DK Grid Mix</td>
<td>Total/50 years</td>
<td>305.490,16</td>
<td>-9,39</td>
<td>0,12</td>
<td>238,24</td>
</tr>
<tr>
<td></td>
<td>Per m²/year</td>
<td>69,24</td>
<td>-0,00213</td>
<td>2,78E-05</td>
<td>0,05400</td>
</tr>
</tbody>
</table>

CONCLUSION

The LCA analysis of the Modern Seaweed House on Læsø proved that with the proper insulation and the usage of wind energy the building has negative carbon footprint and minimal potential environmental impact throughout the assumed lifetime of 50 years. The conservative approach to the data selection for calculations was chosen, especially regarding the End-of-Life scenarios. Such conservativeness reduced the risk of obtaining too favorable assessment which could lead to the erroneous interpretation. In most impact categories the outcome is determined by the type of energy supply. The presented results of calculations carried out for scenarios 2 and 3 show the impact of the choice of the energy source on the environmental performance of the building. In the majority of cases DK wind power energy scenario allows to achieve much better results in comparison with DK Grid Mix.
energy scenario. The values achieved in scenario 1 proved a very low level of the environmental impact of seaweed used as the building material in the Modern Seaweed House on Læsø.

Due to the continuous emission of CO\(_2\) to the atmosphere, the amount of seaweed in the seas and oceans is actually increasing. That should put our attention on this plant as a potential building material and a source of energy, especially today, when many countries are threatened with deforestation and we are looking for cheap materials alternative to wood. The important advantages of seaweed should be widely recognized: it provides good insulation, great acoustics, humidity control, visual comfort and the reduction of CO\(_2\) emission. It is also non-toxic, fireproof, low-energetic, biodegradable with a life expectancy of more than 150 years. The seaweed is covered with the sea salt and thus naturally protected against bacteria or insects that could destroy the structure. However, it is important to note that seaweed is such a good material choice when it is harvested naturally, i.e. collected on the beach, dried on the meadows (not in ovens) and transported on short distances only. Used that way seaweed can promote the respect for the uniqueness of regional architecture but simultaneously can be easily adapted to the specific local conditions, including different cultural and climatic factors. This is in accordance with the statement of Peter Sørensen and Winnie Friis Møller that “Architecture is a connecting link between place, climate and human life” (Sørensen, Møller, 2008, p.13).

Finally, what is also valuable, seaweed can be visually attractive and its usage allows to establish the balance between the traditional and modern architecture. The preservation initiative of Realdania Byg helped to involve local community into the process which increased the awareness both of the natural and cultural heritage of the island. Consequently that leads to the protection of the architecture of the past and at the same time to the development of the sustainable architecture of the future.

ACKNOWLEDGMENTS

The author wishes to express her thanks to the non-profit organization Realdania Byg who build and preserve the seaweed houses in Denmark, Jørgen Sondermark and architectural studio Vandkunsten who designed the Modern Seaweed House on Læsø, Jan Schipull Kauschen who carried out LCA analysis and the photographer Helene Hoeyer Mikkelsen, Realdania Byg.

REFERENCES

DESIGN BEST PRACTICE METHODS TO MINIMIZE THE IMPACT OF BUILDING MATERIALS ON URBAN MICROCLIMATE

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ABSTRACT

Urban spaces in tropical country like India have always been the focus of socio cultural activities. In recent times these activities are stressed by increased urbanization. Among many factors that influence outdoor ambient temperature (traffic, pollution, population density…) the building surface treatments have also contributed in challenging the urban micro climate. Insufficient open spaces, diminished wind movement and strong irradiation from the high rise densely packed built environment has very much reduced the quality of urban outdoor life. Though there are many individual studies on the built form and building material influence on urban micro climate, they seldom give comprehensive guidance to the city designers, essentially the planners and the individual architects.

This paper investigates the influence of building materials on the micro climate of urban commercial streets (pedestrian users) by comparing their thermal performances. The study also tries to explore possible design interventions to minimize the impact of the building materials on the urban micro climate. Henceforth the outcomes will create cognizance among the designers to evolve climate sensitive design and material choice. Urban Micro Climate - Building Materials - Design Solution. The inferences in this paper will enable the architects and planners to design buildings with the understanding of their response to the urban microclimate and comfort of the pedestrian users.

KEY WORDS Urban Microclimate, Building Materials, Heat Transfer, and VASARI

INTRODUCTION

The phenomenon of city - induced environmental change has been known for many centuries. The ancient Indian Architectural manual “Silpa Sastra”(translated by Acharya 1979) laid out rules for the siting of villages, towns and forts based on prevailing wind directions and solar orientation.( Rohinton Emmanuel,2005). The city design is basically composed of many elements like the buildings, open spaces, networks (roads, streets, pathways, and bridges), traffic (vehicle & pedestrians), and vegetation. The inter relationship among these elements influence the quality of the urban environment. Though there are many factors that define the quality of urban life (environmental, functional, and aesthetic) this paper focuses on the environmental quality of the cities.
A large number of road users in India are pedestrians. (Gururaj G, 2006; Peden M, Scurfield R, Sleet D, Mohan D, Hyder AA, Jarawan E, et al.). The environmental comfort of the pedestrian users is seldom given a thought by the planners, developers and designers. The factors that influence the outdoor thermal comfort of the pedestrian users can be broadly classified as the **Climatic Factors** (Solar Radiation, cloud cover, precipitation, wind speeds, Humidity, and air temperature) and the **Physical Factors** like (orientation, Aspect Ratio, Vegetation, Sky View Factor (SVF), Building Materials) (Oke et al., 1987 and Santamouris, 2001). The influence of the building materials on the urban microclimate focusing on to the pedestrian users and the possible solution is a part that still needs to be explored by the planners and designers.

Hence the aim of this paper is to analyze the building material contribution on the urban microclimate, specially focusing on the pedestrian users. The result of the analysis enable in arriving strategies to improve the microclimatic condition as this will facilitate the architects and planners to design buildings with the understanding of their response to the urban microclimate and comfort of the pedestrian users.

**METHODOLOGY**

To evaluate the influence of building materials on the urban microclimate of the pedestrian user’s two commercial streets of the CBD (Central Business District) is chosen with different orientations. The surface radiation in the streets were calculated for five different time periods. The climatic data was calibrated with an Infrared Thermometer, air temperature and wind speed was calculated with hand held devices. The radiation of the surfaces were calculated through the Stephen Boltzmann Constant. The radiation values were mapped. The radiation values of the individual materials were analyzed for surfaces with different orientation and aspect ratio. The result of the comparison enabled this study to derive strategies that would assist the designers and planners to work on options so as to minimize building material influence on the microclimate the urban pedestrian users. Since the study area is a CBD there was no scope for vegetation. Hence the impact of vegetation on the microclimate of the study area is not considered.

**SITE DESCRIPTION**

The study was conducted in Tiruchirappalli City (Tamil Nadu, India) located at 10° 48' North and 78° 41' East. The city is at the altitude of 88 m above sea level. The climate of Tiruchirappalli is Hot Humid. The state of Tamil Nadu has a clear climate change scenario. The study was done in the month of April - 2013, based on the IMD report April month has recorded the highest. (State Level Climate Change Trends in India, Meteorological Monograph No. ESSO/IMD/EMRC/02/2013).

**Traffic Pattern**

The commercial streets (NSB Road, Big Bazaar Street) of the CBD (Central Business District) of Tiruchirappalli City was chosen for the study. The streets are both high density and high rise in character with no scope for vegetation. These streets are significant because they are mostly used by the pedestrians. At the time of festivals like Deepavali and Pongal the streets are completely pedestrianized.

![Traffic Pattern in NSB Road and East Andar Street](Source: Tiruchirappalli city Traffic Police)
The buildings of both the NSB road as well as the Big Bazaar Street are of different heights and different surface treatments. The common material used on the building skin are the Aluminum composite panel, Structural glazing (both doubly as well as single glazed layer) and Cement plastered wall with paint. The road surface is made of asphalt.

Solar Access

The urban microclimate is influenced by many anthropogenic induced factors like Pollution, High density construction that cause less wind (A.M. Papadopoulos 2001, B. Givoni 1998), building material choice (H. Taha, 1997), Orientation of buildings, streets (M. Santamouris, N. Papanikolaou, 2001), Lack Of Shading (L. Barring et. al., 1958), Canyon Geometry (S. Yamshita, 1986). The incident solar radiation influences significantly on these anthropogenic factors. Unlike the western countries the right to solar radiation has to be controlled in Tropical country like India to achieve an ambient urban microclimate. The incident solar radiation contributes significantly to the heat transfer phenomenon of the building materials (C. Conner, 1985).

The urban canyon is a more useful city unit for the study of the microclimate of urban environment.

The energy balance of the ‘Earth surface’s – ambient air’ system in the urban environment is governed by the energy gains and losses as well as by the energy stored in the opaque elements of the city, mainly buildings and streets. (M. Santamouris, 2001)
Energy gains = Energy losses + Energy Storage

Incident solar radiation values are based on two primary components: Direct Radiation from the sun (direct beam radiation = $I_b$) which is always measured perpendicular to the sun’s rays. Diffuse radiation that is both scattered by the clouds and atmosphere (diffuse sky radiation = $I_d$) and the ground in front of the surface ($I_r$). This is always measured on a horizontal surface.

i.e. Incident Solar Radiation = ($I_b \cdot F_{Shading} \cdot \cos \theta$) + ($I_d + F_{Sky}$) + $I_r$ (2)

Where:
- $I_b$ = direct beam radiation
- $I_d$ = diffuse sky radiation
- $I_r$ = radiation reflected from the ground
- $F_{Shading}$ = Shading factor (1 if a point is not shaded, 0 if a point is shaded, a percentage if measured on a surface)
- $F_{Sky}$ = Visible sky factor (a percentage based on the shading mask)
- $\theta$ = angle of incidence between the sun and the face being analyzed.

Heat Transfer

The heat transfer phenomenon between the buildings and the environment is very complex (R. Priyadarsini and N.H. Wong, 2005). This phenomenon can be defined on the basis of three basic parameters (A.M. Papadopoulos, 2001):
1. The insolation of the buildings, which is a direct function of the orientation, the morphology of the building and the shading factor due to opposite buildings and the existing shading devices;
2. The wind flow in the street canyon that depends on the road’s orientation in relation to the prevailing wind direction, the geometric characteristics of the canyon and the temperature conditions on the surfaces of the buildings and the road; and
3. The additional heat emission from local points like the air conditioning systems and the road traffic.

Temperature and Radiation

The three main methods of heat transfer resulting in change of temperature are conduction, convection and radiation. All bodies with a temperature greater than absolute zero radiate energy. Absolute zero is the temperature at which there is no molecular or atomic random motion. It’s denoted by 0 Kelvin degrees, which is equivalent to -273.15°C or -459.67°F. Late in the nineteenth century, Stefan experimentally and Boltzmann theoretically developed a relationship between the temperature of a body and the amount of power it radiates.:

To determine outgoing radiation power, we utilize the Stefan-Boltzmann Law

$$P = A \cdot \varepsilon \cdot \sigma \cdot T^4$$

Where
- $P$ (watts) is the radiated power from a body of area $A$ (m2) at temperature $T$ (K).
- $\varepsilon$ is emissivity
- $\sigma$ is the Stefan-Boltzmann constant, 5.67x10^-8 Wm^-2T^-4
- $T$ is the body temperature in Kelvin.

Hence the radiation emitted by buildings, streets and all emitting surfaces in the canopy layer can be calculated through the Stefan-Boltzmann Law (M. Santamouris, et al., 2001)
Material Map

The materials of the streets are mapped and the area for the individual materials are calculated, the surface temperature of the materials are measured for five different time period (7.00 am, 11.00 am, 13.30 pm, 15.00 pm, 17.00 pm).

Observation

The documentation of the building in NSB Road and the Big Bazaar Street resulted in thirteen different materials. (Table 1).

When the radiation of the materials were calculated using Stephen Boltzmann Law, it was observed that due to more emissivity value and substantial percentage of usage in the surfaces, concrete and asphalt contribute significant radiation for all the five time periods analyzed. The radiation value of concrete range between 0.0841 W to 0.0878 W and that of asphalt range between 0.042 W to 0.046 W (Figure 6).

![Figure 5: Shows the materials map on the building façade - the streets in elevation.](image)

![Figure 6: Shows the radiation value of the materials](image)

<table>
<thead>
<tr>
<th>S.no</th>
<th>Material</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Concrete</td>
<td>5727.3</td>
</tr>
<tr>
<td>2</td>
<td>Glass</td>
<td>1477.14</td>
</tr>
<tr>
<td>3</td>
<td>Plastic Board</td>
<td>626.1</td>
</tr>
<tr>
<td>4</td>
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</tr>
<tr>
<td>5</td>
<td>Metal</td>
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</tr>
<tr>
<td>6</td>
<td>Granite</td>
<td>9.9</td>
</tr>
<tr>
<td>7</td>
<td>Asphalt</td>
<td>2722.9</td>
</tr>
<tr>
<td>8</td>
<td>ACP - white</td>
<td>286</td>
</tr>
<tr>
<td>9</td>
<td>ACP - Red</td>
<td>87.3</td>
</tr>
<tr>
<td>10</td>
<td>ACP – Grey</td>
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</tr>
<tr>
<td>11</td>
<td>ACP - Gold</td>
<td>186.2</td>
</tr>
<tr>
<td>12</td>
<td>Gypsum – White</td>
<td>20.3</td>
</tr>
<tr>
<td>13</td>
<td>Gypsum - Gold</td>
<td>39.7</td>
</tr>
</tbody>
</table>

Table 1: Shows the materials and the area on the building façade.
The surface temperature value of the materials in the NSB Road (East – West orientation) was 3° C more in comparison with that of Big Bazaar Street (North – South Orientation) and this difference was more significant in the early evening time (15.00 pm) when the materials start reradiating the incident radiation. Hence it was evident that the materials in particular, concrete and asphalt influence the microclimate of both the streets.

**Street Geometry – Materials – Urban Microclimate**

This study further explored the relationship between urban canyon and urban microclimate. There were very interesting relationships observed.

- The open space between the buildings in the Urban Canyons along the East - West orientation streets experienced more radiation on the base surface (roads) compared to that of the vertical surfaces (building façade). This phenomenon was opposite in the urban canyons of the North - South orientation. (Figure 7).
- The urban canyons with Aspect Ratios (2 – 5) in both the NSB Road and the Big Bazaar Street had air temperature values less compared to that of the urban canyons with Aspect ratios (0.3 – 0.5). But when the PET (Physiological Equivalent temperature) values were calculated using RAYMAN software for the five different time periods, the values were above the normal comfort range. The PET values (22° C min. - 43° C max), which is much above than the normal range of comfort. (When the comfort range for Tiruchirappalli City was calculated using the weather tool of Ecotect 2011 the range was found to be 26° C - 31° C). The reason behind this discomfort range even in canyons with more aspect ratio is because of very poor wind speed (range between 0.27m/s – 0.54 m/s) due to the high density. When the study area was simulated using the Autodesk Vasari software it was found that practically no wind movement at the height of 2.8m from the ground surface, which is almost the height of the space used by the pedestrians (Figure 8).

**Figure 7:** Shows the solar irradiation value of surfaces in NSB Road and Big Bazaar Street. (Simulated Using Autodesk VASARI)

- The open space between the buildings in the Urban Canyons along the East - West orientation streets experienced more radiation on the base surface (roads) compared to that of the vertical surfaces (building façade). This phenomenon was opposite in the urban canyons of the North - South orientation. (Figure 7).
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**Figure 8:** Shows the wind movement along NSB Road and Big Bazaar Street. (Simulated Using Autodesk VASARI)
• Since Tiruchirappalli belongs to hot humid climatic zone, the problem of humidity was also felt in certain canyons with poor wind movement. Increased air temperature (almost 42°C) and humidity as high as 63% further deteriorated the outdoor comfort condition of the pedestrian users.

• Autodesk Vasari, Ecotect and RAYMAN were all validated with the questionnaire survey. The Percentage of people Dissatisfied were more in NSB Road (East - West) compared to the users of Big Bazaar Street (North – South) for all the five time period (Figure 9).

**Design Best Practice Methods**

After careful study and analysis of the urban canyon and urban microclimate interactions following design best practice methods were derived (Figure 10):

• The choice of building material used on the surface of all planes of urban elements (Base plane – floor, Vertical Plane – walls, Overhead Plane – Building Projections) should be more environment friendly, in radiating heat.

• The street orientation has to be considered while deciding on the material choice for roads. (In the case of NSB road maximum radiation was from the asphalt used on road).

• As how the built space - open space ratios are worked out in 2 – D plans of individual building designs, similar structure has to be considered for the city planning to enable and enhance wind movement. But in areas of high density and high rise buildings like the study area (CBD), outdoor microclimate can be resolved only by providing shading, as wind movement is restricted.

• In order to enhance wind movement among high density built spaces, regulations can be formulated to design buildings with solid and void volumes.

*Figure 9: Shows the PPD value for NSB Road and Big Bazaar Street*

*Figure 10: Design best practice methods*
The planning of cities should also consider the 3-D of the built volumes, since aspects like SVF can be resolved. The canyons can be designed with surface projections and overhanging to reduce the impact of surface radiation of the materials as well they can provide shading for the pedestrian users.

Since there is less scope of vegetating spaces near buildings, greening of roofs and walls can be done to minimize the impact of radiation.

Conclusion

In a Tropical country like India, where more activity is extended outdoors, climatic comfort of pedestrians is inevitable in the design of urban spaces. Though there are many climatic factors that control urban microclimate, the most important of them is the air temperature, since it directly influences the PET (Physiological Equivalent Temperature). From the study of the commercial streets in the Tiruchirappalli city it was obvious that the air temperature value can be controlled with the help of canyon geometry as well as by enhancing the movement of wind. The increase in wind also offers important role in minimizing the impact of excess humidity in air. These design best practice methods has to be executed right from the level of individual building design to the scale of city design in coherence with the climatic factors. Because the physical factors of the urban canyon and the city climatic factors mutually interact and influence one other. This influence has to be made positive to achieve better comfort condition for the urban pedestrian user.

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Re-evaluation of Passive Design Measures in the BASF House in Recognition of Uncertainty and Model Discrepancy

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ABSTRACT
Located in Nottingham, the BASF house serves as an example for energy efficiency and affordability. The house incorporates a number of passive and active measures to allow thermal comfort for residents. The success of these passive strategies appears to be supported by energy simulation studies. However, before establishing confidence in the results attained by energy simulations, it is critical to understand that energy modelers rely on simulation software to predict building energy performance. Despite the maturity of current energy simulation tools, they are inadequate to make precise predictions for the obvious reasons that local conditions, physical parameters, and usage scenarios are not fully known. As a consequence, passive design measures may fail to achieve their expected benefits. Indeed, models may show predictions that deviate from what we would observe in the realized building. The primary cause of such deviation is uncertainties in the model parameters and formulations. The important question to be raised is whether the recognition of the performance gap between design and reality would lead us to rethink the applicability of passive design measures. This paper focuses on analyzing the impact of those uncertainties on the evaluation of passive design measures in the BASF house. The exploration focuses on the risk that a passive design solution may cause unacceptable discomfort, which could potentially lead to its rejection despite its initial selection based on the results of a conventional energy simulation. This level of understanding is essential if we are to make rational design decisions regarding the applicability of passive strategies.

INTRODUCTION
In 2007, BASF, a German chemical company devoted to energy efficiency and resource protection, initiated a project to design, construct, and test modern methods of construction in six innovative, flexible houses. The first to be completed was the BASF house, located in Nottingham, England. Built in wet, cold weather, the house contains both active and passive strategies, the latter of which play a crucial role in establishing thermal comfort of residents.

Passive Strategies
Passive design arises with the desire to maximize thermal and environmental benefits. Building
designers need to thoroughly investigate the thermal characteristics of building components and systems to determine the optimal solution to minimizing heat loss in the winter and heat gain in the summer. Although a purely “passive” design without any mechanical intervention is preferable in terms of energy, more often than not, it does not meet the thermal comfort requirements, leading to the creation of hybrid systems, that is, incorporating mechanical devices into passive elements allowing the latter to function appropriately. One example is the BASF house, which combines a range of strategies such as shading, buffer zones, compactness, highly insulated building fabric, and double-glazed windows, as well as phase-change materials on the ceiling, an earth-air heat exchanger for cooling and pre-heating air, and natural ventilation in order to achieve desired performance.

Earth-Air Heat Exchanger

Earth air heat exchangers, buried to moderate depths, are generally underground horizontal ducts or pipes in which outside fresh air or re-circulated air is conditioned by the thermal mass of the earth and channeled into the house. To enhance heat transfer, pipes are usually made of polypropylene.

Phase-Change Materials

Because of their high storage density and latent heat property, phase-change materials are critical in the thermal energy storage of the building envelope system. One of the potential applications for phase-change materials is to incorporate them into the envelope system in buildings for energy conservation. During the summer, benefits include a time shift in the thermal load during the day and thus a decrease in the peak temperature. Since they will help reduce cooling loads by absorbing heat during the day and recycling it during the night, it is hypothesized that phase-change materials will work efficiently in the climate of Nottingham with warm days and cold nights.

A METHODOLOGY FOR EVALUATING PASSIVE MEASURES UNDER UNCERTAINTY

To evaluate the performance of passive strategies, designers base their decisions on energy simulation results to predict building behavior after implementation. However, when predicting the performance of buildings, current building performance assessment tools do not account for risks that can lead to designers’ having false confidence about the expected performance of sustainable measures and an impression about the likely underperformance of passive houses in reality. Mlakar and Strancar (2011), and Rodrigues and Gillott (2011) showed problems of overheating in passive houses during operation in the summer with in-situ measurements. Furthermore, Larsen and Jensen (2011) acknowledged that possible problems with high indoor temperatures are not anticipated during the design process via simulations but observed after the building is finished at the site. These findings motivate us in proposing a methodology for evaluating passive design measures with a clear indication of the risks of indoor discomfort. Additional risk information will infuse confidence about the effectiveness of proposed design measures for improving the thermal comfort of a passive house.

The probability that an unfavorable event will occur is referred to as “risk.” To measure risk, one must analyze the indefinite nature of the outcome of a situation, or uncertainty. Such is the case in predicting building performance, which entails two main sources of uncertainty. The first is uncertainty related to the physical properties of building components, system parameters, and operational scenarios. For example, the performance of building HVAC systems generally deviates from their nameplate efficiency, which stems from industrial compliance tests. Instead, their on-site performance may vary, depending on the local environments and construction and installation circumstances such as the effect of bad workmanship. Another source of uncertainty is the reliability of the model itself. Current most state-of-the-art energy simulation tools represent complex physical processes in reality through certain levels of abstraction and simplification. In addition, the modeler has to make assumptions resulting from a lack of information or expertise, which can lead to an overstatement of performance. In reality, no model can capture all aspects of a system and predict its full spectrum of performance during operation. The need to translate the identified uncertainties to risks has called for a type of uncertainty analysis that
quantifies the impact of physical parameter uncertainties, modeler assumptions, and model simplifications on the outcomes. Such an analysis is typically carried out using a Monte Carlo approach with an appropriate sampling technique in order to increase computational efficiency. The Monte Carlo (MC) simulation uses random number generators to model stochastic event occurrences.

de Wit and Augenbroe (2002) and MacDonald (2002) introduced a general procedure for uncertainty analysis of building thermal performance. Khazaii (2012) studied different sources of HVAC system uncertainty such as equipment manufacture tolerance, system degradation, and duct leakage. Wang, Augenbroe and Sun (2014) quantified the impact of realization uncertainty of construction detailing and workmanship on building energy performance. Their studies showed that a quantitative uncertainty assessment is essential in a design decision making process. These efforts represent only a small slice of a growing body of work that studies the effect of uncertainties encountered at various model levels (e.g., micro-climate, building level, and system level). Referring to the above sources, this paper uses the parameter uncertainty quantifications and techniques.

This paper casts new light on the evaluation of passive design strategies, which will explicitly show risks associated with design decisions. It will provide designers with quantitative evidence that certain levels of building performance will be accomplished or not. In this study, we propagate uncertainties through GURA-W (Georgia Tech Uncertainty and Risk Analysis Workbench) (Lee, Sun, Augenbroe and Paredis 2013). The probability distributions of uncertainty parameters are contained in an XML repository and sampled with Latin hypercube sampling. We then feed these uncertainty parameters into an EnergyPlus simulation engine. Eventually, the simulation results will show the performance of passive design strategies and their associated risks. The following sections present a case study showcasing the validity and value of our proposed methodology.

**BASF HOUSE AND MODEL ASSUMPTIONS**

The BASF house has an area of about 100 m² divided into ground and first floors as depicted in Figure 1. The ground floor mainly consists of an open-plan living room and a kitchen with a staircase connected to the first floor, allowing natural ventilation from the stack effect. The first floor comprises of two main southern bedrooms and a smaller one on the north (unoccupied). The house has a fully glazed double-height southern sunspace with external shading and internal adjustable blinds. Openings are carefully placed around the house, facilitating optimal use of natural cooling in the summer.

![Figure 1. the BASF house](image)

In terms of construction methods, ground floor walls are made of insulated concrete formwork (ICF) while the first floor walls and the roof are constructed of structural insulated panels (SIPs). In total, 100 m² of PCM boards that store and release heat from the living room, bedrooms, and the sunspace are sandwiched between plasterboards and oriented strand boards (OSB). Windows and curtain walls are double glazed and filled with argon with a U-value of 1.66W/m²K. The interface between multiple construction methods eliminates easily avoidable thermal bridges. In addition, the air permeability of the house is addressed by incremental pressurization tests and vulnerable area treatment, so the final house is among the most airtight in the United Kingdom (3.38 m³/h/m² at 50 Pa). An earth air heat exchanger containing 36m of piping buried at a depth of 1.5m supplies 0.05 m³/s of precooled or preheated air to the sunspace from 11am to 5pm and to the living room from 12pm to 2pm.
Information on construction types, occupancy schedules, and internal heat gains are loyal to the design intention and onsite implementation. PCM boards are simulated using the conduction finite difference solution algorithm in EnergyPlus, which uses an implicit finite difference scheme coupled with an enthalpy-temperature function to account for phase-change energy accurately. The local soil type is assumed to be standard (density 1800kg/m$^3$, conductivity 1.45W/mK, and thermal diffusivity $6.015 \times 10^{-7}$m$^2$/s) in the calculation of the average temperature, the amplitude and the phase constant of the soil surface. Then the performance of the earth-air heat exchanger is determined given these boundary conditions. Figure 2 showcases the ventilation strategy. More information about the BASF house can be found in Rodrigues (2010).

**Figure 2.** Ventilation strategy in the BASF house

The development of thermal models requires a series of further assumptions. Information on construction types, occupancy schedules, and internal heat gains are loyal to the design intention and onsite implementation. PCM boards are simulated using the conduction finite difference solution algorithm in EnergyPlus, which uses an implicit finite difference scheme coupled with an enthalpy-temperature function to account for phase-change energy accurately. The local soil type is assumed to be standard (density 1800kg/m$^3$, conductivity 1.45W/mK, and thermal diffusivity $6.015 \times 10^{-7}$m$^2$/s) in the calculation of the average temperature, the amplitude and the phase constant of the soil surface. Then the performance of the earth-air heat exchanger is determined given these boundary conditions. Figure 2 showcases the ventilation strategy. More information about the BASF house can be found in Rodrigues (2010).

**RE-EVALUATION OF MEASURES IN THE BASF HOUSE**

Following the previous reasoning, risks associated with passive design strategies cannot be thoroughly understood without acknowledging the uncertainties. Uncertainty analysis can provide information with respect to whether investigated strategies can meet the comfort requirement with a
specific degree of confidence, for instance expressed as a discomfort risk tolerance such as the allowed probability that the number of discomfort hours is exceeded. Rodrigues and Gillott (2011) compared deterministic simulation results with actual measurements for the BASF house and concluded that the simulation results are similar to the actual measurements except that the former over-predict the overheating issue in the sunspace and underestimate it in the north bedroom. The recorded observations seem to strengthen our argument that relying totally on deterministic results may give rise to false confidence and be insufficient in supporting design decision making. Therefore, the proposed design measures for the BASF house must be reevaluated under uncertainty. As an example, this study analyzes the risk of overheating in July, when the peak temperature might occur in Nottingham.

Risk of Overheating

According to CIBSE, the benchmark for overheating is 26°C in the living room and 25°C in the bedroom. If the benchmark is exceeded, the duration of the time above 28°C in the living room and 26°C in the bedroom should be no longer than 1%. Therefore, we first take the percentage of occupied time (12am to 9am, 5pm to 12am on weekdays; all the time on weekends) outside the above comfort zone as the performance indicator to evaluate the risk of overheating in the BASF house. Another way to rate discomfort is the absolute number of hours that a certain threshold is exceeded during a given critical month. The following results can be easily translated to the absolute number of hours in July by realizing that 1% corresponds to 5 to 6 hours. It should be noted that in order to identify if certain measures could fail the comfort tolerance of future occupants, a risk conscious measure will have to be established. If, for the sake of the argument, we assume that the risk tolerance of the occupants is that in the southwest bedroom in July, the probability that the number of discomfort hours above 28°C exceeds 35 (or 6% of the occupied time) cannot be higher than 8%, we would see that the current design would be acceptable based on Figures 3a and 3b. Figure 3a shows the distribution of the number of hours in July, when the temperature in the southwest bedroom exceeds 28°C during occupied hours. The predicted range is the combined effect of the uncertainties mentioned above. In Figure 3b, the error bar represents the 90 percent confidence interval of the quantity of interest. For example, for the southwest bedroom, the bar chart suggests with 90% confidence that the percentage of time during which the indoor temperature is higher than 25°C will be between 16.3% and 26% with a median value of 20.6%. The measurement data from Rodrigues and Gillott (2011) are in close agreement with the confidence interval predicted through our uncertainty analysis, confirming the validity of our model.

Figure 3a. Histogram (left) and cumulative relative frequency (right) of hours of discomfort in July.
Effectiveness of EAHE

Since the EAHE ventilates only the living room/kitchen area and the sunspace on the ground floor and because the benefits of natural ventilation in the bedrooms through open doors have not been proven, this section simulates the model developed previously without including the EAHE module to validate its effect. The EAHE supplies 0.05 m$^3$/s of precooled or preheated air, which translates to 0.68 ACH for the living room/kitchen areas and 2.6 ACH for the ground floor sunspace. As the results show (Figure 4), these two areas benefit most from the EAHE air supply: While the percentage of time exceeding the comfortable temperature of 25°C in the living room increases from 11% ~ 17% to 14.8% ~ 20.7% without the EAHE, that in the sunspace increases only slightly from 8% ~ 10.3% to 9% to 11.8%. Only a minor impact on the rest of the house suggests the intended air movement by design might need a more sophisticated fluid dynamics model to guide and validate it.

Effectiveness of PCM Boards

Rodrigues and Gillott (2011) observed that PCM boards are not below their phase-changing zone long enough to completely release the heat they absorb on a daily basis, which may undermine their effectiveness. Their work in TAS for the BASF house is incapable of simulating the effect of the PCM boards, leaving several hypotheses unproven.
According to the product specs from Rodrigues (2010), the operating temperature of the Micronal Knauf SmartBoard 23 is between 19°C to 23°C, and the maximum enthalpy slope is at 20°C. Figure 5 shows the prediction interval of the temperatures of the PCM boards in the living room on July 1. For example, their minimum temperature (around 8am) could be somewhere between 21.6°C to 22.8°C instead of a deterministic value. Unfortunately, PCM boards exceed their phase-changing temperature most of the time without major solid-liquid transitions. Therefore, they are not very effective in absorbing excessive heat from the room. Our finding supports the original argument by Rodrigues and Gillott (2011).

Exploring Ventilation Strategies

In this section, we test how the previous outcome is sensitive to the ventilation strategy presented in Figure 2 to account for another layer of uncertainty resulting from occupancy and use. We confine the ventilation air exchange rate per hour for each room as no larger than 15 for exterior spaces and 10 with adjacent spaces, which mimics the window/door closing behavior of users in case of undesirable effects such as a draft. Compared to the results in Figure 2, those in Figure 6 show only minor differences. However, for the southwest bedroom, the risk tolerance of occupants is exceeded: the probability that there are more than 35 occupied hours that the temperature exceeds 28°C is higher than 8%. We could conclude from the variability of outcome that the current design given the more realistic ventilation strategy would be unacceptable assuming the above risk tolerance of occupants.

CONCLUSION

The contribution of this paper is that we have proposed a methodology for evaluating the effectiveness of passive design strategies under uncertainty. Given the risk tolerance of the intended
occupants of the building, this methodology enables risk conscious design for clearly identified risk measures. Although the analysis in the study was confined to the BASF house, the proposed method has generality to guide future practice. We simulated passive measures in the BASF house and inferred the variability of uncertainty parameters from previously published work. The dynamic energy simulations led to the following conclusions:

1. Our proposed methodology excels in the following ways: It is able to predict the probability of the occurrence of extreme conditions inside buildings such as overheating while the conventional simulation approach cannot; the merit of different design options could be assessed against an occupant specific discomfort tolerance which will lead to superior decision making on which measures improve on the current design and which do not. We have demonstrated this point by showing that for a reasonably chosen, explicitly defined discomfort risk tolerance of an occupant, the BASF house would be deemed unacceptable. Such outcomes would have necessitated the BASF design to undergo additional measures that reduce the risk to fall within the tolerable range.

2. In terms of the earth-air heat exchanger, with the current limited operation time, it does not address the problem of overheating in the bedrooms although the comfort level in the living/kitchen area improved: The occupied time period when the temperature was higher than 25°C declined by 17% on a median level. The PCM boards did not contribute significantly to maintaining indoor comfort during the summer because of the lack of sufficient natural cooling to discharge stored heat. Thus, we recommend that designers have a good sense of the operating temperature range before choosing a specific product. In addition, we found the ventilation strategy an important piece of our jigsaw puzzle of maintaining a desirable indoor environment with passive measures. Even when the exterior condition is appropriate for natural cooling, the fact that an over-ventilated space with drafts could be as uncomfortable as an overheated one, may deem some passive designs unacceptable after all. Discomfort from drafts can be assessed with an uncertainty analysis of the airflows using a CFD model, which could be a topic of future work.

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Life Cycle Assessment as a tool for Material Selection - A comparison of Autoclaved Aerated Concrete and VSBK Brick Wall Assembly.

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1.0 ABSTRACT

Energy use of a building can be derived from five sources: Embodied Energy from mining and manufacturing of materials, Energy from transportation of materials, Energy from construction of the building, Energy use during operation of the building, and Energy used in the disposal of the building at the end of its life. Buildings use many materials with a high Embodied Energy, and it is estimated that, 10% of its total energy use comes from Embodied Energy in materials. Thus, the use of low Embodied Energy Materials for the sustainable development is preferred. Life cycle assessment (LCA) offers a comprehensive approach to evaluating and improving the environmental impacts of buildings materials, buildings and its products through all of its life stages.

Brick and Cement are majorly used materials in building industry. Kiln Burnt Brick is majorly use exterior wall material in the market. Also, Aerated Concrete (AAC) is a non-combustible, cementitious building material that is expanding into new worldwide markets.

The Paper will be aimed to compare the environmental impact of materials- Kiln Burnt Brick and Autoclaved Aerated Concrete used for wall assemblies. Study will be focused on evaluating the materials with respect to its Embodied Energy, Energy and Resource consumption, Environmental Impact in terms of CO2 Emissions, Cost, Health safety etc. The functional unit and unit distance will be defined to allow comparisons to be made between materials. The study will include interaction with the Manufacturers, Market study of the materials, and use of material in a particular building. The final objective of the paper is to evaluate the materials on the bases of Life Cycle Assessment Impact Categories which includes: Raw Material Index (RMI), Water consumption, Embodied Energy (EE) and Operational Energy (U-Value), Electricity, Occupational Health and Safety (OHS Index), Total Cost, CO2 Emissions.

Key words: - Life Cycle Assessment, Materials, Kiln Burnt Brick, Autoclaved Aerated Concrete, Life Cycle Assessment Impact Categories.

2.0 INTRODUCTION

Building construction in India is estimated to grow at a rate of 6.6% per year between 2005 and 2030 (McKinsey and Company, 2009). The building stock is expected to multiply five times during this period, resulting in a continuous increase in demand for building materials, which could have long lasting implications in terms of natural resource depletion, future energy demand, local pollution, contributions to greenhouse gas emissions as well as socio-economic conditions of a significant number of low-income workers. Thus it is an imperative and urgent need to have a comprehensive plan for development of walling materials production in India, with the least impact to the earth.
All materials have environmental implications. Thus the choice of materials for a project requires considerations of aesthetic appeal, initial and ongoing costs, life cycle assessment considerations (such as material performance, availability and impact on the environment) and the ability to reuse, recycle or dispose of the material at the end of its life. It is estimated that, 10% of buildings total energy use comes from embodied energy in materials. Thus, the use of low embodied energy materials for the sustainable development is preferred. Life Cycle Assessment (LCA) offers a comprehensive approach to evaluating and improving the environmental impacts of buildings materials, buildings and its products through all of its life stages from cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling).

Brick and Cement are majorly used materials in building industry. Kiln Burnt Brick is majorly used exterior wall material in the market. Also, Aerated Concrete (AAC) is a non-combustible, cementitious building material that is expanding into new worldwide markets.

3.0 AIM AND OBJECTIVE

The Paper is aimed to compare the environmental impact of materials- Kiln Burnt Brick and Autoclaved Aerated Concrete used for wall assemblies.

The final objective of the paper is to evaluate the materials on the bases of Life Cycle Assessment Impact Categories which includes: Raw Material Index (RMI), Water consumption, Embodied Energy (EE) and Operational Energy (U-Value), Electricity, Occupational Health and Safety (OHS Index), Total Cost, CO2 Emissions.

4.0 METHODOLOGY

In this assessment the tools of Life Cycle Assessment are integrated, which includes due consideration of all life cycle stages fixed in the ISO 14040 –14043 standards: Goal and Scope Definition, Life Cycle Inventory Analysis, Life Cycle Impact Assessment and Life Cycle Interpretation.

Life Cycle Inventory Analysis includes assembling data and analyzing it on a suitable system boundary. Life Cycle Impact Assessment is the evaluation of the material and energy flows raised in the inventory analysis according to certain environmental effects.

![Figure 1](image.png)

*Figure 1 Methodology use for Life Cycle Assessment.*

Thereafter, Impact Assessment categories are selected, which includes: Raw Material Index (RMI), Water Consumption, Embodied Energy (EE) and Operational Energy (U-Value), Electricity and other Resources, Occupational Health and Safety (OHS Index), Total Cost, CO2 Emissions. Life Cycle Interpretation consists of Identification of significant issues, evaluation and conclusions.
5.0 SCOPE AND LIMITATION

Study is focused on evaluating only two walling materials - Kiln Burnt Brick and Autoclaved Aerated Concrete with respect to its formulated Impact Assessment Categories. The functional unit and unit distance is defined to allow comparisons to be made between materials. The study includes interaction with the Manufacturers, Market study of the materials, and use of material in a particular building.

Building use: Evaluation of the materials and energy consumptions is restricted to the use of a building only, its maintenance and restoring, not considered within this study. Also, Transport of the wastes generated during the Construction and Demolition phase, not considered within this study. No consideration of labour cost as it will have negligible effect on the results.

To understand the implication of these materials, the live site data collection is limited to pune (moderate climate), but to understand the impact of operational energy a theoretically comparative study base has been done with a case study of composite climate.

6.0 LIFE CYCLE ASSESSMENT

A Life Cycle Assessment (LCA) provides a mechanism for systematically evaluating the inputs, outputs and the potential environmental impacts linked to a product or process throughout its life cycle. (ISO 14040). LCA addresses the impacts of a product through all of its life stages.

Life Cycle Assessment is a technique to assess environmental impacts associated with all the stages of a product’s life from cradle to grave.

6.1 EMBODIED ENERGY

Embodied energy is the total energy required for the extraction, processing, manufacture and delivery of building materials to the building site. Energy consumption produces CO2, which contributes to greenhouse gas emissions, so embodied energy is considered an indicator of the overall environmental impact of building materials and systems. It does not include the operation or disposal of materials.

The total amount of embodied energy may account for 20% of the building’s energy use, so reducing embodied energy can significantly reduce the overall environmental impact of the building.

Energy consumption during manufacturing can give an approximate indication of the environmental impact of the material, and for most building materials, the major environmental impacts occur during the initial processes.

![Figure 2](image-url)  Typical phases of materials Life Cycle, along with inputs and outputs at each phase.

7.0 LIFE CYCLE INVENTORY ANALYSIS OF AAC BLOCKS AND VSBK BRICK

7.1 Autoclaved Aerated concrete and Vertical Shaft Brick Kiln (VSBK)

AAC is lightweight, precast building material that simultaneously provides structure, insulations, and fire & mold resistance. Main ingredients include fly ash, water, quicklime, cement, aluminium powder & gypsum. The block hardness is being achieved by cement strength, & instant curing mechanism by autoclaving. Gypsum acts as a long term strength gainer. The chemical reaction due to the aluminium paste provides AAC its distinct porous structure, lightness & insulation properties, completely different compare to other lightweight materials.

The VSBK is a vertical kiln with a stationary fire and a moving brick arrangement. The figure below shows the VSBK principle in a schematic diagram. The kiln operates like a counter current heat...
exchanger, with the heat transfer taking place between the air moving upwards and the bricks moving downwards.

\[\text{(a)}\]

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Quantity</th>
<th>Unit</th>
<th>Embodied Energy Unit</th>
<th>Total Energy Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>lime</td>
<td>90.00 kg/cu.mt</td>
<td>5.63 Mj/kg</td>
<td>506.7 Mj</td>
<td></td>
</tr>
<tr>
<td>fly ash</td>
<td>450.00 kg/cu.mt</td>
<td>2.2 Mj/kg</td>
<td>1010 Mj</td>
<td></td>
</tr>
<tr>
<td>cement</td>
<td>70 kg/cu.mt</td>
<td>4.2 Mj/kg</td>
<td>294 Mj</td>
<td></td>
</tr>
<tr>
<td>aluminium powder</td>
<td>0.5 kg/cu.mt</td>
<td>130 Mj/kg</td>
<td>75 Mj</td>
<td></td>
</tr>
<tr>
<td>gypsum</td>
<td>5 kg/cu.mt</td>
<td>1 Mj/kg</td>
<td>5 Mj</td>
<td></td>
</tr>
<tr>
<td>Total RM EE</td>
<td>935.7 Mj</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td>150 Km.</td>
<td>11.93 Mj/Km.</td>
<td>1789.5 Mj</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2725.2 Mj</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electricity (kWh)</td>
<td>9 kWh/Cu.m.</td>
<td>9.28 Mj/kWh</td>
<td>83.52 Mj</td>
<td></td>
</tr>
<tr>
<td>Coal (kg)</td>
<td>0.03 ton/cu.mt</td>
<td>12.3 Mj/ton</td>
<td>0.369 Mj</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2809.09 Mj</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water consumption</td>
<td>400 l/cu.mt</td>
<td>10.04 Mj/day</td>
<td>499.63 Mj</td>
<td></td>
</tr>
<tr>
<td>human resource</td>
<td>60 no.s</td>
<td>10.04 Mj/day</td>
<td>602.4 Mj</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>275.29 CO₂/cu.m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Quantities of AAC Wall yearly 100000 cum

Energy content of furnace oil = 42.25 MJ/l; energy content of grid electricity = 9.28 MJ/kWh; and energy content of cement = 4.20 MJ/kg. All Embodied Energy reference:

\[\text{(b)}\]

\[\text{Figure 4} \quad \text{(a) Process Flow Chart and (b) Table 1 Embodied Energy calculations for AAC Block Production.}\]

\[\begin{align*}
\text{Note: Data Collection for production process of AAC Blocks is taken from company Anjali Ventures Ltd., Surat.}\end{align*}\]

\[\text{(a)}\]

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Quantity</th>
<th>Unit</th>
<th>Embodied Energy Unit</th>
<th>Total Energy Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fired Brick</td>
<td>555.00 unit/cu.mt</td>
<td>7.9 Mj/unit</td>
<td>4384.5 Mj</td>
<td></td>
</tr>
<tr>
<td>Total RM EE</td>
<td>4384.5 Mj</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td>50 Km.</td>
<td>11.93 Mj/Km.</td>
<td>596.5 Mj</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4981 Mj</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electricity (kWh)</td>
<td>1 kWh/Cu.m.</td>
<td>9.28 Mj/kWh</td>
<td>9.28 Mj</td>
<td></td>
</tr>
<tr>
<td>Coal (kg)</td>
<td>6 ton/cu.mt</td>
<td>18 Mj/ton</td>
<td>108 Mj</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5098.28 Mj</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water consumption</td>
<td>420 l/cu.mt</td>
<td>10.04 Mj/day</td>
<td>499.63 Mj</td>
<td></td>
</tr>
<tr>
<td>human resource</td>
<td>9 no.s</td>
<td>10.04 Mj/day</td>
<td>90.36 Mj</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>499.63 CO₂/cu.m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Energy content of furnace oil = 42.25 MJ/l; energy content of grid electricity = 9.28 MJ/kWh; and energy content of cement = 4.20 MJ/kg. All Embodied Energy reference:

\[\text{Figure 5} \quad \text{(a) Process Flow Chart and (b) Table 2 Embodied Energy calculations for VSBK Block Production.}\]
Table 3  Embodied Energy calculations involved in constructing the Wall Assembly of AAC and VSBK.

8.0 CASE STUDIES (CLIMATE: COMPOSITE CLIMATE)

8.1 Fortis Hospital – 3 Star rated. (Location: Shalimar Bagh, New Delhi)

The 500 bedded Fortis hospital at Shalimar Bagh is designed with a vision to provide an environment friendly health care facility in an area of 64,400 sq mts. It is the first hospital building in India to have registered for the GRIHA green building rating system.

9.0 LIVE CASE STUDY (CLIMATE: MODERATE)

9.1 Park Turquoise (Location: Wakad, Pune)

Turquoise is Apartment Flats of 2 bhk (1150 sq. ft), 2.5 bhk (1330 sq. ft), 3 bhk (1550 sq .ft).

A Park Turquoise is the luxurious 70-acre township boasting of ample landscaped and open areas.

9.2 Construction Techniques

The building envelope has used Autoclaved Aerated concrete blocks instead of conventional bricks. The windows are glazed units with low thermal transmittance. Building Envelop is of AAC blocks with external 1:4 cement and sand plaster and internal gypsum plaster.

U-value calculations for 150mm and 200 mm AAC wall=0.76 w/m² degC and 0.61 w/m² degC.

U-value calculations for 150mm and 230 mm VSBK wall = 1.95 w/m² degC and 1.77 w/m² degC.
9.3 Cost Analysis of the Project

All required quantities are referred based on the data collected from the Live Case Study to allow comparison between the two materials.

10.0 LIFE CYCLE IMPACT ASSESSMENT OF AAC BLOCKS AND VSBK BRICKS

Based on the data collected from the live case study, Comparative Analysis has been done between both the materials on various parameters and the results derived from these calculations are as follows:

10.1 Raw Material consumption (per cubic meter of 150 mm thick Non-Loadbearing Wall)

Raw Material Index = (Clay quantity x 2 + Silt quantity x 1 + Sand quantity x 1 + Lime quantity x 1 + Cement quantity x 1 x 1.45 + Fly ash quantity x 0)/5


Figure 9 Raw Materials in block production and construction of Wall Assemblies.

10.2 Water Consumption (l/m³ for 150 mm Non Loadbearing wall).

Figure 10 Water Consumption in block production and construction of Wall Assemblies.
10.3 Energy Consumption (Embodied Energy and Operational Energy of 150 mm Non Loadbearing wall).

![Embodied energy and operational energy](image.png)

About 0.098 tonnes of CO2 are produced per gigajoule of embodied energy = 0.098Kg of CO2 per MJ of embodied energy.

**Figure 11** Embodied energy (MJ/m3) and Operational Energy (W/m2.deg C) in Wall Assemblies.

10.4 Productivity and OHS (for 150mm Non Loadbearing wall)

Scores for each sub-parameter: High (H) = 3’, ‘Moderate (M) = 2’ and ‘Low (L) = 1; Available (A) = 1’, ‘Inadequate (I) = 2’ and ‘Not available (NA) = 3, NA = 0 for (d), OHS Index = (Sum of scores for each sub-parameter)/9

**Figure 12** Occupational Health and Safety Assessment for masonry Wall Assemblies.

10.5 Wall cost for 150mm (AAC) and 230mm (VSBK) Non Loadbearing masonry Wall Assemblies:

**Figure 13** Total Wall Cost for masonry construction of Wall Assemblies.

10.6 Emissions:

**Figure 14** Emissions related to Wall Assemblies (kg of CO2).
10.7 Resources used:

<table>
<thead>
<tr>
<th>Non-Load bearing wall: AAC blocks</th>
<th>Production</th>
<th>Construction</th>
<th>Total water consumption</th>
<th>Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electricity (kWh)</td>
<td>Coal (ton)</td>
<td>Electricity</td>
<td>Total</td>
</tr>
<tr>
<td>AAC blocks</td>
<td>9.00</td>
<td>0.03</td>
<td>2</td>
<td>11.00</td>
</tr>
<tr>
<td>Burnt bricks</td>
<td>1.00</td>
<td>6.66</td>
<td>4.00</td>
<td>5.00</td>
</tr>
</tbody>
</table>


The total emission factor for electricity is 16.43g CO2 / MJ.

About 0.098 tonnes of CO2 are produced per gigajoule of embodied energy = 0.098Kg of CO2 per MJ of embodied energy.

Figure 15  Resources used in wall assemblies /cu mt.

11.0 LIFE CYCLE INTERPRETATIONS

11.1 Overall Comparison

1. It is apparent that masonry units with the least or no clay content (i.e AAC blocks which contains waste material such as Fly Ash) have low impact. Density also influences raw material impact, thus AAC blocks resulting from the aerated nature (approximately 80% air) have lower raw material impact. Larger block size reduces the quantity of mortar wastage on construction site. Additionally, the raw materials that are consumed are generally abundant and found in most geographic regions, allowing them to be locally sourced. Furthermore, much of the raw materials used in AAC production may consist of recycled materials, including copper mine tailings and flyash, a byproduct of coal-fired power plants.

2. AAC blocks use cement in the production process and require curing. However, steam curing under high pressure (autoclaving) results in significantly lower water consumption. Larger block size reduces the quantity of mortar used in construction and thus the water requirement on site. Whereas, Water requires for curing Brick Masonry for 7 days is much large, thus the water consumption increases.

3. Burnt bricks show much higher embodied energy compared to AAC Blocks. The thermal performance of AAC wall assembly is also generally superior to Burnt bricks as reflected in the U-values. AAC blocks wall assembly have the lower U-value due to the porous nature of the material.

4. Burnt brick production is traditionally a labour intensive process. The use of manual labour for moulding therefore results in significantly lower productivity compared to mechanized processes.

   Block size also influences construction productivity and a larger block size requires less time and effort for construction. Poor conditions for labour at brick kiln sites are reflected in OHS index compared to AAC. Units producing AAC Blocks are generally located close to large urban areas and do not require labour to live on site during the production period as in the case of Burnt Brick.

5. Cost of AAC block is higher but the overall cost of the construction reduces drastically. Due to the larger block size of AAC masonry reduces the mortar quantity contributing to lower cost for the wall assembly. Also due to its lightweight characteristics the steel consumption reduces by 0.4kg which lower the total cost of construction.

6. CO2 emissions are lower for AAC Production and Wall Assembly compared to Burnt brick Walls and its production. Also, Resource Consumption of AAC is lower and thus the CO2 emissions.

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12.0 REFERENCES

First monitoring results of three straw bale buildings in Belgium

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ABSTRACT
Straw bale use in buildings may be an interesting way to decrease our energy needs and our impact on environment. The present paper describes an experimental set up to monitor three straw bale buildings recently built in Belgium. For each building, results on temperature and relative humidity, inside and outside, are analyzed, as well as internal evolution of temperature and humidity distribution in the walls. The first building is an office building where two finishing are compared. Measurements also provide additional data on CO$_2$ levels and electric consumption. The two other buildings are dwellings where live one single family. In the first one, a wall in the bedroom and a retaining wall are analyzed. In the second one, a wall in the bedroom and a wall in the bathroom are analyzed. Their hygrothermal behavior is discussed based on simulation results obtained with WUFI Pro and WUFI Plus software. The criterion for the validation of wall behavior is based on water content distribution through the walls. The paper confirms the great potential of this type of building technology and helps to identify how to assess and validate their effective hygrothermal behavior.

Key words: Straw bale, field measurements, whole building simulation, water content criterion

INTRODUCTION
Straw bale building techniques are evolving since the XIX$^{th}$ century. Some techniques are still evolving and prefabrication of entire walls has started in Belgium since few years. The present paper presents results based on an experimental setup installed in three straw bale buildings in Belgium. For each of these cases, the straw bale walls were prefabricated in the same factory with the same building technique, except small variations. The wall is built with 46 cm or 36 cm of straw (structured with a timer framed structure), covered on the inside with an 4cm earth plaster and on the outside with a 1.6 cm bracing panel (open to vapor). This walls typology was presented in [Evrard et al., 2012].

The first building is a small office building (approx. 80m$^2$) built in a large industrial hall in Franière. It is thus protected from rain and direct sun. The walls are built with 46 cm of straw. Preliminary simulation results were presented in [Evrard, 2013]. As the building is occupied since September 2013, almost 9 months of monitoring can be analyzed.

The second building is a family house (approx. 225 m$^2$). The monitoring also started in September 2013, but because of undesired power supply failure, only less than 5 months of data can be analyzed. Two different walls are compared, both built with 46 cm of straw. One is facing west and inside environment is a bedroom; the other is a retaining wall in the entrance hall.

The third building is also a family house (approx. 120 m$^2$) built in an urban context in Uccle. It has an attached house on one side. The monitoring started in November 2013 and around 7 months of measurements were thus analyzed. The walls are built with 36 cm of straw in this case. As in the other house, two different walls are compared. One is facing north and inside environment is a bathroom; the other is facing south and inside environment is a bedroom.
METHODOLOGY

The main objective of the monitoring setup presented in this paper is to enable the calibration of numerical simulations and to validate the performances of straw bale walls. It was thus necessary to gather complete climate data for each building (having a different location). For the three buildings, outside temperature and humidity was measured. Sun radiation was measured for the two family houses (west for the first one and south for the second one). Rain load was only measured for west wall in Tongrinne (second building). In addition, temperature and humidity of inside environment of the three buildings was measured, as well as temperature and humidity at different places through the wall. In this first building, complementary sensors were installed to measure CO\textsubscript{2} concentration, windows and doors openings, as well as a webcam to be able to assess occupation. Electrical consumption of monitored room is also measured.

All measures of temperature and humidity were made with the sensors Sensirion SHT75 (except surface temperature made with PT100). A special tube containing a chain of sensors was developed to monitor the temperature and humidity inside the wall, at specific positions. In the two first buildings, 5 sensors are respectively positioned at 2cm (under earth plaster), 11cm (first quarter in straw), 22cm (middle position in straw), 33cm (last quarter in straw) and 44cm (under bracing panel) from inside surface. In the last building, two chains of sensors were used, each with 4 sensors, respectively positioned at 2cm (under earth plaster), 11cm (first third in straw), 22cm (second third in straw) and 33cm (under bracing panel) and at 1cm, 12cm, 23cm and 34cm from inside surface. CO\textsubscript{2} concentration is measured with Gascard NG (3000ppm) sensor. All sensors are connected to a data logger Campbell CR1000 and sent by Internet on a dedicated sever. The data are processed with Microsoft Excel software to allow their use and comparison with numerical simulations. Simulations at wall level are achieved with WUFI Pro 5.2 software and WUFI Plus 2.1 software was used at the building level.

RESULTS

Building n°1: Small office building in Franière

Two different earth plasters on inside surface are compared. For each plaster, three chains of sensors were installed (high, medium and low height). Temperature and humidity evolution are similar for all of these cases, only small variation were observed. Temperature under inner plaster follows very closely the temperature of inside air, and temperature under the bracing panel follows approximately the temperature of outside air (in the hall). The difference is due to the thermal inertia of earth plaster (discussed in [Evrard, 2013]).

As shown in Figure 1 (left), outside temperature (in the hall) was almost never under 0°C. Inside temperature of monitored room falls sometimes under 12°C (6 times between end of November and beginning of February) and do not reach 20°C every working days even if the company installed three simple halogen lamp (400W) to heat the building (one in monitored room) end of November. The lamps are turned on in the morning (between 6am and 9am) and turn off at the end of the day (between 6pm and 8pm). As Figure 1 (right) shows, the occupancy is not regular and, sometimes, nobody is working in the office (i.e. end of December).

Figure 2 (left) presents the data collected in the straw bale for the wall with the plaster n°2, at an approximate height of 1m50 (medium height). It shows the evolution of relative humidity at the most humid point of the wall in winter, i.e. 1cm under the outer bracing panel, as well as the evolution of relative humidity at the driest point of the straw bale in winter, i.e. just under inner earth plaster. It appears that the relative humidity is always under 86% under the bracing panel. According to the sorption curve of straw bales measured in the laboratory, at this humidity, water content is around 16% of mass. Results obtained for plaster n°1 are relevant in this paper. Despite current regulation, no ventilation was installed. Figure 2 (right) shows the evolution of CO\textsubscript{2} concentration in monitored room.
Figure 1 (left) inside and outside air temperature of monitored room in Franière (right) electric consumption of monitored room in Franière.

Figure 2 (left) relative humidity under inner plaster and under outer bracing panel of the wall with plaster n°2 in monitored room in Franière (right) CO₂ concentration of inside air in monitored room in Franière.

Building n°2: Family house in Tongrinne

The monitoring of this building started in September 2013, but because of undesired power supply failure, only less than 5 months of data can be analyzed. Two different walls are compared, both built with 46 cm of straw. One is facing west and inside environment is a bedroom; the other is a retaining wall in the entrance hall.

West wall is submitted to driving rain. A water-repellent render system (board, mineral under layer and finishing) was applied on outer surface. Figure 3 shows cumulative rain quantity and sun radiation for this wall, as well as relative humidity through the straw bale.

Figure 3 (left) cumulative rain quantity and sun radiation of vertical west wall surface in Tongrinne (right) relative humidity through the straw bale of west wall monitored in Tongrinne.

The other wall monitored in Building n°2 is a retaining wall. Inside environment is the entrance hall of the house. Outside environment is in the earth. A water barrier was installed again outer bracing panel, avoiding water to penetrate the wall, but preventing also vapor to transfer out of the wall on this side. Figure 4 (left) shows relative humidity through the straw bale in this wall (the sensor under the bracing panel do not send any information).
Building n°3: Family house in Uccle

The monitoring of this family house started in November 2013 and around 7 months of measurements could thus be analyzed. As in previous house, two different walls are compared, both built with only 36 cm of straw in this case. The first wall is facing north and inside environment is a bathroom; the other is facing south and inside environment is a bedroom. Figure 4 (right) shows relative humidity under bracing panel (the most humid position in the walls) for both walls.

DISCUSSION

Building n°1: Small office building in Franière

Outside temperature and relative humidity from measurements, as well as heating input of electric power released in the room, where used as input in a WUFI Plus simulation (hygrothermal building zone analysis). All necessary material data were gathered during previous step of aPROpaille research. Main parameters are presented in [Evrard, 2013] (exterior wall type “S”). Occupation profile (one man working from 9am to 6pm on week days, with a break between 1pm and 2pm) did not take into account the lightings and the computer, as they are considered in the heating input of the room. Other inputs of the simulation represent real conditions of the unventilated office. A natural ventilation through door and window of 1vol/h between 9am and 10am and between 1pm and 2pm is considered together with a constant infiltration rate of 0.024 vol/h (equivalent to n50 = 0.6 vol/h, even if there was no blower door test). This case is thus similar to case S-2 of preliminary simulations presented in [Evrard, 2013].

As illustrated in Figure 5 (left), inside temperature resulting from simulation follows the same trend that measured values. Daily maximum temperature is quite close, but minimum temperature (i.e. after each week-end) is lower in reality. This difference can be due to the hypothesis on ventilation rate and occupation profile. The company should install an adapted heating system to reach comfortable temperature during working days.

Figure 5 (right) shows the evolution of relative humidity at the most humid point of the straw bale in winter, i.e. 1cm under the outer bracing panel, as well as the evolution of relative humidity at the driest point in the straw bale in winter, i.e. just under inner earth plaster. There is a sensible difference between measurements and simulation results in terms of relative humidity in the straw bale. Simulated relative humidity in the straw bale follows the same trend; however, the maximum value under the bracing panel and minimum value under inner plaster are respectively 5% higher and 5% lower in the simulation. This rather small difference is not further analyzed in this paper. As a matter of fact, the relative humidity is always under 90% under the bracing panel. At this humidity, water content of the straw bale is under 20% of mass. According to [Wihan, 2007], no decomposition will occur under a water content of 25% in mass and a degradation of 0.009% a day appears when water content of straw is between 25% and 39% of mass. This analysis depends on the sorption curve of the straw bale and on organic decomposition rate (the values may depend on the density of the straw bale, the type of plant…).
One last remark can be made on the evolution of CO$_2$ concentration in the simulation. As we defined a constant occupation every week-days (with a break at noon) and almost no ventilation, CO$_2$ concentration rises every week-days until around 3700ppmv (vs. maximum value measured is 3000ppmv). A ventilation system (around 30m$^3$/pers) can be used to reduce CO$_2$ concentration under 1000ppmv (Belgian regulation NBN EN 1377-2007). A precise occupation profile could be assessed based on measured CO$_2$ concentration, but this goes beyond the scope of this paper because it would need, in addition, a complementary analysis of ventilation rate.

Building n°2: Family house in Tongrinne

Outside and inside temperature and humidity, as well as sun exposure and rain load on west wall were used to run WUFI Pro simulations (1D hygrothermal analysis). Missing data between the 28th of February and the 19th of March were filled with data measured between the 7th of February and the 26th of February for continuity of the climate file. Material data were gathered in previous step of the research (see [Evrard, 2013]).

For the water-repellent render system, density, thermal conductivity and vapor diffusion resistance factor of each layer were collected from producers. Other parameters (porosity, specific heat capacity, sorption curve…) correspond to a “Cement Plaster” in WUFI database, except liquid absorption coefficient (A-value). Finishing mattering is announced to be “water repellent” and A-value is set to 0.0017 kg/m$^2$s$^{-1/2}$. The producer indicates that sd-value of this layer is higher than 0.5m. As layer must be minimum 1mm in WUFI Pro, the vapor diffusion resistance factor of this layer is set to $\mu=500$ (500*0.001m=0.5m). A-value of the board and render are set to 0.0083 kg/m$^2$s$^{-1/2}$ corresponding to the worst value in class II of standard NF EN 1062-1 (W2 announcer by producer).

Figure 5  (left) inside air temperature in Franière, simulated with WUFI Plus software (right) relative humidity under inner plaster and under outer bracing panel in the straw bale with plaster n°2 in Franière, simulated with WUFI Plus software.

Figure 6  (left) relative humidity through the straw bale wall orientated to the west in Tongrinne (first period), simulated with WUFI Pro software (right) relative humidity through the straw bale wall orientated to the west in Tongrinne (second period), simulated with WUFI Pro software.
Figure 6 (left) shows the simulated relative humidity through the straw bale wall of the west wall in Tongrinne. Initial humidity of the straw bale was set to 80% (constant through component). The two first months are thus very different from measured value, but from the 15th February until 15th of May, the results are in very good agreement. The main difference is the higher daily amplitude of the variations of relative humidity (especially close to outside) in the measurements, but average values are similar.

Measured values are very often over 91.4% of relative humidity, corresponding to a water content over 25% in mass. Simulated values rise until 90% of relative humidity and seem to continue to rises as time passes. A second period (with the same climate file) was simulated starting with water content profile obtained at the end of the first period (which was rather rainy). Figure 6 (right) shows that an accumulation of humidity can be observed. The maximum water content during second period is over 25% of mass. An explanation of this problematic behavior is the rather high vapor permeability of finishing layer (sd = 0.5m or more). If this layer has a sd-value of 0.05m, the simulation shows no moisture accumulation and relative humidity under the bracing panel stays under 90%.

A this point, it has to be noticed, that equivalent simulations, using “test reference year” (TRY) in Uccle (50 km from Tongrinne) for outside climate and EN15026 standard for inside, do not reveal any problem in the wall. The relative humidity of the straw under the bracing panel gets close to 90% but decrease after the month of June. No accumulation is observed and no degradation should occur. It is thus too early to conclude that organic degradation will occur in the straw over time as a significant decrease of relative humidity at this specific place may be observed in following months (summer period).

To simulate the retaining wall, only inside climate was used as an input for simulation. For outside climate (in the earth), a sinus variation of temperature around 15°C and with amplitude of 3°C (maximum on the 1st of August) and a constant humidity of 99% are chosen. No absorption of water is allowed in the wall and a 1mm layer with very low vapor permeability is considered (sd=1500m). As in previous simulation, initial humidity of the straw bale was set to 80% (constant through component). Figure 7 (left) shows that there is a difference of around 5% of relative humidity between simulated results and measurements at the end of the first period. Under the bracing panel, the relative humidity seems to decrease after the 15th of April (the sensor at this position does not send any information). At the opposite, relative humidity under inner plaster seems to increase after end of March. When repeating simulating a second period, starting with water content profile obtained at the end of the first period, a significant decrease in straw bale humidity can be observed, as shown in Figure 7 (right). The results are similar when using a usual inside climate (“normal moisture load”) based on standard EN15026 with TRY reference climate in Uccle (50km from Tongrinne): the maximum relative humidity under the bracing panel during the third year is 83% (86% with “high moisture load”), with no accumulation. Before drawing any conclusion, positive results from simulations suggest to wait to have a longer measuring period to further discuss measured values.

Figure 7 (left) relative humidity through the straw bale retaining wall in Tongrinne (first period), simulated with WUFI Pro software (right) relative humidity through the straw bale retaining wall in Tongrinne (second period), simulated with WUFI Pro software.
Building n°3: Family house in Uccle

Outside and inside temperature and humidity (in both rooms), as well as sun exposure on south wall were used to run WUFI Pro simulations (1D hygrothermal analysis). Material data were gathered in previous step of the research (see [Evrard, 2013]). A render on outside surface (2cm) was applied on both walls on a wood-cement board (2.5cm) fixed on a wood structure (unventilated air layer of 3cm) directly on bracing panel. The total complementary sd-value of those three layers is supposed to be around 30cm. Rain absorption of outside surface is neglected in the simulations (no rain load was measured in Uccle and the render is supposed to be water-repellent). Inner finnishing is also neglected for both walls (thin lime plaster).

Figure 8 shows that there is a significant difference of relative humidity under the bracing panel between measurements and simulation results. In the bedroom, simulation results are 10% to 15% higher during the two first months and after four month. In the bathroom, results are similar at the beginning and at the end of the period, but diverge between the second and the seventh months (difference up to 15%). At this point, these simulation results cannot be used because they may not be relevant. This might be due to hypothesis on rain, or on material parameters (outside render and inner plaster). Further research is needed. However, it has to be noticed that measured values are fine in the bedroom (relative humidity of the straw under the bracing panel is always under 80%) and, for the bathroom, they exceed 91.4% of relative humidity under the bracing panel, only during few days.

**Figure 8** (left) relative humidity under bracing panel of south wall in the bedroom in Uccle, simulated with WUFI Plus software (right) relative humidity under bracing panel of north wall in the bathroom in Uccle, simulated with WUFI Plus software.

**CONCLUSION**

The paper presents the first analysis of the data collected in three straw bale buildings in Belgium: one office and two family houses. All data are collected on a dedicated server and are analyzed after a processing with Microsoft Excel software. Based on [Wihan, 2007] and [Evrard et al., 2012], validation of wall behavior focuses on the humidity in the straw bale. Relative humidity of straw should not exceed 91.4% (corresponding to a water content of 25% of mass). The most humid place in the walls (if no undesired source of humidity exists), is located few centimeters under the outer bracing panel. Results at this place are discussed based on simulation results, either with WUFI Pro (using indoor and outdoor climate from field measurements) or with WUFI Plus software (when data on occupation and heating load are also available).

The office building in Franière (Building n°1) was built in an industrial hall and is not submitted to rain or sun. Therefore, the analysis of occupation and heat load was simplified. All data were analyzed with WUFI Plus software. The behavior of all walls was validated (no decomposition will occur). A relatively good agreement between measured relative humidity and simulation results were observed (i.e. less than 5%). Inside temperature from simulation follows the same trend as measured values, but do not decrease as fast at night and during the week-end. Additional research on occupation profile and ventilation rate should help to calibrated more precisely the simulations (e.g. in terms of CO2 concentration of inside environment).
In Tongrinne (Building n°2), west wall seems to have a problematic behavior as the relative humidity in the straw under the bracing panel is often higher than 91.4%. In addition, simulation results indicate that the wall may have a moisture accumulation problem. However, other simulations using test reference year (TRY) in Belgium did not confirm this result, and a new analysis of monitored data should take place after summer period. This uncertainty may come from unknown material parameters of outer render added on prefabricated straw bale walls.

The second wall in Tonginne is a retaining wall. Unfortunately, one sensor (under bracing panel) does not send any data. The simulation is rather positive as it shows that on a longer period, the humidity of the wall should decrease under critical value. A special attention will be given to this wall in the future as it is normally avoid designing retaining wall with straw bales.

In Building n°3 (in Uccle), simulation results did not fit measurements. Again, this could be due to unknown material parameters of outer render added on prefabricated straw bale walls. In addition, west wall is submitted to driving rain, but no rain measurement was implemented in this case. Further analysis of this building is needed to validate hygrothermal behavior of the walls. Nevertheless, measured values are not considered to be critical (only few days over 91.4%) in this case.

If many data can still be not explored, the monitoring implemented in three straw bale buildings can already confirms that it is possible to design and validate straw bale walls based on a single quantified criteria: moisture content of straw few centimeters under the bracing panel. More research is needed to understand the link between critical moisture content and other parameters (density of the straw bale, type of plant, forming process of the bale…).

In the meantime, straw bale walls can be trusted to design high efficiency house and to offer comfortable and sustainable living places.

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REFERENCES

Microclimatic Effects of Individual Trees with Their Transpiration

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ABSTRACT

This paper quantifies whole-tree transpiration rates for urban tree species using a weighing lysimeter and identifies the microclimatic cooling effect of the individual trees. A novel weighing lysimeter was developed for measuring the whole-tree transpiration rate with a high degree of accuracy. Eleven urban tree species were selected and their whole-tree transpiration rates were measured during the summer season. The daily transpiration amounts of the selected trees, whose heights ranged from 3 m to 7 m, varied from 10 kg to 30 kg under clear skies and water supply conditions. The ratio of the daily transpiration amount to potential evaporation was $0.6 \pm 0.3$ when using the standard of crown projection area. The vapor diffusion conductance peak appeared during the morning, and that of transpiration appeared in the afternoon under clear sky conditions. The peak values of transpiration rates for tree species that showed large transpiration amounts were over 3 kg/h. This value is equivalent to more than 2 kW of latent heat flux. The peak values of transpiration rate and vapor diffusion conductance decreased as soil water content decreased, and the latent heat flux decreased from 2 kW to 0.7 kW by the water stress of the tree. This means that the cooling effect decreased to one third. The relationship between vapor diffusion conductance and soil water content was hysteretic when the soil water content was varied by the water-supply stop test. A decrease in vapor diffusion conductance appeared two days after the water supply was terminated, and it recovered three days after water supply resumption.

INTRODUCTION

In order to understand the microclimatic cooling effects of trees in urban spaces, it is important to quantify their transpiration rates and latent heat fluxes, taking into account species characteristics and soil water content. In previous studies that dealt with the transpiration of trees, transpiration characteristics were reported and compared among different tree species and sizes (Chen et al. 2011; Peters et al. 2010). Whole-tree transpiration rates in these studies were mainly estimated by sap flow measurement using the Granier method (Köstner et al. 1998), or via transpiration measurements for several leaves using the porometer method (DeRocher et al. 1995). However, these methods provide an indirect estimation of whole-tree transpiration, and it has been difficult to obtain accurate whole-tree transpiration rates. Therefore, differences in whole-tree transpiration rates between differing species and tree sizes are uncertain, as is the averaged value of the transpiration rate among tree species in urban environments.

Whole-tree transpiration measurement data are important and useful for assessing the environmental performance of built environments, including urban greening, as well as for the selection of input and validation data for microclimate simulations. In Japan, the Japanese government has

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promoted the use of CASBEE (Comprehensive Assessment System for Built Environmental Efficiency) (Murakami et al. 2014), which has been developed by the Japan GreenBuild Council (JaGBC) and the Japan Sustainable Building Consortium, for use in building developments by construction companies, design offices, and real-estate developers. CASBEE-HI (Heat Island) is a component of CASBEE, and is focused on the evaluation and promotion of countermeasures that can mitigate the urban heat island effect. In CASBEE-HI, the cooling effect of tree transpiration is simply evaluated using data from forests and trees under different conditions, therefore, the applicability of the data and the reliability of the evaluation criteria have been discussed in both academic fields and in terms of practical use (Teshirogi and Koshimizu 2011). This discussion has been spurred by a lack of reliable and applicable data for urban trees and the above issue is indicative of the importance of measurement data related to whole-tree transpiration.

This paper reports a novel attempt to measure whole-tree transpiration rates for urban tree species by use of a large weighing lysimeter, and compares the transpiration rates and cooling effects among these tree species. In addition, the effect of soil water content on the transpiration rate is examined for *Zelkova serrata* during the summer season. The obtained data will contribute to the creation of a fundamental database for heat island countermeasures using urban trees.

**METHODS**

**Materials and Site**

Previous studies of plant physiology have discussed the effects of leaf life-span (evergreen or deciduous), xylem porosity, trunk diameter (sapwood area) and tree height on transpiration characteristics. The leaf life-span correlates with photosynthetic capability and xylem porosity, while trunk diameter and tree height affect the water supply capability to the leaves. In the present study, we selected 11 tree species for the comparison experiment, taking into account leaf life-span (evergreen and deciduous) and xylem porosity. Table 1 shows the selected trees and their characteristics. The tree heights varied from 3 m to 7 m in the year 2012, during which many of the measurements were conducted. These trees were planted in individual large planters with areas of 1 m² and depths of 0.6 m.

The measurement site is an experimental field with an area of 8800 m² in Miyoshi city of Aichi prefecture, Japan. The positions of the trees are shown in Figure 1 and Figure 2. The distances between the trees were greater than 4 m, so that each tree could easily receive solar radiation and air flow. This planting condition was considered for application of the experimental results to urban environmental conditions.

Table 1. Trees characteristics and daily transpiration values

<table>
<thead>
<tr>
<th>Species</th>
<th>Leaf Life-span [month]</th>
<th>Xylem Porosity</th>
<th>Crown Projection Area (8 points) [m²]</th>
<th>Tree Height [m]</th>
<th>Basal Diameter [cm] (below the lowest living branch)</th>
<th>Trunk Diameter [cm]</th>
<th>Daily Transpiration [kg/tree/d]</th>
</tr>
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<td>Z. s. 2012</td>
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<td>9.2</td>
<td>6.4</td>
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<td>Q. m. 2012</td>
<td>36</td>
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<tr>
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<td>Diffuse</td>
<td>6.9</td>
<td>4.7</td>
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<td>9</td>
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<td>4.1</td>
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<td>8</td>
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</table>

30th INTERNATIONAL PLEA CONFERENCE
16-18 December 2014, CEPT University, Ahmedabad
Measurement devices and methods

Whole-tree Transpiration Rates. In order to accurately measure whole-tree transpiration, weighing lysimeters were developed using weighing load cells (Asawa et al. 2012). Whole-tree transpiration rates were measured by the change in tree weight within the planter. For the long-term measurement of *Zelkova serrate*, a platform weighing machine (Sartorius AG, CAPS4-1500LL-I) was used. The water balance was also measured, including the amount of supply and drainage water. The evaporation from the soil surface was restricted by a cover, and the soil surface was shielded from rain water by a shed. Therefore, the weight change was clearly identified as the transpiration rate. For short-term measurements of the other tree species, S-type load cells (Minebea, U3S1-100K~5T-NS) were used. The planter was suspended by the load cells at three points, and the weight change was measured (Figure 3). In outdoor experiments, wind can be the source of noise and error in weighing measurements. In the previous study, we showed that this method removed the effects of wind by allowing the selection of data recorded when the fluctuation of weight values were small and stable in a short time span, and we confirmed that the measurement error of whole-tree transpiration rates was within 100 g/h when wind velocity was below 1.5 m/s (Asawa et al. 2012).

<table>
<thead>
<tr>
<th>Measurement devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (Tree=Soil+Planter)</td>
</tr>
<tr>
<td>1) <em>Zelkova serrata</em></td>
</tr>
<tr>
<td>2) Other species</td>
</tr>
<tr>
<td>Soil water content</td>
</tr>
<tr>
<td>ADR soil moisture sensor</td>
</tr>
<tr>
<td>Air temperature</td>
</tr>
<tr>
<td>Relative humidity</td>
</tr>
<tr>
<td>Global solar radiation</td>
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<tr>
<td>Photonsynthetic photon flux density</td>
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<tr>
<td>Wind direction and wind velocity</td>
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<td>Photosynthetic photon flux density</td>
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<td>Precipitation</td>
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<tr>
<td>Tipping bucket type rain gauges</td>
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<td>Tipping bucket type rain gauges</td>
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</tbody>
</table>

Meteorological Data and Water Balance. The meteorological data was measured at the northern part of the experimental field. The measurement devices are shown in Table 2. The measurements consisted of global solar radiation, air temperature, relative humidity, three-dimensional wind direction and velocity, and photosynthetic photon flux density. The measurement height for wind direction and velocity was 4 m. Soil water content was measured by an ADR soil moisture sensor with a ThetaProbe. The water supply and water drainage volumes were measured by tipping bucket-type rain gauges. The water supply volume was fully controlled and the water supply was automatically implemented at midnight on each day.

Measurement Periods and Conditions. The transpiration rate of *Zelkova serrate* was measured continuously from July 2010 to the end of 2013. During the water stress test for *Zelkova serrate*, the water supply was stopped for several days. The transpiration rates of the other ten species were
measured for about two weeks in the summer of 2012 and 2013, and three species were measured at a time. The results obtained during clear sky days were selected and used for the analysis, so as to select data gathered under identical conditions.

**Estimation of Vapor Conductance.** The transpiration from a leaf can be described as a vapor diffusion process, and expressed in an equation as the product of vapor pressure deficit and vapor diffusion conductance. The physiological characteristics of transpiration, including stomatal control, find expression in the vapor diffusion conductance. The vapor pressure deficit is the difference between the saturated vapor pressure of the leaf and atmospheric vapor pressure. In this study, whole-tree vapor diffusion conductance is estimated by Eq. (1) using measured whole-tree transpiration rates and vapor pressure deficit. Eq. (2) shows the components of vapor diffusion conductance.

\[
G = \frac{ET}{W} \quad (1)
\]

\[
G = \frac{1}{(r_a+r_s)} = g_a \cdot g_s / (g_a+g_s) \quad (2)
\]

**RESULTS AND DISCUSSION**

**Comparison of Transpiration Rates among Urban Tree Species**

**Daily Transpiration Amount.** The measured daily transpiration amounts are shown in Table 1. For *Quercus mirsinifolia*, the transpiration rate was measured in both 2012 and 2013, because the tree had been moved from an area enclosed by other trees to an open space before the 2012 measurement. The tree species that showed the largest daily transpiration amounts were *Zelkova serrata* (2010), *Quercus serrata* and *Cinnamomum camphora*, the values of which were approximately 30 kg. The next largest amounts were observed in *Quercus mirsinifolia* (2013), *Quercus acutissima* and *Zelkova serrata* (2012), which showed values of approximately 25 kg. In contrast, the smallest transpiration amounts were observed in *Quercus mirsinifolia* (2012), *Styrax japonica* and *Magnolia sellata*, with these species showing values of approximately 10 kg. The transpiration amounts of *Zelkova serrata* and *Quercus mirsinifolia* largely varied from year to year. Although the leaf area of *Zelkova serrata* increased from 15.4 m² in 2010 to 28.9 m² in 2012, the transpiration amount slightly decreased. Water conductance in trunks and branches are restricted by the area of the roots and sapwood, therefore, the maximum transpiration value of *Zelkova serrata* was 30 kg/day under the conditions of planter size (1 m × 1 m × 0.6 m) and trunk diameter (0.1 m). In contrast, for *Quercus mirsinifolia*, although the crown shape and leaf area did not change considerably from 2012 to 2013, the transpiration amount increased by a factor of three. These findings indicate that photosynthetic ability largely increased due to the change in tree location from an enclosed space to an open space, which resulted in changes in the surrounding conditions.

**Diurnal Changes of transpiration rate and latent heat flux.** Figure 4 shows diurnal variations in transpiration rate, vapor diffusion conductance and latent heat flux for 11 tree species. A peak in transpiration rate appeared in the afternoon for tree species that showed large transpiration amounts. In contrast, for trees that displayed small transpiration amounts, the peak appeared in the morning. The peak values for *Zelkova serrata* (2010), *Quercus mirsinifolia* (2013), *Quercus serrata* and *Cinnamomum camphora* were over 3 kg/h. This value is equivalent to more than 2 kW and 400 W/m² of latent heat flux. A peak in transpiration rate for these trees, whose heights ranged from 3 m to 7 m, varied from 1.3 kg to 3.6 kg. These values are equivalent to the range from 880 W to 2400 W for latent heat flux. Therefore the difference in cooling effect was approximately 1500 W between these trees. Peaks in vapor conductance appeared in the morning and the values decreased into the afternoon for all species. This result indicates that the stomata were closed in the afternoon, during which solar radiation and vapor pressure deficit were high, so as to minimize the water deficit. The species with small transpiration amounts were more sensitive to the water deficit than those exhibiting large transpiration amounts.
Analysis of Daily Transpiration Amount Based on Potential Evaporation

**Priestley–Taylor Equation.** Transpiration is influenced by meteorological conditions, so this section analyzes and compares the transpiration characteristics among these tree species based on the standard of potential evaporation (ET\textsubscript{pot}). ET\textsubscript{pot} is estimated by the Priestley–Taylor equation (Eq.(3)) (Priestley and Taylor 1972).

\[
\lambda E = 1.26 \frac{S}{S + Y} (R_n - G)
\]

(3)

The Priestley–Taylor equation is a semi-empirical model that predicts the evaporation rate of water surfaces based on the heat balance. The coefficient, 1.26, on the right side on the equation was empirically obtained from measurements on water surfaces, on which there was no horizontal advection. The heat conduction, G, was assumed to be negligible in this study.

**Creation of a Database of Daily Transpiration Amounts Per Ground Area.** Figure 5 shows the ratio of the measured transpiration amount to potential evaporation (ET/ET\textsubscript{pot}) during clear sky and water supply conditions. In the field of hydrology and meteorology, the crown projection area is generally used as a standard when comparisons are made with potential evaporation. In this study, the area of the planter (1m × 1m) is also used as a standard, as well as the crown projection area.

The average and standard deviation of ET/ET\textsubscript{pot} was 0.6 ± 0.3, when using the standard of crown projection area. The reason why this averaged value was smaller than 1 is that the stomata restricted transpiration to prevent water loss. This result corresponds to previous measurements made in forests and croplands. Although ET/ET\textsubscript{pot} is smaller than 1 on average, *Cinnamomum camphora* displayed a value of 1.1 in this experiment. It is considered that the transpiration amount of *Cinnamomum camphora* is large for its crown size, and that the transpiration rate per LAD and leaf area is also high.
The averaged value and standard deviation of $\frac{ET}{ET_{pot}}$ was $2.7 \pm 1.1$ when using the standard of planter area, and this large value is due to the fact that the transpiration area of the crowns is much larger than the planter area. This result indicates that the planting of tall trees is more effective than the use of water surfaces in urban spaces, because the space under the crown can be used while obtaining the cooling effect.

**Influence of species and crown features.** Figure 6 shows $(\frac{ET}{ET_{pot}})$ for all tree species when using the standard of planter area. In general, there is a correlation between whole-tree transpiration and leaf area, so it is considered that there is also a correlation between whole-tree transpiration and the crown projection area and basal diameter. However, an obvious correlation could not be confirmed in Figure 6. In future studies, we intend to analyze the effect of LAI (Leaf Area Index) and LAD (Leaf Area Density) on whole-tree transpiration.

Focusing on differences in xylem porosity, *Quercus acutissima*, *Zelkova serrata* and *Quercus serrata*, which are ring-porous and have thick trachea, showed relatively large transpiration amounts. In general, the photosynthetic rate is inversely proportional to leaf life-span, and transpiration and photosynthesis are simultaneously controlled by the stomata. Therefore, we expected a difference in transpiration amounts based on leaf life-span (evergreen or deciduous), but any clear differences were not observed.

**Relationship between Soil Water Content and Transpiration**

Transpiration characteristics depend on soil water content. In many urban spaces, planted trees often suffer from water stress, due to insufficient precipitation and water supplies (Kagotani et al. 2013). Figure 7 shows measurements collected during the water stress test, in which the water supply was stopped for three days from August 24 to 26, 2010. The soil water content shown in Figure 7 is the
averaged value of five measurements taken at different depths. The transpiration rate and vapor diffusion conductance decreased as soil water content decreased. The peak value of the transpiration rate and vapor conductance decreased to one third and one half, respectively, from August 24 to 26. The peak value of latent heat flux decreased from 2 kW to 0.7 kW by the water stress of the tree. This means that the cooling effect decreased to one third. Although the water supply was resumed early on the morning of August 27, the transpiration rate on the day was almost equal to that observed on August 26. Therefore, transpiration did not recover quickly from water stress.

Figure 8 shows the transition in soil water content and vapor diffusion conductance during the water stress test. The relationship between soil water content and vapor conductance was hysteretic after the water supply was halted and resumed. A decrease in vapor conductance appeared two days after the supply of water was stopped, and it recovered three days after water supply resumption. This finding suggests that soil water content levels should be considered during any evaluation of the cooling effects of trees in urban environments.

Figure 7. Relationship between transpiration rate and soil water content (Zelkova serrata)

Figure 8. Transition in soil water content and vapor diffusion conductance (Zelkova serrata)

CONCLUSIONS

This paper shows the characteristics of whole-tree transpiration rates for urban tree species, using a weighing lysimeter. The daily transpiration amounts of the trees, whose heights ranged from 3 m to 7 m, varied from 10 kg to 30 kg under clear sky and water supply conditions during the summer. The ratio of the daily transpiration amount to potential evaporation was 0.6 ± 0.3, when using the standard of crown projection area. The vapor diffusion conductance peaks appeared in the morning, and that of transpiration appeared in the afternoon under clear sky conditions. The peak values of the transpiration rate for tree species that displayed large transpiration amounts were over 3 kg/h. This value is equivalent to more than 2 kW and 400 W/m² of latent heat flux. A peak in transpiration rate for these trees varied from 1.3
kg to 3.6 kg. These values are equivalent to the range from 880 W to 2400 W for latent heat flux and the difference of 1500 W is regarded as the difference in the cooling effect. The peak values of transpiration rate and vapor diffusion conductance decreased with soil water content. The cooling effect of the tree decreased to one third when the tree was under water stress. The relationship between vapor conductance and soil water content was hysteretic when soil water content was varied by the water-supply stop test. A decrease in vapor diffusion conductance appeared two days following the cessation of the water supply, and it recovered three days after water supply resumption. This observation suggests that soil water content levels should be considered for the evaluation of the cooling effect of trees in urban environments.

ACKNOWLEDGMENTS

We express gratitude to the TOYOTA Motor Corporation, Biotechnology & Afforestation Business Division for their assistance with the experiments.

NOMENCLATURE

\( ET \) = Whole-tree transpiration rate [mol/(m\(^2\)s)]
\( ET_{pot} \) = Potential evaporation [mol/(m\(^2\)s)]
\( G \) = Vapor diffusion conductance [mol/(m\(^2\)s)]
\( W \) = Vapor pressure deficit [kPa/kPa]
\( r_a \) = Boundary layer resistance [m\(^2\)s/mol]
\( r_s \) = Stomatal resistance [m\(^2\)s/mol]
\( g_a \) = Boundary layer conductance [mol/(m\(^2\)s)]
\( g_s \) = Stomatal conductance [mol/(m\(^2\)s)]
\( \lambda \) = Latent heat of vaporization [J/mol]
\( E \) = Evaporation rate [mol/(m\(^3\))]
\( s \) = Slope of the saturation vapor pressure-temperature relationship [K\(^{-1}\)]
\( \gamma \) = Psychrometric constant [K\(^{-1}\)]
\( R_n \) = Net radiation [W/m\(^2\)]
\( G \) = Conductive heat flux into ground [W/m\(^2\)]

REFERENCES

Assessment of the double-skin façade passive thermal buffer effect

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ABSTRACT

Double Skin Façades (DSFs) are becoming increasingly popular architecture for commercial office buildings. Although DSFs are widely accepted to have the capacity to offer significant passive benefits and enable low energy building performance, there remains a paucity of knowledge with regard to their operation. Identification of the most determinant architectural parameters of DSFs is the focus of ongoing research. This paper presents an experimental and simulation study of a DSF installed on a commercial building in Dublin, Ireland. The DSF is south facing and acts to buffer the building from winter heat losses, but risks enhancing over-heating on sunny days. The façade is extensively monitored during winter months. Computational Fluid Dynamic (CFD) models are used to simulate the convective operation of the DSF. This research concludes DSFs as suited for passive, low energy architecture in temperature climates such as Ireland but identifies issues requiring attention in DSF design.

INTRODUCTION

A Double Skin Façade (DSF) or Multi Skin Façade (MSF) is generally composed of a glazed curtain offset from the line of the building envelope (Figure 1). DSFs have continued to increase in popularity, particularly in commercial architecture, yet still today there remains a paucity of comprehensive studies proving the benefit of DSFs in different climate regions, and at different seasons. Although there are many published case studies e.g. (Hashemi, Fayaz, & Sarshar, 2010) (Pasquay, 2004) a lack of reliable experimental data and validated simulation studies is oft commented in the literature (Gertis, K., 1999) (H. Manz, Schaelin, & Simmler, 2004).

Ever more studies of DSF systems are required as their characteristics and operation are directly related to the climate in which the building is located, with solar radiation, wind and ambient air temperature all having an impact. This paper presents an experimental study focused on the temperature profile in a DSF in the maritime Irish climate during winter. This experimental study will form the basis for an extensive Computational Fluid Dynamic (CFD) study of different configurations of MSFs in the maritime climate. This study will in turn enable an evaluation of the appropriateness of MSFs in the context of the Irish climate and their ability for energy savings and comfort enhancement in Irish buildings.

DSFs are generally designed for different operation in summer and winter conditions. During Irish summer months DSFs generally operate in the ‘open’ mode. This implies that vents are opened at the bottom and top of the façade cavity. The air in the cavity removes excess heat by means of convective
flow induced by the stack effect. This action prevents excessive heat accumulation in the cavity. If this occurs unwanted heat can transmit into the internal spaces. This can have a significant impact on the thermal comfort conditions within the building and create a greater necessity for the use of auxiliary cooling systems, hence resulting in an increase in energy consumption.

When the air is cleared from within the cavity, the temperature of the building envelope skin is lowered and heat transfer from the internal skin to the occupied space is reduced. Accordingly less heat is transferred from the outside to the inside, and less energy is required to cool the space.

In winter common DSF operation utilizes a sealed cavity, with no air circulation. For the winter scenario, the DSF cavity is warmer than the exterior temperature. As the air in the cavity is heated by the sun the temperature of the envelope skin increases and the temperature difference across the envelope skin reduces. Accordingly less heat is transferred from inside the building to the outside given a reduced temperature differential between interior conditioned space and the adjacent thermal zone. Significantly less energy is required to heat the space.

A greater proportion of research focuses on the evaluation and modeling of the summer operation of DSFs (H. Manz & Frank, 2005) with a paucity of investigation of the winter thermal buffer effect. Similarly the majority of studies investigate the airflow in DSFs with less emphasis on investigation of the temperature profiles in the cavity. In an 11 story building in Iranian winter conditions Hashemi et al (Hashemi et al., 2010) document a difference in temperature of 5–12 °C on the 7th floor and on 11th floor 7.5–10.5 °C more than the outside temperature. Vertical thermal stratification in the cavity is common in DSFs. The heated air in the cavity rises due to natural buoyancy, and a drop in air velocities at the top of the cavity leads to stratification. Thermal stratification is identified in monitored data (Hashemi et al., 2010) and simulation studies of mechanically ventilated facades (Pfühler, Sikorski, & Kuhn, 2012). Hamza and Abohela (Hamza & Abohela, 2013) present an exploratory study of cavity stratification in non-uniform DSFs. Thermal stratification in the cavity has been shown to be influenced by a number of design and climatic parameters including solar radiation levels, shading device use and their colour, depth of the cavity of the double-skin, glazing types on both façade layers and design of inlets and outlets in relation to prevailing wind direction and speed amongst others.

This paper presents an experimental monitoring study of the temperature profile in the DSF of a commercial building in Dublin, Ireland that will form the basis of an extensive and validated modeling study of the appropriateness of DSF for this and similar climates. The impact of solar radiation levels, surface and cavity temperatures on DSF operation are presented.

**EXPERIMENTAL METHODOLOGY**

Experimental monitoring of a case study DSF is presented with focus on temperature characterization. Temperatures in the DSF were extensively monitored, with 9 temperature sensors installed on the three floors of the cavity. Interior temperature and external temperature are also monitored. Surface temperature readings were taken at intervals. Solar irradiance data was also attained for the location.

The DSF under consideration in this study is installed on the upper stories of an office building in Dublin, Ireland. It is a three-story façade (width x depth = 12m x 0.7m), is south facing and composed of external double-glazing and a single interior sheet of glass. The air cavity includes timber sun-shading louvers that drop approx. 750mm from the top of each level, are 250mm wide and horizontal. Automated venetian blinds shade the building envelope skin, and adjust their angle throughout the day. A metal grill divides each level of the DSF, which enable accessibility to each level and air movement between levels.

Although the DSF is analyzed in the ‘closed’ state there are 10mm gaps between the 100mm louvers, which allow ingress and exhaust of air. Such small openings have been shown to generate significant air flows (Gratia & De Herde, 2004).
Dublin is located on the eastern coast of Ireland, on the northwestern periphery of Europe (latitude: 53°20′N and longitude: 6°15′W). It has a temperate maritime climate, of mild winter and summer seasons.

RESULTS

Winter temperatures were measured from January to April 2014. The following figures document the typical observed temperature profile for the DSF.

**Cavity temperatures.** The temperature in the 3 Levels of the cavity over a typical 4-day period in February is shown in Figure 2.

![Figure 2](image)

**Figure 2.** Temperature profile over 4 days of a typical sunny winter week, with outdoor temperatures in an 8-15°C circadian swing. Solar radiation is shown in brown and scaled to (W/m²)/10.
The results show that $T_{cav}$ during the day and night exceeds $T_o$ on all levels except Level 1 of the cavity. The air temperature on Level 1 deviates little from the outdoor temperature but is often below even when exposed to high solar radiation. This phenomena is further shown in Figure 3 and 4. The outside temperature fluctuates in a 6°C range, whereas the temperature fluctuations in Level 2 and 3 are in the range 20-28°C on different days. This is in contrast to other studies in winter conditions that show the fluctuation in $T_{cav}$ to be less than that of the outside temperature (Hashemi et al., 2010). The temperature difference between the cavity temperature on Level 2 ($T_{cav2}$) and outside is 18°C at midday and 2-3°C at night. Similarly for Level 3, $T_{cav3} - T_o$ is approx. 20°C at maximum and 2-3°C at nighttime. Maximum $T_{cav3}$ reaches 35-39°C, when the outdoor temperature is 15°C. These high cavity temperature on the upper levels reduce the temperature difference across the building envelope, thereby impacting the heat loss across this boundary.

**Temperature and solar incidence.** Figure 3 and Figure 4 show the solar irradiance and the temperature on each level of the DSF for typical sunny and overcast days, characterised by high and low solar radiation. $T_o$ differs by 5°C between the days shown. However, $T_{cav3}$ is almost 18°C higher on the sunnier and warmer day, showing the significant impact of solar radiation on a closed cavity in winter in sunny conditions.

Vertical thermal stratification is evident between the different facade levels with a large jump from the inlet level ($T_{cav1}$) to the middle of the facade ($T_{cav2}$) of up to 12-15°C.

In contrast on a typical overcast day the temperature in $T_{cav1}$ is 2-3 greater than $T_o$. It is difficult to explain this given that all Levels of the cavity are exposed to high solar radiation with no overshadowing. The surface temperatures of the walkway grill and glass at Level 1 are significant lower than temperatures at other levels and these possibly act to reduce the air temperatures in

![Figure 3. Temperature profiles for each level of the facade on a typical sunny day. Solar radiation (brown) is scaled to (W/m²)/10.](image-url)
Surface and cavity temperatures. Outdoor, indoor and cavity air, and boundary layer surface temperatures are shown in Figure 5. On this day the temperature in the interior space is controlled by the BMS from rising above 24°C. The surface temperature of the internal face of the building envelope boundary gains heat from the auxiliary internal space heating. Although Figure 5 shows temperatures for a discrete day of average solar radiation, the temperature profiles display a common trend on the different levels. The temperature gradient across the building envelope glazing surface drops in the upper floors; $T_{\text{env\_ext\_3s}} - T_{\text{env\_int\_3s}} = 3.5^\circ$C and $T_{\text{env\_ext\_3s}} - T_{\text{env\_int\_1s}} = 1.5^\circ$C. The gradient in surface temperature in Level 1 in contrast, increases $T_{\text{env\_ext\_1s}} - T_{\text{env\_int\_1s}} = +5.8^\circ$C.

As expected, and similar to results reported by studies in hot arid climates Hamza et al (Hamza, Gomaa and Underwood, 2007), the surface temperature on the in-cavity surface of the exterior glazing of the DSF ($T_{\text{dsf}}$) is lower than the surface temperature of the in-cavity surface of the building envelope glazing ($T_{\text{env\_ext}}$).
In Figure 5, Levels 2 and 3 cavity temperatures ($T_{cav2}$, $T_{cav3}$) are approximately equal to the indoor air temperatures ($T_{Lev2a}$, $T_{Lev3a}$). On Level 1 the cavity air temperature is significantly lower than on Level 2 and 3 (approx. 5°C lower) and on Level 1 the air temperature in the cavity is lower than that in the conditioned space in the building interior.

SIMULATION STUDIES

Data presented in this paper is being used as the basis for a comprehensive simulation study of (i) zonal energy analysis using EnergyPlus and (ii) CFD modeling study using ANSYS. Further monitoring is planned during coming summer and winter seasons to enable validation of CFD and energy models. This will enable assessment of the specific conditions a DSF can benefit building performance and the optimum configuration and operation of the façade to enable passive heating and cooling and hence energy savings for the building. Airflow patterns in the closed and open states are investigated for turbulent and laminar patterns given different boundary conditions.
CONCLUSION

Due to these higher air temperatures in the cavity relative to the outdoor temperature the external walls lose heat more slowly. This is beneficial to preheating of the inside spaces and heating energy conservation. However, in the DSF close to the building envelope the air temperature is often significantly higher than the heating set point implying a reversal of the standard winter temperature gradient seen across single skin building envelopes. Hence, the DSF can act to increase the internal air temperature even causing overheating, when the building is in free running mode. On days of high solar radiation levels it is proposed that the cavity be ventilated. Again this is not the case in Level 1, where the cavity temperature is regularly up to 10°C lower. Hence, the thermal buffer benefit of the DSF at the lower level is not discernible.

In contrast to many studies in the literature this study documents a consistently lower inlet temperature than outdoor air temperature. Saelens et al (Saelens, Roels, & Hens, 2004) demonstrated that the difference between the inlet temperature and the outdoor air temperature depends on the solar intensity and airflow rate. With solar radiation they showed the inlet temperature to be higher than the
outdoor temperature, as did other authors (Heinrich Manz, 2004) (Fuliotto, 2010). Based on a review of these studies He et al (He, Shu, & Zhang, 2011) use a constant difference of +4°C difference in the summer case and +2°C difference in the winter case, between the inlet temperature and outdoor air temperature.

Based on standard heat loss assessment through the building envelope the DSF can be beneficial to

ACKNOWLEDGMENTS

The authors would like to thank Arup for enabling this research and for the case study building.

NOMENCLATURE

\[ T_{\text{cav}X} \] = air temperature in cavity

\[ T_{\text{dsf}X} \] = surface temperature on external skin of dsf

\[ T_{\text{env\_ext\_Xs}} \] = surface temperature on external skin of building envelope

\[ T_{\text{env\_int\_Xs}} \] = surface temperature on internal skin of building envelope

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Low-Energy Industrial Buildings for Climates of Emerging Countries

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ABSTRACT

The economic growth of developing and emerging countries pushes particularly the industrial sector, why a large demand for new industrial buildings arises. Though in many of these markets there is no traditional climate adapted architecture for industrial buildings as it mostly exists for dwellings. Thus many buildings for industrial applications are mainly built after European or American standards without respecting the local climate. Missing or misleading building regulations as well as missing general awareness and know-how in the local communities enhance this problem. The risk is to build a new generation of industrial buildings in these countries, having an unnecessary high energy demand for heating and cooling just by neglecting the climatic characteristics. Therefore this study proves the applicability of European concepts for low-energy industrial buildings for different climates for example from Russia and North Africa. Parameters such as air-tightness, window quality, solar orientation, thermal insulation and radiation reflectivity are analyzed and adjusted for optimizing the energy demand. The reduction of summer overheating is further under consideration because the post-installation of air conditioning systems should be avoided at any rate. For this purpose transient building simulations and air-flow-network simulations are used. As the basis for simulations of air-infiltration by appropriate product specific models, typical industrial building components are measured in an air-tightness test stand. The project focuses on light steel structure buildings which are often exported from Europe and the U.S. to emerging and developing markets. It is demonstrated how the energy demand of such buildings can be decreased already by small but efficient design changes.

INTRODUCTION

Emerging Countries mainly gain their economic growth by the industrial sector for which low labor cost and natural resources are usually the push factors. Thus a particular demand for new industrial buildings arises in these countries. However as large scale industry has often no tradition in these newly industrializing countries there is even little experience in buildings for industrial applications. For dwellings there is usually a long building tradition that was adapted for the local climate. But production buildings or plants are often imported from western regions such as Europe or the US. Due to the shipping constraints such imported buildings are usually built in light steel structure. Their design is typically executed in the producing country why the local climate and environment is often not well considered. Furthermore many of the companies settling down in threshold countries are global players who have already standardized their production buildings based on western climate requirements. Often only the insulation thickness is simply increased or decreased whether the building will be erected in a...
“warm” or “cold” climate. Other parameters such as window orientation or air-tightness are rarely recognized. Moreover the local authorities do not always have the expertise to assist and building regulations setting an energy standard as in Europe mostly do not exist or are at least less elaborated, as e.g. in Russia where the last recast of the building regulations dates from 2003 (SNiP 23-02-2003, 2003). That goes along with a still missing awareness for the need for reducing GHG-emissions. The risk is to build a new generation of industrial buildings having an unnecessary high energy demand. Hence in this project the energy demand for heating and cooling of light steel industrial buildings was analyzed for different climates. These analyses were determined by transient building simulations using the software package TRNSYS.

CLIMATE

As every climate needs an individual design, only general advises can be given in this project to make designers aware for how to reduce the energy demand dependent on the climate. For this purpose two hot North African climates (Casablanca, Morocco and Dar El Beïda, Algeria) and three cold Russian climates (Moscow, Samara and Irkutsk) were selected. Besides Ankara (Turkey) was chosen as this climate is hot in summer and cold in winter. A typical climate for exporting Central European countries is Würzburg, Germany. Exemplary the data for Irkutsk, Dar El Beïda and Ankara is shown in figure 1-3. Most important is the outside temperature, but also the solar radiation, the wind velocity and the temperature difference between day and night have a certain impact on the building performance.

Figure 1  Radiation, temperature and wind velocity (Meteonorm) for Irkutsk (South Siberia)

Figure 2  Radiation, temperature and wind velocity (Meteonorm) for Dar El Beïda (Algeria)

Figure 3  Radiation, temperature and wind velocity (Meteonorm) for Ankara (Turkey)
BUILDING PERFORMANCE

Industrial buildings in warm climates as Dar El Beïda or Casablanca usually never have any heating device. The temperatures during daytime are usually high enough also in winter and the temperature requirements in such buildings are in general quite low. Also cooling devices are still rare due to high investment and energy costs even if a cooling demand actually exists. But the economic growth will allow the installation of more and more air-conditioning systems in the future. To reduce the costs and the emitted GHGs, and of cause to improve the thermal comfort, the focus must therefore be set on overheating protection. Post-installation of cooling devices caused by misleading building design should be avoided at any rate. For the cold Russian climates cooling is not required, even if some hot summer days exist in the continental Siberia, but these temperature peaks are usually buffered by the thermal mass of the interior and the concrete slab. Most difficult is the design for climates like in Ankara, where the average temperature in July and August reaches 23 °C and in January it goes down to 0 °C. To find the right balance between a passive solar building and reduced summer overheating is the challenge.

Summer Overheating

The main summer overheating problems arise by wrong orientation of glazed surfaces. Movable shading devices are often not applicable and usually too expensive for industrial buildings. As summer overheating is a minor problem in Central Europe and as illumination is easy to ensure with horizontally oriented glazed surfaces, many exported industrial buildings have skylights. Figure 4 shows the simulated influence of the orientation and size of glazed surfaces in a typical light steel industrial building (1950 m² ground area, concrete slab). Internal loads by machines were considered with 40 W/m², as also used for production buildings in (DIN V 18599, 2011), based on (VDI 3802, 2003). In figure 4 the overtemperature degrees over 27 °C are shown. This method is used in Germany to limit overheating (DIN 4108-2, 2013). It sets a limit of 500 Kh per year which must not be exceeded if no air condition exists. Figure 4 shows that this limit is usually not reached in Central European climate why skylights are less critical. In warm climates like Ankara or Casablanca the horizontal orientation of glazed surfaces causes vast overheating if no air-condition exists and no controlled ventilation is used. If vertical glazed surfaces are used and oriented to the north the overheating is reduced significantly compared to skylights. The vertical south orientation also improves the overheating but for buildings without any heating demand the north should always be preferred. West and east oriented glazing is usually critical as well why for deeper buildings a combination of north and south oriented glazed surfaces in the facades is reasonable for North African Climate. For maritime climates like Casablanca the climate can already get tolerable by avoiding skylights. But for continental climates like Ankara other actions are required.

Figure 4    Overtemperature degrees (Kh/a > 27 °C) for different climates and glazing orientations
Figure 5 shows the impact of a controlled ventilation which is always turned on when the inside temperature exceeds the outside temperature. Costs and energy demand of such ventilations are much lower than of air-conditions. Such mechanical ventilation should also be supported by natural ventilation to save energy, which can reach high ventilation rates like shown for the ventilation of industrial buildings in (Kistelegdi and Háber, 2012). Already existing openings like industrial doors and smoke vents can be used for it. How openings can be optimized for summer ventilation is e.g. analyzed in (Stephan, Bastide and Wurtz, 2011). Cross-ventilation though large openings like industrial doors including wind influences is discussed in (Seifert et al., 2006).

![Figure 5](image)

**Figure 5** Influence of controlled ventilation on the summer overheating

The simulations in figure 5 show that even the German overheating requirements can be met for Ankara with glazed surfaces in the south façade, if there is a strong controlled ventilation. This is mostly due to the high temperature difference between day and night visible in figure 3. For Casablanca with its coast to the Atlantic Ocean the summer overheating is quite easily to reduce by controlled ventilation. At the Algerian coast to the Mediterranean Sea (Dar El Beida) overheating is again much more difficult to avoid. Here the north orientation should always be chosen for window orientation.

In addition to the window orientation and the ventilation also the solar absorptance of the building envelope and the thermal capacitance of the interior are deciding for the thermal comfort in summer. Figure 6 (a) shows that an overheating reduction by low absorbing coatings is possible but the effect is not as important as e.g. night ventilation.

![Figure 6](image)

**Figure 6** (a) Influence of the solar absorptance of the building envelope (roof, walls) (b) Influence of the capacitance of interior on summer overheating (glazing south)
Figure 6 (b) shows the other important parameter, the thermal capacity of the interior. This of course interacts with the ventilation, as a higher capacitance can only reduce the inside temperature if the thermal mass is regularly cooled down by ventilation. The considerable effect is visible but anyway the simulation results can just be seen as an indicator for the importance of thermal mass. The real influence depends on many parameters such as the surface of the interior, the material and its heat-transmission resistance. These parameters will never be assessable in a design process but it is clear that an empty building overheats much easier than a filled storage.

The impact of air-tightness on summer overheating and the cooling demand is very low. In the simulations the differences between the cooling demand of an untight building ($n_{50} = 5 \text{ h}^{-1}$) and a very tight building ($n_{50} = 0.5 \text{ h}^{-1}$) was only about 2%. Anyway big leakages should always be avoided.

Heating Demand

Air-tightness. Aside from the thermal insulation of a building the air-tightness is a major parameter for the energy performance. In many European countries like Germany, UK and France, tightness requirements already exist also for industrial buildings D: (EnEV, 2014), UK: (The Building Regulations 2010, 2013), F: (Méthode de calcul Th-BCE 2012, 2012). Even if these requirements are not always mandatory to meet, verifying the tightness allows lowering the infiltration losses in the energy performance calculation. In Russia unfortunately only tightness requirements for single building components of industrial buildings exist (SNiP 23-02-2003, 2003). To check if these single requirements are met is not possible on site and also fan pressurization tests after erecting the building are usually not carried out. This leads to a lower workmanship on site and probably increases the infiltration. In particular for cold Russian climate this is very critical. As air infiltration is caused by wind pressure and stack effects, beneath the wind velocity also the difference between the internal temperature and the ambient temperature is deciding for the amount of infiltration losses (Brinks, Kornadt, and Oly, 2014a), (Younes et al., 2011). Thus the infiltration in cold climates like Russia is even much higher than in temperate European zones. In warm climates like North Africa, where buildings are not heated and the climate inside and outside is similar during the year, infiltration is rather small (see figure 7). Adapted from measurements in an air-tightness test stand and air-flow network simulations, an infiltration model described in detail in (Brinks, Kornadt, & Oly, 2014b) was developed. This model was used to simulate the infiltration for typical light steel industrial buildings in the here mentioned climates. Detailed information about the air-flow network model is given in (University of Wisconsin Madison, 2009) and (Weber et al., 2003). In figure 7 the results for the infiltration of an 8 m high building (65 m x 30 m) with an $n_{50}$-value of 3 h$^{-1}$ are shown. Due to the low temperatures in Irkutsk the infiltration is much higher during winter than for warm climates like Dar El Beïda.

![Figure 7](image_url)

**Figure 7** Air infiltration for an industrial building ($n_{50} = 3 \text{ h}^{-1}$) in different climates
Figure 8 shows the impact of the tightness on the heat energy demand. Especially for Siberia it is even more important to tighten the building than to increase the insulation thickness of the roof and walls. Reducing the $n_{50}$-value from $3.0 \, \text{h}^{-1}$ to $1.5 \, \text{h}^{-1}$ saves as much energy as reducing the U-value of the roof and all walls from $0.4 \, \text{W/m}^2\text{K}$ to $0.2 \, \text{W/m}^2\text{K}$. In general promising methods for air-tightness design in light steel buildings were already developed e.g. described in (Brinks, Kornadt, and Oly, 2013). But tightness is not only a question of design but of workmanship, thus it cannot be assured, that European standards are realized in Russia as well. Anyway tightness requirements for Russian industrial buildings are currently not existing even if requirements for Russian dwellings are in the range of European standards (SNiP 23-02-2003).

Another important aspect is that infiltration losses via open doors are not recognized at all in any known building regulations or codes. For dwellings such losses may mostly be negligible but losses via large industrial doors can have a large impact on the energy balance. This lack was already discussed in (Brinks, Kornadt, & Oly, 2014c) where rough simulations based on (Dascalaki, E. et al., 1995) were carried out. These calculations already show a significant impact for Central Europe but it seems to be even higher for Russia due to larger buoyancy effects.

Solar Gains and Orientation of Glazed Surfaces. The orientation of glazed surfaces is not only important for summer overheating, but passive solar gains can reduce the energy demand of buildings considerably. For residential and office buildings this is already shown by many studies as (Cappaletti et al., 2014) or (Boubekri and Boyer, 1993) and also first analysis for industrial buildings in Central European climates exist (Brinks, Kornadt, & Oly, 2014d). Figure 9 shows how the heating demand changes for different oriented glazed surfaces (40 mm polycarbonate, $U = 1.10 \, \text{W/m}^2\text{K}$, $g = 0.56$) in Russian climates. Here a low-energy production building with 17 °C inside temperature, 40 W/m² internal gains, an $n_{50}$-value of 0.5 h⁻¹ and a U-value of walls and roofs of 0.20 W/m²K was simulated. Due to the high solar radiation in Irkutsk during winter (approximately twice as high as in Central Europe), here the orientation has the most significant impact.
Installing large glazed surfaces on the south façade instead of skylights can reduce the energy demand by up to 30% if the façade is not shaded. For Moscow the effect is smaller as the solar radiation is lower. Anyway in Russian climates it is advised to use as much glazed surfaces in south façades as possible if facades are not shaded. The glazing quality, particularly a high g-value, is of course to be respected. In climates like Ankara with hot summers and cold winters the situation is more complex. Thus the impact of the glazing orientation and surface on the energy demand for both, heating and cooling, was simulated. The results in figure 10 show that increasing the glazed surface in general decreases the heating demand and increases the cooling demand. But the leverage effect of this parameter is different for all orientations. For the south façade the total energy demand (heating + cooling) decreases with a larger glazed surface. For the north façade it increases slightly and for the horizontal (skylights) it increases considerably. This means that increasing the horizontal glazing area should usually be avoided. Anyway general advises to increase the glazed south façade area in such climates cannot be given. This decision depends on if a cooling device is installed at all and which (primary) energy is used for heating and cooling. Thus a decision has to be taken individually for any project.

![Figure 10](image)

**Figure 10**  Energy demand for heating and cooling dependent on the glazed surfaces for Ankara

**CONCLUSION**

The building simulations carried out show the consequences of exporting industrial buildings designed for Europe without adapting the building envelope design to the local climate.

In hot climates it is mandatory to avoid skylights and replace them by glazed surfaces in the façade. If summer overheating is not critical and a heating demand exists in winter, the glazed surfaces should be oriented mainly to the south, otherwise to the north. To keep the cooling demand low or even avoid it, controlled night cooling is an energy-saving solution. Especially at night high ventilation rates are required that should be ensured by mechanical ventilation supported by natural ventilation. Reflective coatings of the roofs can be a small added value as well. Buildings with little thermal capacity are usually more susceptible for overheating why overheating protection becomes more complex.

In cold climates like in Russia the saving potential by orienting vertical glazed surfaces to the south is very high. Due to very high solar radiation in winter especially in Siberia these glazed surfaces should be increased as much as possible as overheating usually is no problem in such regions. Furthermore the air-tightness of industrial buildings in Russia is very important but is unfortunately not considered sufficiently by current building regulations. Improving the tightness is even more effective here than increasing the insulation thicknesses. Moreover this solution is also low cost, but appropriate quality controls like fan pressurization tests should become mandatory also for production buildings and warehouses. Here the most important need for action exists.

Most difficult is the design for regions with hot summers and cold winters like Turkey. Here building simulation should be used, as general advises are difficult to give and the design also depends a lot on the kind of energy used. A potential for heating in these countries is surely the use of solar energy. Here further research for seasonal thermal solar storages is required. Due to the long heating period and the high solar radiation in South Siberia this could also be interesting as a heating support for Russia.
ACKNOWLEDGMENTS

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Flexible and Environment Responsive Mass Housing in Bangalore, India

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ABSTRACT

Bangalore is one of the fastest urbanizing cities in India due to rapid increase in population and migration of people from varied and distinct cultural backgrounds. This has resulted in rapid development of high density housing characterized by towers of repetitive units. Most modern housing developments are focused on the repetition of units suitable for an average dweller, without taking into consideration the diverse and dynamic needs and wants of individuals and society.

What is ironic is that for centuries now, most societies have produced housing it requires, naturally and indigenously. The traditional vernacular architecture has always been in empathy with the environment.

This project develops options for a prototype housing unit and tests it by an analysis using the TAS software package for achieving flexibility without compromising on natural ventilation. It then develops a residential cluster which can be used as a model for future developments in Bangalore.

INTRODUCTION

India is urbanizing at an unprecedented rate due to an immense increase in population and migration of people from distinct cultural backgrounds and traditions from the suburbs and villages into cities. This has resulted in rapid high density housing development in the city resulting in towers of repetitive units. Migration has given rise to more mixed-cultural societies. These residents from varied cultural backgrounds and traditions, therefore, require residential areas or spatial configurations of apartments to be adaptable, comfortable and culture friendly for a better living. This cultural heterogeneity demands a different approach to housing. Also, the current housing industry is very limited when it comes to catering for long term social needs. It is crucial to take into consideration the different needs and patterns of individuals or each family.

While traditionally most buildings fundamentally responded to the climate, in the recent times, the dependence on mechanical heating and cooling devices has increased immensely, bringing about a change in the housing form and also the lifestyle of the people. Energy consumption in the building sector alone is more than one-third of the national energy use in India (Plea, 2013).

In architect Charles Correa’s words:

“In a third world country like India, we simply cannot afford to squander the kind of resources required to air-condition a glass-tower under a tropical sun.” (Correa, 2012, p.21)

India being home to diverse climatic conditions and energy availability being scarce it is important that buildings use passive means rather than mechanical air conditioning and heating. The term ‘passive’ refers to those design techniques which, in order to enhance thermal comfort, utilize the favourable and
minimize the unfavourable elements of the local climate.

This project aims at developing a prototype for urban high-density mass housing to accommodate passive design features while providing flexibility in design to cater to the varying cultural backgrounds of the migrant population in Bangalore and assessing it using TAS software package.

The objective is to develop a flexible unit to suit the demographics and the changing family needs. The current housing industry is very limited when it comes to catering for long term social needs. It is crucial to take into consideration the different needs and patterns of individuals or each family. Currently most mass housing in the city are being taken up by commercial real estate developers resulting in high rise structures with repetitive units.

CONTEXT

Bangalore, situated in the south of India, is the third most populous city in the country with a population of 8.4 million. It is located at 12.97°N 77.56°E with an average elevation of 920m on the Deccan Plateau.

The climate of the district is classed as the seasonally dry tropical savanna climate. Bangalore experiences a pleasant climatic condition, with occasional heat waves during the summer. In summer the temperature goes up to 38°C during the day and falls to 20°C at night. In winter the maximum temperature goes up to 27°C during the day and goes below 17°C during the night (Pib, 2008). The primary wind direction in Bangalore is south-west. During the months between January and March and October and December the wind direction is from north-east to south-west and between April and September it is from south-west to north-east.

The design criteria in this zone are to reduce heat gain by providing shading, and to promote heat loss by ventilation. Bangalore being located on a relatively higher altitude experiences a pleasant climate and does not require mechanical cooling for most part of the year. Effective ventilation and air circulation can cut down the energy needs in the city.

The city, earlier, known as the “Pensioner’s paradise” is now India’s Silicon Valley with the unprecedented rapid growth caused by the boom of the Information Technology sector. Also, various MNCs have set up their R&D centres in Bangalore, attracting young professionals in search of career or entrepreneurship (Forbes India, 2014).

As a result of the migration from other cities and town, the demand for housing has really gone up in the city, mostly in the rental market. Bangalore witnessed the launch of 35,000 residential units in the year 2012 and nearly 8,100 in the first quarter of the year 2013 (The Hindu, 2013). However, the current housing developments follow a trend of “cloning”, where the developments are focused on the repetition of units suitable for an average dweller, without taking into consideration the diverse and dynamic needs and wants of individuals and society.

The potential occupants of the residences mostly being young professionals migrating from other cities, an ideal solution would be to incorporate flexibility in the planning to suit the different lifestyles and also provide for incremental growth in the housing. Also, the demand for rental properties being high, flexibility in the planning would help cater to a diverse crowd. For instance, the potential residents may vary from a group of individuals sharing a unit to a newly married couple or a growing family.

Living Arrangement in India

The living arrangement in India traditionally has been a multigenerational household where it is the duty of the child, especially the male, to provide parental support in their old age. Nowadays the shift in the demographics such as migration for employment has resulted in children leaving the residences shared with their parents and has resulted in many nuclear families in the city.

For instance, 73.6% of the household in this state are working couples and these young working populations mostly take up studio apartments as a temporary base and move out to a bigger place after a few years when the family expands or when the elderly parents move in with them.
In Bangalore, in the past few decades, it has mostly been plotted developments where people buy the land and develop their house according to their requirements.

Site

The site measures 1.6 acres and is located in South Bangalore, situated off Bannerghatta Main road, on Ranka Colony Road. Ranka Colony Road is developing to be one of the busiest roads, connecting Bannerghatta road to rest of South Bangalore.
DESIGN

Concept

The design attempts to bring together flexibility and passive design strategies in a prototype housing unit providing for expansion and division within a mass housing to suit the Indian living patterns. The design comprises of group housing with set defined boundaries for each housing unit.

![Figure 4 Orientation (Source: Authors)](image)

The basic form was developed based on certain passive design strategies suitable for the tropical savanna climate of Bangalore.

- Orienting the longer façade in the North-South direction as east and west façade receive higher intensity of solar radiation throughout the year.
- Shading the east and west façade by staggering the units.
- Facilitating stack effect, which is very effective in the Bangalore climate.
- Taking advantage of the predominant wind originating from the east and west direction by having more openings in that direction, maximizing cross ventilation
- Possibility for controlled adjustable shading on the east and west façade.

![Figure 5 Passive Design Strategies (Source: Authors)](image)

The concept of flexibility has been worked upon based on the ideology of providing a framework and giving indication to the possibilities of spatial arrangements. Initially, all units have the same basic essential form along with a steel frame structure for future expansion. The frame structure sets the boundary of the unit and gives the occupants the freedom to expand at their convenience and also to decide the materials for the infill. When it is just a basic unit, the open spaces enclosed by the frame, serve as a garden space or a backyard for the house. The framed structure forms a grid plan allowing the occupants to construct anywhere along the grid forming arrangements to suit their requirements. The planning has been done in such a way that each unit has its own court and once the unit is fully expanded, it encloses the court.

Also, two units have been interlocked together to develop a pattern of massing to achieve high density housing. At the same time, the upper unit shades the lower one from the harsh west sun. Also, the arrangement provides for unblocked cross ventilation as shown in figure 5.
In the case of a contraction in the family size, there is the possibility of dividing a single unit into two small units which can be used as an office space or a studio apartment. The frame structure defines the boundary for each unit providing three grids for future expansion with the fourth grid serving as an open court all throughout. Also, the units have fixed entries, even upon division.

![Figure 6 Cases of Expansion and Division (Source: Authors)](image)

The above image shows the possibilities of arrangement as the unit expands. The first is the basic unit with a kitchenette space and a toilet and a mezzanine space which can be used as a bedroom. This would suit a single occupant or a couple.

As the family expands and requires more space, the unit can be expanded by constructing along the grid as seen in the second, third and fourth case where the unit can be transformed from a studio apartment to a three bedroom housing unit.

However, if the family contracts, for instance, the children move out and the elderly parents are the only occupants of the unit and they do not require so much of space, the unit can then be divided into two. This can be done by constructing a wall between the basic unit and the expanded wing forming two units with separate entries.

**Massing**

The massing in this context has been worked out along a central pedestrian pathway with the interlocking housing units on either side, while the vehicular movement has been restricted to the periphery. Also, the units on either sides of the central path have been staggered to maintain privacy in all the units.

The central pedestrian route opens up to several shared courts which lead on to the private courts of the housing units.

The prototype units can be arranged to form different types of massing ranging from row housing to low-rise apartments and high rise apartments where there is a space constraint.

**PASSIVE DESIGN STRATEGIES AND ANALYSIS**

**TAS software**

The software is split into three main programs, the 3d Modeller, Building Simulator and Results Viewer. As the first step, the 3d modeller is used to create the building model for simulation. Here, the
different spaces are assigned different zones.

Next, the model created is exported to the building simulator. In this program, the building components are assigned its materials. Using this program, one can choose which apertures are open, when and by how much. The internal conditions are assigned for the different zones depending on the number of people occupying the space and considering factors such as lighting, etc.

Once all the information has been entered, the model is exported to the result viewer. Here, any number of parameters such as relative humidity, dry bulb temperature, etc. from any number of zones or surfaces can be displayed and compared in a tabular and graphical format.

**Parameters considered:**

**Materials**

- External and Internal wall – Brick wall
- Floor Slab – Concrete
- Window frame – wood 50mm width

**Aperture type and schedule**

The stack windows in the double height space were considered to be open all through the day. The windows in the main living room were kept open during the day from 7:00 to 10:00 and in the evening from 17:00 to 19:00. The bedroom windows were considered to be open during the night from 18:00 to 07:00.

Finally, in the Result Viewer the dry bulb temperature for all the zones were compared to study if it was within the comfort range. This was repeated for the different stages of flexibility.

**Comfort Range**

For all climate and building types, the National Building Code of India specifies the use of two narrow ranges of temperature: summer (23–26 °C) and winter (21–23 °C), (BEE, 2005). These standards are based on ASHRAE standards, which are not validated through empirical studies on local subjects. However, India experiences diverse climates, thus it is not proper to define a single comfortable temperature for the entire country, as it would vary region wise.

Based upon a comfort survey conducted all over the world, a relation has been derived between comfort temperature (Tc) and outdoor temperature (T0) [3] as

\[ Tc = 12.1 + 0.53T0. \]

Another relation was obtained for Pakistan which has almost similar climatic conditions as in India as

\[ Tc = 17.0 + 0.38T0. \]

Where,

- Tc is comfort temperature and T0, mean monthly maximum and minimum external temperature.

(Chandel and Aggarwal, 2012)

Based on this relation, the comfort range for Bangalore for the month of May was calculated to be 26°C - 29°C and 24°C - 28°C for December.

The analysis has been carried out based on both the comfort ranges, the one based on the ASHRAE standards and the one derived from the equation.
Figure 7 Variation in dry bulb temperature in a basic unit (Source: Authors)

Figure 8 Variation in dry bulb temperature after expansion and division
Design iterations

First, the basic unit was simulated and it was observed that the double height space helped reduce the dry temperature within. However, it was more effective when the outlets were at the highest point and the inlets were narrow. From a comparison of the dry bulb temperature of the internal zones, it was observed that the temperature in the mezzanine was always maintained at a higher level making it an ideal zone for winter time.

Also, it was observed that the temperature within reduced with the addition of a covered balcony on the west façade. And as the housing unit expanded, the temperatures in the rooms were maintained within the comfort range when the central portion of the unit was left open with no partitions.

CONCLUSION

In a country like India, the cultural heterogeneity and the changing living patterns demands a flexible approach to housing. Also, energy consumption in the building sector alone is more than one-third of the national energy use in India. India being home to diverse climatic conditions and energy availability being scarce it is important that buildings use passive means rather than mechanical air conditioning and heating.

In terms of the factors contributing to the success of a flexible housing, most often a combination of both use and technology prove to be more effective as seen from the case studies. When the method of flexibility is just confined to the interior of an existing shell, the amount of choice and control of the occupants get limited. From the scale of a single housing unit to mass housing, with careful consideration of use and technology without much additional costs and over complicated technological systems, flexibility can be achieved successfully.

Coming down to the project, in a climate like Bangalore’s with careful planning and by adopting climate responsive strategies, the energy use in the residential sector can be cut down drastically. It is evident from the TAS energy modelling analysis that the indoor temperature can be maintained to suit the comfort of the occupants without depending on mechanical cooling systems.

In terms of flexibility, the frame structure defines a boundary for each of the unit allowing it to expand or contract without affecting the neighbouring units much. Also the prototype design of the unit can be adopted to develop a variety of housing types such as row housing, high rise or even just a group of four houses.

REFERENCE

Session 8C : Building reuse and refurbishment

PLEA2014: Day 3, Thursday, December 18
14:10 - 15:50, Grace - Knowledge Consortium of Gujarat
A Multi-Stage Approach to Low Carbon Housing Renovations

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ABSTRACT HEADING

In 2009 the European Union approved “Roadmap 2050” to reduce greenhouse gases by at least 80% below 1990 levels by 2050. In 2012 the Danish Government established to achieve 100% autonomy from fossil fuels by 2050 by implementing a strategy that included reducing energy demand of existing housing that accounts for about 40% of the national gross energy consumption. A mass retrofit of the existing housing stock could lead to 75% reduction of energy use and carbon emissions. However due to the cost and disruption of retrofits that can radically improve energy performance of buildings, strategies that address both disruption and cost have to be considered. One such potential strategy examined in this paper is a staged approach, which involves different elements of a building to be upgraded over several years, thus spreading the capital cost of the work and enabling the occupants to remain in their homes. Applied to the Danish context this approach can also benefit from financial incentives currently in place. Adopting a case study approach in conjunction with IES modelling, a cost analysis and interviews with industry experts, this research examines the energy savings, capital cost, cost savings of a selection of energy improvements measures, and the implications of undertaking the building work on the occupants of typical Danish detached houses built between 1850-1930. It concludes by proposing a decision matrix for home owners to achieve the most cost-effective and least disruptive approach to undertaking radical energy upgrades.

INTRODUCTION

Background

In 2009 the European Union approved “Roadmap 2050” to reduce greenhouse gases “by at least 80% below 1990 levels by 2050” (Roadmap 2050). In March 2012 the Danish Government established a new, ambitious Energy Policy, to achieve a 100% autonomy away from fossil fuels by 2050. The strategy adopted to reach such results involves a consistent reduction of the energy demand. According to the Danish Energy Policy Report (Ministry of Climate, Energy and Building, 2012), the existing building stock accounts for about 40% of the total energy consumption; more specifically in 2010 the 69% was related to the housing sector, and the 36% to non-residential buildings (IEA, n.d.; Agency Danish Energy Agency, 2011). Thus, the biggest savings could be achieved by improving the energy performance of the less efficient housing stock. However, this mass-retrofit meets two barriers, involving the government and the private owners: one is financial (Kragh and Rose, 2011, p2252) and
one is practical (Thorpe, 2010, p.2). The first requires financial help from the government to the private owners, and second one requires a solution to prevent the occupants from moving to a temporary home. A multi-stage or “stepwise” (Galiotto et al., 2012) approach to energy efficient retrofits could address these issues.

Aim of the research

This paper investigated a staged retrofit strategy as feasible solution to finance a national mass retrofit; to make an expensive housing retrofit more financially sustainable and more practical. Smaller and less disruptive works carried out in several stages could distribute the total investment in more than one transaction; they could also allow the occupants to stay in their homes and avoid additional expenses to rent a temporary accommodation.

METHODS

Due to time limitations this research has focused on a specific category of detached houses, built between 1850 and 1930. Detached houses were identified as most diffused and the worst performing housing type; they account for the 52% of the entire housing stock (Statistics Denmark), and for more than 330,000 units (53%) with EPC labels between D and G and a heating consumption requirement above 240 kWh/m²/yr (Aggerholm et al., 2010).

The construction details and materials of the housing type analyzed were sourced from the Danish report for TABULA Project (Wittchen and Kragh, 2012). The reference retrofit measures used were collected from a previous research by SBi, the Danish Building Research Institute (Galiotto et al., 2012), by VTT, the Technical Research Institute of Finland, (Häkkinen et al., 2012) and Larsen et.al (2011).

IES- VE was chosen as dynamic simulation tool to test the effect of several retrofit measures on the building performance. A 3d model of a real detached house from 1917 and located in Copenhagen was built in IES. It was used an average floor, window and floor area; average construction, materials and shape; the U-values, infiltration rate, boiler type were conformed to those specified in the TABULA project report (Wittchen and Kragh, 2012). The NCM heating, appliances and occupants’ profiles were used. The details of the model created and the average building described in TABULA are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Multi-Stage Plan. Number of Years for Each Stage.</th>
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</thead>
<tbody>
<tr>
<td><strong>U-values</strong></td>
</tr>
<tr>
<td>Wall</td>
</tr>
<tr>
<td>Roof</td>
</tr>
<tr>
<td>Ground Floor</td>
</tr>
<tr>
<td>Windows</td>
</tr>
<tr>
<td>Door</td>
</tr>
<tr>
<td>ACH</td>
</tr>
<tr>
<td>Boiler</td>
</tr>
<tr>
<td>Fuel</td>
</tr>
<tr>
<td>Area</td>
</tr>
<tr>
<td>Windows area</td>
</tr>
<tr>
<td>Wall area</td>
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<tr>
<td>Roof area</td>
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<tr>
<td>Slab</td>
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<tr>
<td>Ceiling Height</td>
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<tr>
<td>Location</td>
</tr>
<tr>
<td>Age of construction</td>
</tr>
<tr>
<td>Heating consumption</td>
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</tbody>
</table>
ANALYSIS

IES modelling

A first series of simulations was carried by introducing one variable at a time in the model’s building construction; such as wall, slab or roof insulation, new windows, mechanical ventilation, heating system. All the measures were previously collected from other research. The results were organized in reduction of the heating consumption (%), the reduction of Carbon Emissions (%), the grade of disruptiveness and invasiveness of each measure (low- medium and high). Table 2 shows the percentages of reduction achieved by the measures belonging to the different building’s systems.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Heating reduction</th>
<th>CE reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall insulation</td>
<td>51.2%</td>
<td>39.7%</td>
</tr>
<tr>
<td>Slab’s insulation</td>
<td>16-20%</td>
<td>12-22%</td>
</tr>
<tr>
<td>Mechanical ventilation combined with airtightness of 0.15ACH</td>
<td>10%</td>
<td>7%</td>
</tr>
<tr>
<td>Windows</td>
<td>5-7%</td>
<td>4-6%</td>
</tr>
<tr>
<td>Roof and ceiling insulation</td>
<td>6-8%</td>
<td>4-5%</td>
</tr>
<tr>
<td>Heating system</td>
<td>0%</td>
<td>7%</td>
</tr>
</tbody>
</table>

Cost Analysis

In order to identify the most cost-effective and less invasive measures, it was important to compare the costs, the savings and their grade of disruptiveness. The comparison was carried only for wall and slab’s insulation as the measures tested varied for thickness, type of material and strategy adopted (internal or external insulation).

The prices were found online, and on Spon’s Architects’ and Builders’ Price Book 2013, available at the University’s Library (Langdon, 2013). The Danish prices were available on V&S Prisdata, provided by Byggecentrum, with an annual price. For this reason, the labour prices were searched in Spon’s, while the materials’ costs were found on the sellers’ websites (listed in the references), and by asking quotations to the manufacturers.

The external insulation of the wall with demolition of the cavity wall, and cavity insulation + internal insulation were excluded from the feasible measures because highly invasive and disruptive, less effective than the external insulation, and more expensive. Thus, the most cost-effective solutions with the shortest payback period are the insulation of the cavity wall and an additional external insulation, which can be between 50 and 160 mm., as shown in Fig. 2.

As shown in Fig. 3 the ceiling insulation seemed to be most cost-effective than the roof insulation because it involves a smaller surface to cover, thus lower material costs, but similar savings to the roof insulation (6% reduction of heating demand in both cases, 4% reduction of CE for 200mm insulation and 5% for 400mm insulation). Also the ceiling insulation can be less disruptive than the roof insulation, which would involve a disassembly of the roof cover and waterproof layer. Such measure is suggested only in case the roof needs to be updated because it would solve a problem of thermal bridging in the junction between the roof and the external wall.
A second series of simulations was run to estimate how much the heating demand could be reduced, once all the retrofit measures are completed. For this purpose any possible combination of measures was tested. The ACH used were 0.3 (a medium value); in such old leaky houses a value of 0.25 ACH is hardly achievable. Among 127 simulations the heating demand varied from a maximum of 39 kWh/m\(^2\)/yr, to a minimum of 20.7 kWh/m\(^2\)/yr; both results are lower than the established goal of 44 kWh/m\(^2\)/yr (Danish energy class 1).

According to the results of all the IES simulations, the multi stage plan should follow the next order: cavity insulation, external wall insulation, slab insulation, mechanical ventilation, roof and ceiling insulation, windows and heating system.

However these dynamic simulations cannot considerate the fact that the single measures are part of a staged plan and cannot preclude further works in the future (Thorpe, 2010).

**Interview**

For this reason a semi-structured interview was conducted with a NIRAS’ engineer specialized in energy efficient retrofits. During the interview, the installation of an automatic heating control system was recommended as first measure on the list, being a cheap and very effective solution. In fact, further simulations confirmed that.

The time-temperature control and the time control can both lead to a 38% reduction in space heating demand; while the temperature control only a 10% reduction. The carbon emissions were reduced by 31% with the first two controls, and by 9% with the third one.

The engineer also evidenced how changing windows can be a priority for the occupants to enhance...
the thermal comfort, and avoid air-drafts.

Besides, it was suggested to consider windows and external insulation as a whole package; indeed, if the external insulation is applied first the windows should be moved to the outer layer of the wall to avoid thermal bridges. Thus, the windows could be changed when moved, avoiding extra installation costs.

At last, the mechanical ventilation cannot be considered as measure unless an airtightness test proves that the infiltration rate is lower than 1.5 ACH50.

The limitations of a multi-stage retrofit were also discussed during the interview. Not all the construction details can be solved during a multi-stage retrofit (certain thermal bridges) and these limitations need to be accepted and explained to the owners not to create too high expectations. In fact, the savings obtained by large scale and less expensive retrofit (nearly 80%) can still make a big difference in reducing the gross energy consumption and the CO₂ emissions of a Country.

Multi-stage plan

Based on these suggestions and considerations the final multi-stage plan was organized in 11 stages and the measures of each stage were classified in low-medium and high budget (Table 3). The intent was to produce a flexible scheme that leaves to the single owners the choice of the best measures for their budget.

<table>
<thead>
<tr>
<th>Table 3. Multi-Stage Retrofit Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low budget</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
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<td>5</td>
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<td>6</td>
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<td>7</td>
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<td>8</td>
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<tr>
<td>9</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>11</td>
</tr>
</tbody>
</table>
The list of measures was accompanied by a scheme, shown in Fig.4, with questions and answers (yes/no) that show which is the first stage to undertake and which should follow. For each stage there is a corresponding color, that remands to the first scheme of measures.

![Guiding Scheme to House owners.](image)

**Figure 4** Guiding Scheme to House owners.

**Possibilities to finance energy efficient retrofits**

If the financing barrier is to be overcome, the annual cost of energy renovation investment should at least be equal to the annual savings on energy (Kragh and Rose, 2011), and at the moment, even with the increased energy price, the payback period for energy retrofits is still too long.

In this research an existing tax deduction was used to abolish or reduce the difference between investments and energy savings as shown below:

\[\text{Annual Investment} = \text{Annual Energy Savings} + \text{Annual "Artisan Deduction"}\]

The so called “artisan deduction” consists of about £2000 per salary/yr, to deduce for installation and craftsmen costs, but not for materials and devices costs (SKAT), which account for half of the total investment. In this research it is assumed a modification of the tax scheme, allowing the homeowners of a specific category to deduct also materials and devices’ costs.

Another assumption is that the annual savings on energy are cumulated and saved in a bank account with exclusive use for the next stage, until the whole retrofit is completed.

In Denmark detached houses are often occupied by one or two families, in which case there could be two, three or four salaries that could bring £3496-£5244 of tax deduction per year/house.

A scheme showing the investment, the energy and carbon savings and the tax deduction for 1,2,3 and 4 salaries was created to verify the workability of the new “artisan deduction” and the cumulated energy savings. The final equation is:

\[\text{Annual Investment} = \sum_{n=1}^{n} \text{Energy Savings} + \text{Artisan Deduction}\]

\[n=\text{number of the years since the first retrofit stage}\]
Where the result is negative, the investment is paid back in the same year of realization, through the monetary savings obtained by reducing the energy demand and the incentives. When the difference is positive, the incentives and the monetary savings are lower than the initial investment. In the first case, it could be possible to carry one or more measures during the given year, depending on how much of the incentive is left. In the second case the measures too expensive to be paid in one year, should be carried out in two or more years (i.e. windows can be changed one at a time). Another solution is to wait a couple of years, save the money not spent for heating, and use it to pay in a single shot the works.

In order to estimate the number of years necessary to carry on the whole retrofit, every time the difference was negative, a new calculation was done adding the cost of the next measure and the savings achievable from that. If the difference was still negative the two or more measures could be carried out the same year.

In all cases the first two steps can be completed in one year. The window replacement can require one or two years with one salary, and one year for the other three cases. Only with four salaries per household the windows could be replaced at the same time when adding external insulation. The next steps can be completed in five years with one salary, for a total of seven years, in case the house is connected to the district heating; and twelve years if there is a heat pump. In case the salaries in the house are two, the retrofit could be completed in six-seven years. if there are three salaries four-five years could be enough to complete the retrofit; four with the district heating and five with a heat pump.

Table 1. Multi-Stage Plan. Number of Years for Each Stage.

<table>
<thead>
<tr>
<th>Year of retrofit</th>
<th>1 Automatic Control</th>
<th>2 Cavity Ins.</th>
<th>3 Window Ext. Ins.</th>
<th>4 Ext. Ins.</th>
<th>5 Roof Ins.</th>
<th>6 Slab</th>
<th>7 Door</th>
<th>8 MV Boiler</th>
<th>10 Heating System</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 salary</td>
<td>Yr 1</td>
<td>Yr 1</td>
<td>Yr 2-3</td>
<td>Yr 4</td>
<td>Yr 5</td>
<td>Yr 5</td>
<td>Yr 5</td>
<td>Yr 6</td>
<td>Yr 7-12</td>
</tr>
<tr>
<td>2 sal.</td>
<td>Yr 1</td>
<td>Yr 1</td>
<td>Yr 2</td>
<td>Yr 3</td>
<td>Yr 3</td>
<td>Yr 4</td>
<td>Yr 4</td>
<td>Yr 4</td>
<td>Yr 6-7</td>
</tr>
<tr>
<td>3 sal.</td>
<td>Yr 1</td>
<td>Yr 1</td>
<td>Yr 2</td>
<td>Yr 3</td>
<td>Yr 3</td>
<td>Yr 4</td>
<td>Yr 4</td>
<td>Yr 4</td>
<td>Yr 4-6</td>
</tr>
<tr>
<td>4 sal.</td>
<td>Yr 1</td>
<td>Yr 1</td>
<td>Yr 2</td>
<td>Yr 3</td>
<td>Yr 3</td>
<td>Yr 3</td>
<td>Yr 4</td>
<td>Yr 4</td>
<td>Yr 4-6</td>
</tr>
</tbody>
</table>

Incentives plan to retrofit the detached houses built between 1851 and 1931 by 2030

Supposing the national mass retrofit starts in 2015 detached houses between 1850 and 1930, all the houses with three or four salaries could be completed in 4-6 years. In 2020 the next stage of the mass retrofitting could start with the houses built between 1961-1972. By 2027 the first stage should be concluded and the 11 % of the whole Danish housing stock retrofitted (Fig.5) with 80% energy reduction. As shown in Fig.69 this group of houses accounts about the 31% of the energy used by detached houses, so the 80% reduction would be equal to 24% reduction of detached-houses’ energy use.

CONCLUSIONS

This paper has investigated the possibility of using a multi-stage plan to overcome economic and practicality barriers to energy efficient housing retrofit. The research results have shown that the integration of dynamic simulations and the practical experience of specialists can lead to multi-stage retrofit plans for each housing type.

A financing scheme was proposed to equal the annual investment for retrofit, to the derived energy savings; however, a similar model would be burdensome for the national tax system; which would see the national tax income considerably reduced. On the other hand, without a significant help from the
government, only a few house owners would invest their own savings in such housing retrofit, as “one of the main barriers in renovation” is “financing” (Kragh and Rose, 2011, p. 2252).

Figure 5 Sample of Mass Retrofit Organization.

Most of them would probably decide to upgrade something, not aware of what they could actually do to have an energy efficient house. In conclusion this research suggests that government guidance is essential as government funding schemes. The proposal of recouping a percentage of the monetary savings achieved by the house holders to help the government to finance the second step could make the scheme unpopular, if the advantages derived from such help are not well stated. Nevertheless, this scheme does not require any investment to the owners, which have only to pay upfront.

Educating the householders about the long term and non-monetary advantages is critical to their acceptance of the scheme. This research has shown how tax-related schemes can encourage retrofit initiatives and how technical solutions can help reduce the cash flow and capital cost. Other technical solutions and financial incentives could address these and other barriers to retrofit initiatives and should be further investigated. In addition, all incentive schemes need to be supported by effective information and this area could also benefit from further research.

AKNOWLEDGMENT

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ABSTRACT
The existing building stock in the United Arab Emirates finds it more difficult to compete with the new more environmental friendly and energy efficient buildings and do not fit into the country’s vision of sustainability. Even if all new building have zero CO2 emissions, the older inefficient building stock will cause the CO2 emissions levels to remain unacceptably high which, means older building stock needs to adapt to environment friendly energy efficient measures. The current research focuses on the green retrofitting strategies of an existing building in the hot and arid climate of the UAE. The study examines the existing building envelope of Latifa hospital using the energy simulation software e-QUEST. Using the simulation model, the building behavior was predicted for the retrofitting strategies of thermal insulations, window to wall ratios, wind types, ventilation fans and types of HVAC system to achieve optimal retrofitting of the building.

INTRODUCTION
For the last forty years, the United Arab Emirates (UAE) has witnessed an unprecedented pace of urbanization and population growth due to rapid economic development. The rapid growth of UAE’s economy has been accompanied by a substantial increase in energy consumption. Partly, the significant increase in energy consumption is due to inefficient existing facilities (Elgendy, 2010a, 2010b). The UAE energy intensive construction approach coupled with its extreme hot climate, require heavy cooling and have appointed the UAE in the top 10 countries in terms of electricity usage per capita and the second highest in terms of CO2 emissions per capita (AlNaqbi et al, 2012a, 2012b, AlAwadhi, 2013). The single largest contribution to the electrical load comes from cooling which accounts for an average of 40% of total year around electrical load and up to 60% of the peak electrical load during the summer time (Al Awadhi, 2013). The majorities of UAE buildings stock was constructed long before the introduction to sustainability codes and standards and therefore is incompatible with current standards or the expectations of the users (Shady, 2010). Sustainable retrofit is not a new concept but is gaining recognition and importance owing to current concerns about intensive energy use in buildings leading to climate change (Backer, 2009).

Latifa Hospital (previously Al Wasl Hospital), a 367-bed specialized maternity and paediatric hospital, opened in 1986. The two-story hospital building is oriented east south-east (Figure1) and has a gross floor area of approximately 73,213 sq.m with the central plant area being around approximately 3,300 sq.m (Figures 2, 3).
The building has a reinforced concrete structural frame with foundations on piles and block work for the external envelope and internal partitions. The base structural bays are 7.20m x 7.20m for a 4.5 floor-to-floor height. Ceilings are set at 3 meters, except in wet areas where they are at a standard 2.70 meters. The external walls are made of a double block work with a 40 mm cavity filled with a pre-compressed isolation polystyrene board and a layer of bituminized fiber for dampproofing. The windows and doors are provided with sealed double glass with solar control coating to regulate the UV light and reduce heat gain while providing sufficient and uniform daylight. Double glazing windows are the common hospital window type, solar control reflective insulating glass type, and bronze color, 6 mm. with direct transmittance 21%, total solar transmittance 26%; shading coefficient 0.30% and U value 1.4 w/m2. K.

**METHODOLOGY**

In order to develop effective energy conservation guidelines, the nature and magnitude of the energy usage in the existing hospital was determined through direct collaboration with the hospital facility personnel.
The study investigates the performance of the existing building envelope, the HVAC system and other energy efficiency measures then explores their optimization potential. The inputs for simulation program are collected through extensive review of design drawings.

Figure 3: First Floor Zones Layout

All the collected data has been analyzed to determine the base case of the existing building electrical consumption and compared with the predictions of the simulations to validate the methodology. The existing building model was generated using e-QUEST software. The building was set at its actual orientation with all openings placed per their location and specificities. As a first step, the building was simulated “as is” to determine the base case. All required inputs of insulation level, type of window and glazing, shading, roof insulation, flooring construction materials, type of HVAC systems, building occupancy, operation schedules and loads were added to the program to calculate the annual energy consumption of the base case. Results obtained from the simulation (e-QUEST) software were compared with the actual energy consumption data achieved through bills and energy audit to validate the simulations results. Once the model was validated, the optimization was carried out to determine potential areas of energy savings pertinent to retrofitting.

RESULTS AND DISCUSSION

Various strategies for energy performance optimizations were tested through simulations. The energy performance simulations were performed through eQuest, in order to optimize the envelope for reduced heat gain through insulations, façade construction, envelop colour and glazings. The HVAC system was optimized for ventilation and infiltration, efficiency rating, better comfort settings and better HVAC scheduling. Thereafter based on the results and analysis, recommendations for retrofitting the building are outlined for façade construction and systems integration.
Wall Optimization

At first, the wall colour was studied for its impact on energy performance of the building to attain an optimum wall colour with reasonable energy performance assuming the darker colour as a reference and with no insulation applied. Walls colors were changed from dark abs.=0.9 to light abs.= 0.4 gradually and the electrical energy consumption was computed. The result shows that change in the walls color from dark to deer light (abs= 0.45) has reduced annual energy consumption by 0.13% (Figure 4). As a second measure, the effect of wall insulation was studied on the energy perfomance while changing the insulation gradually from R= 0 to R= 12. The increased insulation yielded a reduction in annual energy consumption of 0.33%. Finally the net effect of reduced colour absorptance and increased insulation was simulated which yielded an energy saving of 0.4%.

![Figure 4: Simulation results of collective wall optimization through wall colour and added insulation for Latifa Hospital, Dubai using 2013 weather data.](image)

Roof Optimization

The building roof was optimized following the same scheme described for wall optimization and the individual impact of color and insulation were studied at first while later the combined effect of reduced color absorptance and increased insulation were computed. Change in roof color from dark (abs.= 0.9) to deer light (abs.= 0.4) yielded a reduction in annual electrical energy consumption of 1.81 % plotted (Figure 5). It was observed that the optimum reduction of 2.59% is achieved at R=9 while the drop in energy consumption at higher R-value is insignificant.

![Figure 5: Simulation results applying roof insulation for Latifa Hospital, Dubai using 2013 weather data.](image)
Envelop Optimization

It was observed that changing the whole envelop color from dark to deer’ light (abs = 0.4) yielded a reduction of 2.0% in annual energy consumption while increasing the envelop insulation from R=0 to R=9 resulted in a 3.41% decrease in annual energy consumption. Finally energy consumption for existing envelop insulation values (Wall Insulation R= 6 and Roof Insulation R=6) was simulated and compared with energy consumption of proposed insulation (wall insulation R=9 and roof insulation R=9) which achieved a further reduction of 1.93% compared to the existing insulation level which emphasized the need for retrofitting and replacing the wall and roof insulation. One very important observation writes the stronger impact of color yielding 2 % decrease in annual energy consumption compared to the darker color, an option that carries minimal cost and would be an economically attractive option for retrofits and new designs.

Figure 6: Simulation results applying façade insulation for Latifa Hospital, Dubai using 2013 weather data.

Comparing the existing façade colour for retrofitting (wall abs=0.6 and roof abs.=0.4) to the proposed façade colour (wall abs.=0.4 and roof abs.=0.4) yields a reduction of 0.1% in annual energy consumption which indicates that the current façade colour is optimized and offers least opportunities for further energy savings.

Figure 7: Simulation results investigating façade colour for Latifa Hospital, Dubai using 2013 weather data.

Window Optimization

Proper placement of windows and optimized window to wall ratio achieves have a strong impact on energy consumption in the climatic context (Fathy, 1986). In order to optimize window to wall ratio
(WWR), it was increased from a minimal of 10 % to relatively higher value of 45 % and a discrete energy performance trend was observed in three different WWR regimes. In the first regime, increasing WWR from 10.5 to 20 % has negligible increase in energy consumption primarily because the increase in heat gain is compensated by the decrease in area lighting load of the indoors. In the second regime increasing WWR from 20% -30% increased the energy consumption modestly which shows that the benefit of increased lighting loads are being outclassed by the increase in heat gain. In the third regime, increasing WWR beyond 30 % yielded a sharp increase in energy consumption which indicated that at this stage only heat gain is the consequencial for the increased WWR which emphasizes economic implications of increased WWR beyond a certain range. The simulated results agree with similar research which recommends WWR of 10-20% for better energy performance [Aboulnaga, 2006]. Comparing the optimum range of WWR of 20-30 % computed through simulations with the existing building WWR of 17 %, it is proposed that for retrofitting the glazings should be increased up to 25 % to have better daylight for a healthier indoor climate critical for hospital buildings even at the cost of affordable extra energy consumption. At the second stage different window types were simulated and it was observed that replacing the existing double clear/ tint glass type to double low-e a reduction of 0.7 % in energy can be achieved which shows that while retrofitting, the window type needs to be re-considered.

Figure 8: Simulation results with various WWR for Latifa Hospital, Dubai using 2013 weather data.

Optimizing HVAC

Energy Efficiency Ratios (EER) of the HVAC was studied against energy consumption in the range of EER =10 to EER= 26 shown in figure 9.

Figure 9: Simulation results for cooling system energy efficiency for Latifa Hospital, Dubai using 2013 weather data.
The existing EER of the system being 17.5 was compared with a higher EER value of upto 26 and it is observed that energy consumption can be reduced by 5.92% while increasing the EER to 22. It is therefore emphasized that selecting a higher efficiency cooling system can save a huge amount of energy and the cooling system should be replaced with more efficient system while retrofitting.

**Optimizing Comfort Conditions**

A general observation made in UAE is a trend of setting thermostat to undesirably (and at times uncomfortably) low temperatures around 20-22 °C which has its implications on energy consumption and operation cost. Effective and comfortable cooling can still be achieved keeping the thermostat set point at a higher temperature and increasing a little more fan ventilation. An attempt was made to simulate the trend of the impact while changing the thermostat set-point from 22 °C to 24 °C in occupied areas and from 26 °C to 28°C in unoccupied areas being still in the comfort zone based on psychometrics of the place. The result shows a reduction of 0.27% in annual energy consumption which emphasized the importance of operating the cooling system at right comfort conditions without sacrificing comfort.

**Optimizing Fan Type**

Installing Variable Frequency Drives (VFDs) on the supply and return fans of the Air Handling Unit (AHU) can reduce energy consumption by 20% (Schneider Electric, 2006). In order to test this, the existing constant-volume air handling system with centrifugal fan type was replaced VFDs on the supply and return ducts of the AHUs. The results show a reduction of 20.23% in the annual energy consumption. Although the simulation result showed a substantial potential reduction in energy consumption, this type of fans cannot be used in the hospital environment as the variable VFD causes ventilation problem in low cooling load conditions and causes associated health hazard. It is therefore proposed to keep the same fan type.

**Integration of Solar Thermal Collectors**

The hospital has a 12,000 lit/day hot water consumption which demands a large amount of energy for water heating. Since UAE has vast solar energy potential, heating problem was solved by integrating solar thermal collector on the roof to provide hot water. The system consists of 18 collectors with aperture area of 1.87 m², water mass flow rate of 35 kg/hr and water tank capacity of 300 lit each. It is coupled with an auxiliary electrical heating system to constantly supply hot water at 63 °C.

*Figure 10 Solar Thermal Collector installed on the roof of Latifa Hospital, Dubai.*

In order to determine its performance, the solar thermal system is simulated in TRNSYS software using...
Dubai weather data to find out the ratio of solar thermal energy supplied to the auxiliary energy needed for the stable 63 °C supply water temperature. The solar thermal system attained a total yearly thermal energy production of 212,224 KWh which contributed 46 % of the total energy consumption for hot water production in the hospital and therefore it is recommended that the share of solar thermal should further be increased to attain energy efficient and cost competitive hot water production.

CONCLUSION

This paper has explored energy saving opportunities while retrofitting an existing healthcare facility in Dubai, UAE through a simulation scheme. The simulations findings resulted in a number of recommendations for energy efficient and cost competitive retrofitting solutions in the climatic context while pointing out indicative impact of occupants’ behavior on energy consumption of cooling system.

The findings are in three different areas. First, for the façade construction, choosing a lighter color has huge impact reaching up to 2 % energy savings with least cost incurred, adding wall and roof insulation yields up to 3.4 % energy savings although they incur additional cost as well, proper window type can yield up to 0.7 % of energy savings with minimal cost addition and the optimum WWR is found between 20-25 % for healthier indoors with little extra energy cost. Secondly for HVAC system operation and efficiency, keeping the cooling set points within acceptable comfort can achieve 0.27 % energy savings with no extra cost and replacing the existing HVAC with a more efficient cooling system can achieve up to 5.9 % energy savings with extra cost of system. Finally integration of 18 solar thermal collectors in the building as a means of renewable and environmental friendly source of energy contributed to 46% energy saving for hot water production economically competitive rates and therefore is recommended for a higher energy share.

REFERENCES

Relating Sustainability Indicators to the Refurbishment of the Existing Building Stock

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ABSTRACT

The construction sector and the associated built environment have an oversized footprint. They are responsible for more than a third of global resource consumption and an estimated 40% of the total waste generation, contribute up to 30% of global annual greenhouse gas emissions and consume a third of all energy. The retention, rehabilitation and reuse of the existing building stock play a pivotal role in the sustainable development of the city. However, there is an ongoing debate on evidencing the sustainability of refurbishment in contrast to demolition and new construction. On the one hand, a newly constructed building can achieve higher operating energy efficiency on the short term, on the other hand, when looking at lifespan, material use and waste generation, re-use or continued use of the buildings is more environmentally sustainable than to demolish and replace them. This paper provides a review of the role of sustainability in the built environment and reflects on this from the perspective of refurbishment; revealing the state of the art regarding the definitions of sustainability, the sustainability legislation on different scale levels and the assessment methods used to certify sustainable buildings. Subsequently, these different aspects will be put in relation to each other and assessed from the perspective of refurbishment.

INTRODUCTION

The construction sector and the associated built environment consume significant quantities of resources and energy, contribute to climate change, and affect the health and well-being of building users and others (Todd, 2012). In 2011 the United Nations Environment Program (UNEP) and the Sustainable Buildings and Climate Initiative (SBCI) released a report (United Nations Environment Programme, 2011) that notes:

1. The built environment is the single largest contributor to global greenhouse gas emissions (GHG), with approximately one third of global energy end use taking place in the operational use of buildings.
2. The construction sector is responsible for more than a third of global resource consumption, including 12% of all fresh water use, and contributes 40% of the generation of solid waste.
3. Constructing new green buildings and retrofitting existing energy- and resource-intensive
buildings stock can achieve savings of about one-third in energy consumption in buildings worldwide and significantly contribute in the reduction of CO₂ emissions.

4. Greening buildings will bring significant health and productivity benefits.

It is made clear that interventions are not only necessary, but possible. According to Petersdorff et al (Petersdorff, Boermans, & Harnisch, 2006), the main energy and CO₂ saving potential lies in the existing building stock. Most developed countries have regulations consisting of national performance standards for newly built houses. The demolition rate in the building stock can be estimated to be ∼1/2–1%, whereas new constructions to be 1% of the total living area per year, thus resulting in a slight increase of the existing building stock (Petersdorff e.a., 2006). Research in the UK (Power, 2008) suggests that even with ambitious new building programs and a high demolition rate, only 10% of the current stock will have been demolished by 2050, arguing the urgent need to upgrade the existing stock on the grounds that 70% of all homes that will exist in 2050 are already built. Consequently, existing buildings must be sustainably refurbished (Häkkinen, 2007),(Sev, 2011), minimizing the operational energy use while taking into account other sustainability aspects. This paper provides a review of the role of sustainability in the built environment and reflects on this from the perspective of refurbishment. Revealing the state of the art regarding the definitions of sustainability, the sustainability legislation on different scale levels and the assessment methods used to certify sustainable buildings. Subsequently these different aspects will be put in relation to each other and assessed from the perspective of refurbishment.

DEFINITION

In today’s world, the term sustainable development is everywhere; over 500 definitions of sustainability and sustainable development have been spawned by various governments, professional bodies, institutions and organizations (Shah, 2012). The growth of sustainable awareness dates back many decades; from Silent Spring written by Rachel Carson (Carson, 2002) and first published in 1962, describing a world affected by pesticides and chemicals, through to James Lovelock’s Gaia (Lovelock, 2000), first published in 1969, stating the role of ‘mother earth’. One of the first definitions of sustainable development was made in ‘Our common future’, the report of the Brundtland Commission, calling for development “that meets the needs of the present without compromising the ability of future generations to meet their own needs”(World Commission on Environment and Development, 1987). Whilst this definition is still used today, a more commonly known terminology encompasses the environmental, social and economic principles captured as the ‘triple bottom line’ (Elkington, 1998), also referred to as the three P’s; Planet, People, Profit.

The definitions of the terms ‘sustainable building’ and ‘building sustainability performance’ vary according to different actors of the construction industry. The internationally standard definition of a green building is provided by ASTM Standard E2114–04 (E06 Committee, 2004), that is, “a building that provides the specified building performance requirements while minimizing disturbance to and improving the functioning of local, regional, and global ecosystems both during and after its construction and specified service life”. Furthermore, “a green building optimizes efficiencies in resource management and operational performance and minimizes risks, which threaten the human health and environment”. By emphasizing performance requirements and human health, the principles of the triple bottom line are integrated within this definition of a green building. Also, it specifically mentions the importance of taking into account the different stages of a buildings lifespan, from construction and service lifespan, to what happens after a buildings service lifespan.

LEGISLATION

Worldwide Legislation

The United Nations Framework Convention on Climate Change (UNFCCC) was negotiated at “the
Earth Summit”, the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992. The objective of this international environmental treaty is to “stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”. The Kyoto Protocol is an international agreement linked to the UNFCCC, which commits its Parties by setting internationally binding emission reduction targets. The main goal of the Kyoto Protocol is to contain emissions of the main anthropogenic (i.e., human-emitted) greenhouse gases (GHGs) in ways that reflect underlying national differences in GHG emissions, wealth, and capacity to make the reductions. The first round of the protocol was completed in 2012, but much greater emission reductions will be required in future to stabilize atmospheric GHG concentrations (Oberthür & Ott, 1999).

European Legislation

For meeting the commitments on climate change made under the Kyoto protocol, the EU has introduced legislation to ensure that buildings will consume less energy in the future. A key part of this legislation is the Energy Performance of Buildings Directives (EPBD). The first directive (Directive 2002/91/EC,EPBD), first published in 2002, requires that an energy performance certificate (EPC) is made available when buildings are constructed, sold or rented out. The certificate has to express the operational energy performance of the building. Also, every country had to insert legislation stating a minimum performance. Subsequently, the second Directive (Directive 2010/31/EU, EPBD) states, that “Measures are needed to increase the number of buildings which not only fulfil current minimum energy performance requirements, but are also more energy efficient, thereby reducing both operational energy consumption and carbon dioxide emissions. For this purpose Member States should draw up national plans for increasing the number of nearly zero-energy buildings and regularly report such plans to the Commission”. Also, being more specific, Article 9 states: “Member States shall ensure that: by 31 December 2020, all new buildings are nearly zero-energy buildings; and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings”.

There are only very limited mandatory requirements related to building components and materials used in buildings, in practice energy-saving measures predominate. The mandatory requirements that currently exist in the EU countries studied by Reijnders & Van Roekel (Reijnders & van Roekel, 1999) deal only with very limited aspects of the interactions between buildings and the environment.

ASSESSMENT METHODS

As mentioned, an Energy Performance Certificate is obligated in Europe when a building is constructed, sold or rented out, therefore this type of certificate will be considered first. Subsequently, a wider range of building environmental assessment (BEA) tools, which are all voluntary and motivational in their application, will be considered. The field of BEA has matured remarkably since the introduction of the UK Building Research Establishment Environmental Assessment Method (BREEAM) in 1990, and the interim period witnessed a rapid increase in the number of tools (Cole, 2005). Reijnders and van Roekel (Reijnders & van Roekel, 1999) have made a rough division of BEA tools into two groups. The first group includes those, which are based on scores and a criteria system and are regarded as qualitative tools, the Criteria Based Tools (CBT). The second group includes the tools that use life cycle assessment (LCA) methodology with quantitative input and output data on flows of material and energy throughout the different stages of a buildings life cycle, from construction and use to demolition and recycling. For each category, the EPC, CBT and LCA, firstly the sustainability criteria and methodology will be introduced, secondly the pros and cons of their application will be elaborated, and thirdly they will be assessed from the perspective of refurbishment.

Energy Performance Certificate

Criteria & Method. The definition of the energy performance of a building is the amount of energy, actually consumed or estimated, necessary to meet the performance requirements associated with
a standardized operational use of the building (Poel, van Cruchten, & Balaras, 2007). The criteria that are used in these calculations are: insulation values, technical and installation characteristics (including own-energy generation), design and positioning in relation to climatic aspects, solar exposure (taking into account the influence of neighbouring structures), and indoor climate factors that influence the energy demand. The Energy Performance Certificate is a document that indicates the operational energy performance of a building as a numerical output, calculated according to a methodology based on the general framework set out by the EPBD. Following the first EU directive, all EU countries have stated a minimum performance. There are many different software programs that allow these calculations to be made, most programs use an interactive model where the user can easily adjust for example the R-value (thermal resistance) of a wall, the type of ventilation system used or whether there are solar panels on the roof or not. These changes immediately result in a change in the Energy Performance, allowing for the user to compare the effect that different options have on the energy use of the building.

**Pros & Cons.** An EPC is based on the quantitative calculation of the operational energy consumption, creating an objective basis to assess and compare design solutions and buildings. These programs are relatively easy to use and allow for the user to integrate the outcomes at an early stage of the design process. Also, a study by Ronan Lyons (2013) has shown a positive impact of the Energy Performance Certificate on sales and rental prices of buildings on average in most of the Member States that were analysed, indicating that better energy efficiency is rewarded in the market. On the downside an EPC only covers the operational energy use of a building, disregarding not only the stages of construction, maintenance and eventual demolition and recycling, but also the resources that are being used and the environmental impacts that are related with them.

**Refurbishment.** Energy Performance Certificates are also applicable to existing dwellings and refurbishment projects. Although, since an EPC focusses on operational energy use and doesn’t take into account sustainability factors like resource use and waste production, it could be considered easier to attain the best EPC rating through rough demolition and new construction rather than through refurbishment of an existing building.

**Criteria Based Tools.**

**Criteria & Method.** The Criteria Based Tools essentially consist of lists of suggestions for the environmental improvement of buildings linked with a score (Reijnders & van Roekel, 1999). Among the criteria-based tools (CBT) are Building Research Establishment’s Environmental Assessment Method (BREEAM) and Civil Engineering Environmental Quality Assessment and Award System (CEEQUAL) (UK), SBTool (International), Leadership in Energy and Environmental Design (LEED) (USA), High Environmental Quality certification (HQE) (France), EcoProfile (Norway), PromisE (Finland), Green Mark for Buildings (Singapore), H K-BEAM and CEPAS (Hong Kong), Green Star (Australia). BREEAM is the leading and most widely used criteria based environmental assessment method for buildings (Nguyen & Altan, 2011). It was developed in the UK in 1990 and is the building environmental assessment method with the longest track record. The CBT’s cover a wide range of criteria which are classified into categories (e.g. BREEAM): Energy, Transport, Water, Waste, Materials, Land Use & Ecology, Health and Wellbeing, Pollution, Management, Innovation. The method of a CBT typically consists of three major components (Cole, 2003).

1. **Structure;** a declared set of environmental performance criteria organized in categories.
2. **Scoring;** the assignment of a number of possible points or credits for each performance issue that can be earned by meeting a given level of performance.
3. **Output;** a means of showing the overall score of the environmental performance of a building or facility, usually involving a weighting system that is assigned to the different categories.

**Pros & Cons.** The Criteria Based Tools offer a wide range of sustainability aspects; there are even credits to be earned considering whether there is a bus stop nearby or not. On the downside, the coverage
is rather superficial (Reijnders & van Roekel, 1999) and is not based on a systematic study of environmental impact related to the factors concerned; it is unclear whether the effects of the environmental improvements suggested are marginal, substantial or large (Reijnders & van Roekel, 1999). Additionally, weighting is inherent to the systems and when not explicitly, all criteria are given equal weights (Todd et al., 2001). According to Lee et al. (2002) weighting is the heart of all assessment schemes since it will dominate the overall performance score of the building being assessed. However, there is still no consensus on the assignment of weightings. The Green Building Challenge aims to provide a default weighting system, taking into account regional differences by encouraging users to change the weights. However, although sustainability issues differ from region to region, there is no consensus on regional weighting systems. There is a concern that it is possible to manipulate the results, if the default weighting system is altered in order to satisfy specific purposes (Larsson, 1999; Todd et al., 2001)(Ding, 2008).

The Criteria Based Tools are very complex, it requires training and certification to be able to use them (Nguyen & Altan, 2011). As a result, they are not accessible and are often used as a checklist at the end of the design stage instead of being used early in the design process while the most important decisions with regard to sustainability should be made at the beginning of the design process (Zeiler, 2011). Environmental issues are broad and difficult to capture, combining qualitative and quantitative data, a balance between completeness of coverage and ease of use remains one of the challenges in developing an environmental building assessment tool (Ding, 2008).

Lastly, developers and designers use the CBT’s to attain an overall desired “score”: a BREEAM “Excellent” or “Very Good,” or LEED “Gold” or “Silver”. The goal of achieving a high score may be considered to be more important than achieving a good overall product (Cole, 2003). In addition, the results of all categories are converted into a score. Each category has to attain at least a "pass", however, categories have very limited or no minimum requirements and a detraction of credits for polluting components does not exist. Therefore, a project can contain very environmentally unfriendly components in a specific category, and still achieve a high final score. This checklist approach, where the meeting of individual performance requirements is pursued in the quest for a certain overall rating, detracts the designer from the more fundamental issue of ethics and professional responsibilities. More skilled design teams recognize that the interrelationship between the different strategies and systems is key to successful sustainable design (Cole, 2003).

Refurbishment. Some CBT’s (e.g. BREEAM) have developed a special tool for refurbishment, in which the criteria and weightings are adapted to suit refurbishment better. Refurbishment can thus be tested by means of these tools, however, cannot be compared to new construction, because it concerns separate tools whose scores are not comparable.

Life Cycle Assessment Tools.

Life Cycle Assessment (LCA) is “a method for analysing the environmental burden of products (goods and services) from cradle to grave, including extraction of raw materials, production of materials, product parts and products, and discarding them by recycling, reuse, or final disposal” (Guinée, 2002). LCA is defined as “the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle” (International Organization for Standardization (ISO), 1997). The most advanced and most used software tools for Life Cycle Assessment of products are Simapro (Netherlands) and Gabi (Germany). Life Cycle Assessment software tools that can be used to assess buildings include: ECOSOFT (Austria), EcoCalculator (Canada), Eco-bat (Switzerland), LEGEP (Germany), GaBi-Build-IT (Germany), SBS (Germany), ELODIE (France) EQUER (France) COCON (France), ECO-QUANTUM (The Netherlands), GreenCalc+ (The Netherlands), EcoEffect (Sweden), IMPACT (UK) and BEES (USA).

The indicator called “embodied energy”, lies at the basis of Life Cycle Assessment. The so called “initial” embodied energy is the sum of the energy that is consumed by all of the processes associated with the production of a building, considered as if that energy was 'embodied' in the product itself. As
buildings are designed to be more and more energy efficient during the operational phase of the life cycle, the initial embodied energy becomes relatively more significant. The initial embodied energy of a building is a significant multiple of the annual operating energy consumed, ranging from around 10 for typical dwellings to over 30 for office buildings (Ciravoğlu & Taygun, 2013).

The “gross life cycle embodied energy” consists of the total embodied energy during the life cycle of a building, taking into account not only the initial embodied energy that was used in initially construct the building, but also the operational energy, the embodied energy used during maintenance and/or refurbishment and the energy used to dismantle or demolish the building and dispose of- or recycle the materials (Ciravoğlu & Taygun, 2013). With the recycling and re-use of the materials, a part of the embodied energy of those materials can be detracted from the gross life cycle embodied energy. Based on LCA, a zero energy building consists of a building which will produce enough energy during its lifetime to recover this energy debt (Storey and Baird, 1999), while a zero energy building generally only accounts for the energy debt created during the operational use of the building.

The aspect of embodied energy, although it is vital to the ideology of Life Cycle Assessment, is only part of the actual assessment methodology. Following ISO 14040, an LCA consists of four components or steps (AIA Guide to Building Life Cycle Assessment in Practice);

1. Goal and Scope Definition,
2. Inventory Analysis,
3. Impact Assessment,
4. Interpretation.

In addition to the calculation of embodied energy, which is part of the inventory analysis, environmental effects and impacts are also assessed in LCA methods. These consist of (e.g. EcoQuantum v.2.00): Environmental effects; Material use, Energy consumption, Water consumption. Environmental Impacts; Depletion of abiotic resources potential (ADP) Global warming potential (GWP), Ozone depletion potential (ODP), Photo-oxidant formation potential (POCP), Human toxicity potential (HTP), Aquatic ecotoxicity potential (AETP), Sediment ecotoxicity potential (SETP), Terrestrial ecotoxicity potential (TETP), Acidification potential (AP), Eutrophication potential (EP)(Itard & Klunder, 2007).

**Pros & Cons.** LCA is a scientific way of determining environmental impacts, based on international databases, calculation methods and ISO standards. The LCA-based methods have an in-depth coverage of environmental impacts associated with design and building materials. The latter is not unexpected because the methodology essentially builds on LCAs of products used in the building industry. Moreover, LCA-based instruments allow for estimates of the relative improvements associated with specified changes in design or the choice of building materials (Reijnders & van Roekel, 1999). LCA is based on a long-term vision, taking into account not only what is sustainable now, but also relating this to the past and the future of a product. Doing an LCA for buildings is very complex (compared to normal ‘products’) for four reasons; firstly buildings have a long and difficult to predict longevity, secondly a building usually undergoes many changes in form and / or function during its lifetime, thirdly a significant part of the environmental impact takes place during its use, fourthly, every building is unique and there are many different parties involved in the life cycle of a building. For these reasons, and because LCA is relatively new to the building industry (AIA Guide to Building Life Cycle Assessment in Practice), they are still less developed and less widely used than the CBT methods. Also, LCA contains no direct coverage of the indoor environment (Reijnders & van Roekel, 1999).

**Refurbishment.** LCA is ideal for evaluating a refurbishment process compared to other options. When taking into account the existing embodied energy already present in the existing building and the energy and materials used during demolition and construction of a new building, it is possible to compare the environmental impacts of refurbishment versus demolition and new construction through LCA.

**CONCLUSION AND DISCUSSION**
When the definition of sustainability, the existing legislation in the field of sustainability and the existing certificates and methods in the field of sustainability are put into relation with one another it becomes clear that these don't match. The legislation, and the consequent Energy Performance Certificate, concentrates on energy consumption during the operational use of a building. The commonly accepted definition of sustainability, the triple bottom line, focuses on environmental, social and economic health; planet, people, profit. These three categories are also reflected in the standard definition of a “green building”, in addition, it specifically mentions the importance of taking into account the different stages of a buildings life, from construction and service life, to what happens after a buildings service life. The latter lies at the basis of Life Cycle Assessment methods: covering a much wider spectrum of environmental sustainability, taking into account different stages of the buildings life cycle and concerning a large range of environmental impact criteria in addition to energy. Social and Economic aspects, however, are not reflected in an LCA. The Criteria Based Tools do take into account economic, social and environmental sustainability aspects, although the main focus lies on the environmental sustainability impacts during the construction and operational use stages. These different areas of sustainability are shown in Table 1, clearly showing the extremely narrow part of sustainability that the legislation and the associated Energy Performance Certificates are focusing on. Also, the Criteria Based Tools have two separate indicated areas, one that stands for its main focus area, and one covering the wide range of rather superficial indicators covering the entire spectrum of sustainability.

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The fact that legislation and regulations are concentrating on energy consumption during the operational use of a building has led to this principle being translated as “sustainable” in practice. A building is considered to be extremely sustainable when a zero energy value is achieved. The fact that in these cases other aspects of sustainability are completely ignored is problematic. Concepts such as "passive building" and "energy-neutral home" are popular, and national and international standards concentrate on attaining extremely high insulation values of the shells of buildings. That this insulation may often be environmentally polluting is completely disregarded. Also, there is for example the extensive use of solar panels to balance out the operational energy, while completely disregarding the embodied energy and environmental impact that was necessary to create the solar panels in the first place, a kind of deceptive sustainability. In relation to refurbishment, these regulations are also very problematic. Buildings that reach a certain age fall short of adequate operational energy efficiency to fill current standards, and are consequently threatened by large-scale demolition; to achieve the highest possible energy label demolition and new construction often are an easier option than refurbishment. The embodied energy present in these buildings will be discarded, the resources used in the new construction...
will not be accounted for, and the waste that is produced because of this is ignored. These things will not stand in the way of the newly constructed building achieving the highest energy certificate level, nor will it stand in the way of the newly constructed building being awarded sustainability prices and being promoted as “best practice”.

However, as described in the article, there are other assessment methods that try to provide a more complete assessment of sustainability. Unfortunately, they are very complex and require training and certification to be able to use them (Nguyen & Al tan, 2011). As a result, they are not accessible and are often used at the end of the design stage instead of being used early in the design process while the most important decisions with regard to sustainability should be made at the beginning of the design process (Zeiler, 2011). They are therefore, and because they are completely voluntary in their application, far from standard in use.

The use of a different list of indicators in different approaches makes a definition of the term “Sustainable Construction” subjective and causes difficulties in comparing results from different tools. A case-study comparison by Zeiler (Zeiler, 2011) where eight different case studies were tested by four of the most popular assessment methods (LEED, BREEAM, Greencalc, Ecological Footprint), proved the outcomes to be completely different. A building could be considered most sustainable by one tool, and least sustainable by another. In order to overcome these constraints, both the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN) have worked actively in the last few years to define standard requirements for the environmental and sustainability assessments of buildings (Mateus & Bragança, 2011). Both standards ISO/TC59 and CEN/TC350 take into account economic, social and environmental sustainability and aspects regarding a products life cycle from cradle to grave, they provide general definitions and principles regarding indicators and calculation methods for assessment tools. These standards do not set the rules for how building assessment schemes may provide valuation methods, nor does it prescribe levels, classes or benchmarks of performance (Technical Committee CEN/TC 350, 2010). Since these standards are not mandatory nor completed yet (especially on the part of social and economic sustainability), they haven’t been fully integrated in the assessment tools yet.

Efforts are being made to integrate LCA methodologies in CBT tools, trying to combine the measurability of LCA’s with the wide range of sustainability aspects covered in a CBT. Environmental issues are broad and difficult to capture, combining qualitative and quantitative data, a balance between completeness of coverage and ease of use remains one of the challenges in developing an environmental building assessment tool.

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Session 8D: Integration of renewable energy

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14:10 - 15:50, Grace - Knowledge Consortium of Gujarat
Zero Energy Solar-House Technology
Aiming Greenhouse Gases Emissions Reduction by Residential Sector in Brazil

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ABSTRACT
This study aims to define a Zero Energy Solar-House and analyses its contribution to global warming mitigation by reducing Greenhouse Gases (GHG) emissions. This study identifies guidelines for a Solar-House project regarding electricity use, environmental conditioning, solar systems and equipment in order to obtain energy efficiency. Data to evaluate the Solar-House model are provided by Ekó House Project, which is a solar house prototype. The balance of GHG emissions reduction focus on electricity consumption, and to account avoided emissions this study considers solar photovoltaic (PV) generation instead of grid electricity, as well as energy efficiency measures harnessing the sun’s energy on a passive way. This study goes through a comprehensive analysis of Brazilian electricity system, the use of electricity by the Residential Sector and GHG emissions associated. As a result, this study sets basic guidelines for a Zero Energy Solar-House and accounts the potential do avoid GHG emissions with this housing model. Benefits due to large-scale implementation of this model in Brazil are evaluated. To measure the impact of these solutions on a larger scale is taken as geographic boundary Southeastern Brazil – a region with high population density and need for importing energy from other regions of the country – where this study considers the adoption of energy efficiency measures and PV generation for a percentage of dwellings. Results show potential to avoid up to 0.9 Mt CO₂ emissions each month. From an interrelated analysis of solar PV generation and energy efficiency assessments, this study concludes that the solar-house taken as a reference has a significant potential to reduce GHG emissions, contributing to Brazil’s sustainable development and global warming mitigation.

INTRODUCTION
The current economic development model considers the environment as an endless source of natural resources and final destination, with unlimited capacity to receive waste generated by human activity, embracing inefficiency and wasteful use of natural resources, especially energy, which is one of the essential supplies for the basic conditions of human life. Such model and the unbalanced operation and use of environment are the vectors of environmental problems.

Brazil is a developing country and as so, the tendency is that energy demand will increase along with the economy, implying the construction of new hydroelectric and thermoelectric plants, causing significant environmental, social and economic impacts. The residential sector consumes 26% of total
Brazilian electricity, and the increment of population purchasing power leads to an increase in energy consumption by this sector. This highlights the need to adopt energy efficiency measures and alternative and renewable energy sources, so that people can have access to consumer goods and improve their quality of life in an efficient way.

The Brazilian energy matrix is considered clean. In the National Interconnected System (SIN), 67% of energy comes from hydropower. Nevertheless, increasing concern with environmental and social impacts of the construction of new plants has been noticed. On the other hand, studies show the enormous potential for the exploitation of solar energy in the country, due to favorable levels of solar radiation throughout the year and photovoltaic systems for distributed generation are approaching an economic feasibility (EPE 2012). Therefore, it is argued that solar energy has demonstrated potential to contribute to supply this growing demand.

Given this scenario, this study aims to determine the contribution of a Zero Energy Solar-House (ZESH) to the sustainable development through energy efficiency and the use of solar energy, allowing the reduction of GHG emissions associated to energy consumption by residential sector in Brazil. To verify the potential of these actions on a larger scale, is taken as geographical boundaries the Southeastern Brazil, considering the replacement of a percentage of single-family houses by units (or systems) in the lines of the CSZE. Methodologically this study adopts a solar-house prototype, the "Ekó House", that verifies the ZESH. Thus, it is possible to predict the effective reduction of GHG emissions associated with energy use by Brazilian residential sector.

The Ekó House prototype was developed by Team Brazil, a partnership between São Paulo University and Federal University of Santa Catarina to participate on Solar Decathlon Europe in 2012. This prototype is adopted because it meets the requirements of a ZESH and simulation data regarding its energy and environmental performance are available.

GUIDELINES FOR A ZERO ENERGY SOLAR HOUSE

This study takes as dwelling unit reference a house that generates locally its own energy from PV modules. The ZESH also uses sun energy in architectural design for passive conditioning of indoor environment, reducing energy consumption. In this sense, geometries that result in elongated facades facing north and south orientation obtain a better use of the sun throughout the year. In summer, when the sun is more directly overhead, radiation is less intense on north oriented facades than is east and west oriented facades (Southern Hemisphere). In winter the sun is lower, and radiation is more intense in north oriented facades than in east and west oriented facades, as shown in Figure 1.

![Figure 1](image)

The envelope elements of a CSZE have appropriate thermal performance, based on climate conditions of the implantation site, through strategies such as insulation, the use of thermal mass and/or natural ventilation. The reference prototype has high thermal insulation levels and windows properly dimensioned and positioned, ensuring natural lighting and ventilation. This results in good comfort conditions with low energy consumption by integrating passive and active strategies. Simulation models
indicate a Daylight Autonomy of 60% for the Ekó House prototype (Projeto Ekó House, 2012).

In Brazil, the high investment required to improve the performance of buildings, leads people to employ low cost and low performance materials. Furthermore, there is usually no concern in adopting bioclimatic strategies to improve the thermal performance of buildings in a passive way. This implies higher energy consumption during building’s life occupancy (CANDIDO, 2010; PIRES et al, 2014).

In a ZESH it is essential to anticipate installation demands of solar systems, considering all components of each system on the architectural programming. The images in Figure 2 illustrate a modular construction system and solar systems in a CSZE.

Figure 2 Solar Systems for a ZESH. (Projeto Ekó House, 2012)

The 48 monocrystalline PV panels, with an 18.5% efficiency and 11 kWp of total installed capacity generate, on average, 1.790kWh/month, enough to meet the prototype energy demand, which is around 735kWh/month, and still provide around 1.055kWh/month of clean energy to the grid (Projeto Ekó House, 2012). This positive energy balance was adopted to meet a specific purpose for which the prototype was conceived in a first moment, that is, hosting in isolated an environmentally sensitive areas in Brazil. The prototype would be connected to a local grid and could export the surplus energy to meet the demand of local facilities, like schools and healthy centers, or dwellings in these isolated locations. The graph in Figure 3 illustrates the prototype energy balance for a typical operation year.

Figure 3 Energy balance for Ekó House prototype. (Projeto Ekó House, 2012)

The use of efficient appliances helps reducing energy consumption. Ekó House prototype uses National Program for Energy Conservation (PROCEL) 'level A' label. Artificial lighting, designed to complement the natural lighting, uses LED, which guarantees higher energy savings, lower maintenance and longer life. A home automation system integrated to the use of equipment and the general prototype operation contributes to a more efficient operation. This system can be programmed to guide the occupant, informing about energy generation and consumption and also control lighting and temperature, activating equipment and systems based on pre-established comfort ranges or person presence in indoor environments. Figure 4 shows schematically the energy generation and consumption in a ZESH.
The National Interconnected System (SIN) is a large hydrothermal system, with a strong predominance of hydroelectric plants. Only 3.4% of the country’s capacity of electricity production is out of SIN, in small isolated systems located mainly in Amazon region (ONS, 2013). Hydroelectric plants correspond to 67% of energy generation, such participation enables to consider the Brazilian electricity matrix a clean matrix. Nevertheless, with the need to build new power plants to meet growing demand for electricity, more pressure comes from society and NGOs because of environmental and social impacts caused by the implementation of such new plants. Even as it is planned to extend the thermal generation in the country, including the completion of Angra III nuclear and coal-fired plants as a complement and rational diversification of usable hydropower potential naturally limited (BRASIL, 2007). It is also important to note that the losses in transmission and distribution stages reach 16.9% in SIN (BRASIL, 2012). The graph in Figure 5 discriminates participation by source in SIN.

Another condition that highlights the need to explore other energy sources is the fact that most of the hydric resources in Southern and Southeastern are already exploited, and most of the remaining reserves are in the Amazon, away from industrial and population centers (OECD, 2001). It is important to note the potential for solar energy exploitation due to favorable annual irradiation levels in the country, ranging on average from 1.260 to 1.420kWh/m²/year (EPE, 2012). Further, the National Electrical Energy Agency (ANEEL) approved in 2012 a resolution that allows installing grid-connected PV micro-generation in dwellings.

On the other side of the equation is the electricity consumption. The residential sector accounts for 26% of total electricity consumption in the country, and it is expected that this participation will remain for the next 10 years, with an estimated increase of 48.3% by 2021. This amount considers energy efficiency measures due to use of more efficient equipment in Brazilian dwellings (BRASIL, 2012).

It is important to notice that peak demand in Brazil usually occurs by the end of the day, from 6:00 p.m. to 9:00 p.m. and is associated to use of artificial lighting, home appliances and electric shower. However, this year during the summer, new records in peak consumption were registered in Southeastern/Midwest and South SIN subsystems, as shown on Figure 6 graphics. Such shift on peak

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**Figure 4**  Energy generation and consumption in a ZESH. (From Projeto Ekó House, 2012)

**Figure 5**  Participation by source in SIN. (EPE, 2012)

---

**Figure 6**  Graph showing peak consumption in Southeastern/Midwest and South SIN subsystems.
time is associated to constant high temperature and thermal discomfort index in these regions, at the time higher insolation, which increased the use of HVAC systems (ONS, 2014).

![Figure 6](image)

**Figure 6** Instantaneous peak demand in SIN subsystems. (ONS, 2014)

Regarding the specific consumption by appliance and equipment, a research on “equipment checkout and use habits” (PROCEL, 2007) indicates the participation of different appliances in energy consumption by the Brazilian residential sector, as shows the graph on **Figure 7**. In Southeastern Brazil the average electricity consumption is around 180kWh/month for each dwelling (EPE, 2013). This indicates that there is room for increasing electricity consumption by this sector.

![Figure 7](image)

**Figure 7** Participation of appliances in Brazilian dwellings. (PROCEL, 2007)

Such data regarding electricity generation in Brazil and specific consumption by the residential sector are applied to assess the benefits of a ZESH, regarding the adoption of energy efficiency measures and the PV generation by reducing energy consumption and avoiding GHG emissions.

**GHG EMISSIONS BY SIN AND PV SYSTEMS**

As already pointed, it is estimated that participation in electricity consumption by the residential sector will continue in the coming years, with an increase in energy consumption and, consequently, in associated GHG emissions, which must pass from 18 Mt CO2-eq in 2011 to 23 Mt CO2-eq in 2021 (BRASIL, 2012).

This study adopts the emission factor of SIN, for which the average of the last five years was 0,2926 t CO2/MWh (MTC, 2014). For the amount of greenhouse gas emissions of PV systems, are assumed values defined in the Special Report of the Intergovernmental Panel on Climate Change (IPCC), according to which the average emission factor for such systems is 0,046 t CO2/MWh (IPCC, 2012). Emissions attributed to solar photovoltaic generation are from the manufacture of photovoltaic systems and can be compensated by the manufacturer or end user.

From the combination of these data it is possible to estimate the reduction of GHG emissions that energy efficiency measures such as those adopted in ZESH and power generation by PV system can represent when applied on a larger scale.

**ENERGY GENERATION AND CONSUMPTION IN ZESH**

To analyze the contribution of ZESH to the sustainable development, data of Ekó House prototype...
are applied. Such data come from computational simulations and estimate values of generation and power consumption over a year of operation. The simulations consider developed countries comfort standards, with the presence of some appliances that, in Brazil, are not common to all population strata in the country. However, with economic development and greater purchasing power of the population, such equipment must be increasingly present in Brazilian homes, increasing the power consumption of residential sector. On the other hand, solar collectors for water heating are adopted and artificial lighting uses only LED. The graph in Figure 8 shows the monthly consumption in Ekó House prototype.

![Figure 8](image)

**Figure 8** Consumption by equipment in Ekó House prototype. (Projeto Ekó House, 2012)

By comparing the simulated consumption for the prototype of 735 kWh/month, with the monthly average consumption of households in developed countries such as the United States, which consumes on average 958 kWh/month (EIA, 2011) per dwelling, it is possible to realize that even keeping comfort levels of these countries, the prototype reaches more efficiency in electricity consumption.

To estimate the reduction in energy consumption, this study considers the adoption of solar collectors for water heating in Brazil. It is assumed that 70% of the annual demand for hot water is provided by solar collectors. Thus, the reduction in power consumption obtained is approximately 17%. Assuming that an appropriate use of the sun for daylighting and passive conditioning associated with the use of LED system and passive thermal conditioning strategies, contribute to energy efficiency with a 30% saving in consumption by air conditioning and artificial lighting systems. Thus, another 10% of total consumption would be avoided, as shown in Figure 9.

![Figure 9](image)

**Figure 9** Energy savings for harnessing solar energy.

ZESH CONTRIBUTION TO REDUCE ELECTRICITY CONSUMPTION AND AVOID GHG EMISSIONS

To demonstrate the contribution potential of harnessing solar energy in architecture, it is taken as geographical boundaries the Southeastern Brazil, which has about 20 million households, of which approximately 80% (or 16 million) are single houses (IBGE, 2010). To account the contribution of using solar PV, it is considered that 50% (8 million) of single-family houses would adopt PV micro-generation system, similar to Ekó House, but a lower cost system to be economically viable. With PV generation, avoided emissions could reach 0.2926 kg of CO₂ for each 1.0 kWh generated. Assuming a PV system
with 24 polycrystalline modules, with a 13.5% efficiency and a 3.24 kWp installed capacity, the generating would be on average 387 kWh, considering the data for São Paulo, according to RETScreen® 4 software simulation. Thus, avoided GHG emissions in SIN would be around 113 kg of CO₂/month per household, or 0.9 Mt CO₂/month considering the adoption of this PV system in 50% of single houses in the Southeastern, totaling 10.8 Mt CO₂ per year.

According to a financial analysis, simulated also on RETScreen® 4, such system would have a price around 0.35 R$/kWh, without considering incentives, which is close to the average electricity tariff in the country of 0.32 R$/kWh (ANEEL, 2014). It is also important to notice that some studies already point to an economic viability of PV systems for distributed generation in Brazil (EPE, 2012).

Taking into account the average dwellings consumption in the Southeastern, 180 kWh/month, and the projected increase in consumption of the residential sector in the ten-year horizon, the average consumption is expected to reach 270 kWh/month in the coming years. With the values assumed for energy savings through solar energy use, this consumption could be reduced by 27%, resulting in a consumption of 197 kWh/month. Such measures would contribute to stabilize consumption on a decennial horizon, even improving comfort conditions in dwellings. Thus, on average, 190 kWh/month would be delivered to the grid by each household with the PV micro-generation system, or 1520 GWh by installing micro-generation in 50% of single houses in the Southeastern, avoiding up to 0.44 Mt CO₂ of emissions per month in SIN. Still, not considering the PV generation, and considering the harness of the sun, as described above, could save 27% on energy consumption, and this would represent a reduction of about 73 kWh/month per household, or 584 GWh for 8 million dwellings, avoiding 0.17 Mt of GHG emissions.

The graph in Figure 10 illustrates the emissions avoided by PV micro-generation in single house units and the adoption of energy efficiency measures focused on harnessing solar energy, through projections to the Southeastern Brazil. The added value comes when the manufacturer is responsible for offsetting GHG emissions from the manufacturing of PV systems. In this case, the SIN emissions factor is adopted to account GHG emissions avoided. But when the consumer assumes such compensation, the emission factor applied is the one for SIN discounting the PV systems emission factor.

Figure 10   Potential to avoid emissions in the Southeastern Brazil through ZESH.

The study considered that the increase in consumption by the residential sector will be made according to PDE 2021 predictions. Nevertheless, this projection was made taking into account a consumption which also expresses a pent up demand for electricity in the country. With a PV with an installed capacity such as the one adopted for this study, it would be possible to reach better comfort conditions, supplying this demand with a clean and renewable source, without additional GHG emissions.

The PV generation in locations where single houses are a predominant typology can contribute to meet the demand on the network at times when other sectors require more energy than residential, like the commercial sector during daytime. The records on peak consumption during summertime point that electricity demand in SIN is increasing during daytime. This highlights that PV systems adopted on a large scale would contribute to supply electricity demand in SIN and avoid GHG emissions, by
exporting energy clean energy to the grid. The use of solar collectors, LED system and the adoption of passive conditioning strategies contribute to reduce the demand for electricity at regular peak consumption time in the end of the day, when electricity demand increases in dwellings due to the use of artificial lighting, thermal conditioning systems and, specially, the electric shower.

CONCLUSION

This study demonstrates that a ZESH can make a decisive contribution to sustainable development. The combination of solar systems and energy efficiency measures demonstrates high potential to contribute in meeting the demand for electricity in the SIN through PV generation, and it also contributes to reduce demand at electricity consumption peak time.

From the projections made in this study, it is possible to conclude that energy efficiency measures help to avoid GHG emissions, mainly in the case of ZESH. The expected increase in demand for electricity by residential sector allows us to observe the relevance of such measures, in order to improve population’s comfort and welfare without necessarily increase electricity consumption. However, the PV generation demonstrated an even greater contribution on avoiding GHG emissions, especially when there is surplus electricity generation that can be exported to the grid.

In short, the ZESH demonstrates potential to contribute to sustainable development of the country and use of solar energy proves to be essential inasmuch a long-term reliability on non-renewable sources can be considered unsustainable economically, socially and environmentally.

ACKNOWLEDGMENTS

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REFERENCES


Development of Multivalent PV-Thermal Collectors for Cooling, Heating and Generation of Electricity

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ABSTRACT

Growth of cities and rising occupant comfort expectations has led to an increasing cooling demand of buildings. The use of solar energy for the production of electricity with photovoltaic modules and hot water with solar collectors is a common application. Operating the PV-T collectors at night is the possibility given to cover the cooling demand with a renewable energy source; radiative cooling. This paper focuses on the potential analysis of PV-T collectors for heating, cooling and electricity production for 6 different climate conditions. First the state of the art, four different PV-T technologies and two examples for building integration are presented. This new prototypes of PV-T collectors with different joining methodologies between the absorber and the PV module have been developed and tested at an outdoor test stand under dynamic conditions. Measurements of these four new collector types are shown and compared with a TRNSYS PV-T collector model. Finally a potential analysis for heating, cooling and electricity production for one of the developed PV-T collector was carried out under different climatic conditions. The simulation results showed that this PV-T collector has the highest cooling potential in cold and moderate climate zones where cooling is needed only temporarily. In hot and humid climates where cooling is needed over the whole year, the cooling potential of the PV-T collector for radiative cooling is less. The increase of electricity production by cooling the PV cells varies between 0,1 and 5,8 %, depending on the inlet temperature and the weather conditions.

INTRODUCTION

Hybrid PV-T (photovoltaic/thermal) collectors usually are used for heating and electricity generation. The combination of both technologies can save valuable building surface space (e.g. roof, facade) for solar installation because of the twofold use, while meeting all the energy demands of a consumer. Moreover, this technology enables retaining the efficiency of PV modules, due to the cooling effect of the thermal fluid on the PV cells, which prevents their overheating degradation. Recently, the possibility of cooling applications of PV-T collectors are being investigated where radiative cooling is employed based on long-wave radiation losses from the roof surface (for example) towards the sky driven by surface temperature difference. On a clear night, cooling capacities of 50-120 W/m\(^2\) can be reached (Cremers et al., 2010 and Beck & Büttner, 2006). New PV-T-collectors have been developed and installed in the building “home+” for the international competition Solar Decathlon Europe 2010 in Madrid, Spain, see section 3. The authors are currently improving this system within two research projects. The goals of the study are is to examine different technical solutions to build such PV-T collectors, to optimize and measure the thermal and electrical performances and to show possibilities for building integration with regard to architectural requirements.

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16-18 December 2014, CEPT University, Ahmedabad
1. PV-T TECHNOLOGIES AND STATE OF THE ART

A PV-T collector is a combination of a thermal absorber and a PV module that can be joined together in different ways. In this section the joining technologies are presented, along with an overview of the classification, historical background, and current market for PV collectors.

1.1. Classification of PV-T collectors

According to the IEA SHC Task 35, PV-T systems can be mainly classified into flat-plate air collectors, flat-plate liquid collectors, concentrating PV-T collectors and ventilated facade integrated PV-modules (Hansen and Sorensen, 2006). PV-T air collectors usually generate electricity that is used only to drive the ventilator and not for feed–in to the net; in this case, solar cells occupy only a small part of the collector aperture. Within this paper only water-based uncovered flat-plate collectors will be investigated and presented. Water-based flat plate collectors can be divided into covered and uncovered collectors (Figure 1). The difference between uncovered and covered PV-T collectors is that the latter are comprised of a top cover with an air gap to the absorber to reduce the long wave radiative heat transfer and convection losses.

Uncovered PV-T collectors usually have a glass or foil protection that belongs to the PV module. The most promising application for this type of collector is radiative cooling during the night because of higher radiative heat transfer due to the absence of a top cover. Covered collectors are more suitable for domestic hot water production and heating since higher fluid temperatures can be reached. However, higher temperatures within the module decrease the electrical efficiency of the PV cells - the cell efficiency decreases up to 0,5% per 1K temperature rise (Weller et al., 2009). To avoid this decrease in cell efficiency, the module has to be cooled by a fluid, which means that the system needs a consumer load to discharge the heat, see section 4.3.

![Figure 1: PV-T flat-plate liquid based collector uncovered und covered (PV on absorber area)](image)

1.2 Historical Background

First investigations on PV-T collectors started after the oil embargo 1973/74. The focus was basically to decrease the consumption of fossil fuels and as most applications require both electricity and heating, thermal and electrical parts were combined. Consequently, there was a need for further research in order to optimize the combination of both technologies. H.A. Zondag summarized in 2008 the historical development of PV-T collectors. The first works on PV-T liquid collectors were done by Martin Wolf in 1976 (Wolf, 1976, Zondag, 2008 and Hendrie, 1982). At the beginning, most of the research was done in the USA (and some in Japan), but in 1979 Karl also published his studies on the development of a PV-T collector in Germany (Karl, 1979 and Zondag, 2008).

Meanwhile, investigations were made to use radiative cooling towards the night sky to cool down water and also air or to discharge thermal mass on the roof (Erell, 2007). One of the first water-based radiative cooling systems was investigated by Juchau (1981). He used a regular solar thermal system for heating purposes to cool down water of a thermal storage tank during the night by circulating it through a standard flat plate collector. During the day, this water was used to cool a building through a radiant floor. In further investigations in Israel, the top-cover of a standard flat-plate collector was removed to increase the cooling power (Erell & Etzion, 1992).

The application of PV-T collectors for night radiative cooling has not yet been thoroughly researched, to the knowledge of the authors. PV-T collectors are becoming better known for cooling
applications through the international competition series of “Solar Decathlons”. Various building concepts with PV-T collectors for cooling purposes, such as the home+ building from the University of Applied Sciences of Stuttgart (Eicker & Dalibard, 2011), have been constructed.

Among the obstacles that constrain the promotion of PV-T collectors on the market is the absence of a corresponding standard for this combined technology. Solar Keymark provides a certification method for uncovered PV-T collectors based on existing standards. Within this certification the PV and Solar Thermal part are tested separately; the electrical performance of the PV part according to IEC 61215 or IEC 61646 and IEC 61730 and the thermal performance according to EN 12975-1 and EN 9806. During the thermal performance test, whether the PV module is operated under MPP, OC or SC condition must be indicated, since the efficiency of the thermal performance is influenced by the electrical part. In contrast, covered PV-T collectors are potentially not covered by the above mentioned standards since they are able to reach much higher stagnation temperatures and therefore potentially will not pass the PV standards (Fritzsche, 2013). In order unify standards for the PV-T collector, the research project “PVT-Norm” (Standardization of PV-T collectors) is being carried out (Bine, 2013).

1.3 PV-T collectors available on the market

Currently, approximately 27 manufacturers are known to produce uncovered PV-T collectors with or without thermal insulation and different technical solutions. Some manufactures produce also only a thermal part of a collector that can be mounted on the back of a PV module as a retrofit. The PV module can be therefore exchanged when needed. The producers of covered PV-T collectors are not so numerous; only 5 manufactures could be identified. PV cells in a covered collector can be attached either on the absorber or on the inner side of the covering. A PV-T collector with vacuum tubes is currently being developed by a company in England, but it has not yet been commercialized.

1.4 Prototypes within the Project

Within this project, different possible combinations of materials are investigated. The aim is to develop a collector that has very good performances and is cost-effective. For this purpose, different collector variants have been built and mounted on an outdoor test stand to characterize their performances in order to evaluate the best material combination and bonding technique, and to compare the results with commercially available products.

![Figure 2](image_url)

Different material combinations investigated

There are many possibilities of PV and absorber combinations including laminated or flexible modules with crystalline or thin film technology, both in combination with a normal deflector plate and pipe installation or holohedral flow through plastic or metal absorber, see Figure 2. The constructive aspects of PV-T collectors that have an impact on the thermal performance are mainly the thermal bond between the PV module and the thermal absorber (e.g. lamination, pressing and gluing) and the thermal resistance of the PV module itself, both of which are dependent upon the design and the manufacturing possibilities. One of the most critical properties is the thermal expansion coefficient of the PV module and thermal absorber. Consequently, the connection has to be flexible enough to balance the forthcoming dilatation of the chosen materials in addition to a small thermal resistance. Besides the thermal performance, there are other important aspects such as costs, durability and recyclability that should be considered with a new collector design.
In this paper, the following PV-T prototypes are presented (Figure 3):

Type 1 uses a polypropylene holohedral absorber fixed in the frame on the back side of a glass-PVB laminated PV module. The PV and the absorber are only pressed together.

Type 2 features the same construction as Type 1, with the difference that the polypropylene absorber is fixed with an air gap to the PV module. This simulates the building integration on a sloped roof when thermal and PV components are mounted separately.

Type 3 is a laminated glass-PV-absorber module with a serpentine copper absorber. The copper tubes and the aluminum absorber are bonded to the PV module back side with heat conductive silicon glue.

Type 4 is a polypropylene holohedral absorber pressed against a laminated glass-PV-glass module with aluminum U-profile in diagonal, providing more contact zones.

Type 5 is almost the same as the Type 3, the only difference is the PV module. In this case, a laminated glass-PV-glass is used. This increases the thermal resistance between the PV module and the absorber.

In section 4, the measurements results of collector type 1-4 are presented.

3. BUILDING INTEGRATION

The type of integration of PV-T modules depends on the application and on the surrounding neighbors. One building integration requirement for a high thermal efficiency for cooling purposes is a good view angle to the sky (180°), which indicates the absorber area is as horizontal as possible. Moreover a higher building next to the PV-T area causes a reduction of the view angle, which results in a smaller radiative heat transfer rate. For cooling applications, the heat losses of the PV-T collector have to be maximized. Therefore an uncovered, uninsulated and well ventilated PV-T module is the most pertinent design. For heating purposes and electricity generation, the PV-T collector performs better if it is inclined to a certain angle, depending on the latitude of the location. However the higher the inclination is, the lower the night time radiative cooling performances are.

Consequently, a compromise must be found between cooling and heating applications. For example, cooling of the PV cell improves electrical performances, which may thereby allow for some deviation from the optimal inclination / sun orientation angles.

Uncovered PV-T prototypes were installed on the roof in two buildings; the Ecolar building (Figure 4a) and home+ building (Figure 4b), collector type 4 and type 5, respectively. In home+, the PV-T modules are mainly used for cooling purposes (Cremers et al., 2010), while in Ecolar they are also used for warm water preparation. Despite the different collector designs, the collectors are both integrated on the flat roof. The PV-T collector area in home+ are totally horizontal with black monocrystalline cells and a white back sheet (module size 2,60x1,20m). In the Ecolar, the PV-T collectors are slightly sloped.
with black monocrystalline PV cells but with a black back sheet (1,03x4,28m). Here the PV-T area is also the water-drainage layer and a post-and-beam construction was chosen (HTWG, 2012). In home+, the rain water from the PV-T surface flows between the gaps of the PV-T modules to the waterproofing layer underneath, where the water is diverted from the inclined plane as depicted in Figure 4c. According to the building simulation of home+ presented by Eicker and Dalibard (2011), 43% of the cooling loads can be covered by the radiative cooling system in combination with a 1.200 liter heat sink tank for the location of Madrid.

Depending on the constructive integration level (e.g. addition, substitution, integration) (Weller et al., 2009), market available PV-T Modules are suitable for all possible building integration methods, such as in-roof mounting on pitched roofs.

4. TEST STAND RESULTS AND POTENTIAL ANALYSIS FOR SIX DIFFERENT CLIMATE LOCATIONS

As described above, PV-T collectors can be used to produce solar hot water and chilled water. At the University of Applied Science in Stuttgart (Germany) an outdoor test stand for the performance analysis of PV-T collectors was set up. The measuring process for the characterization of the PV-T collectors is based on the quasi-dynamic test method for uncovered thermal collectors of the new EN ISO 9806:2014. All important boundary conditions like wind, temperature, global radiation and longwave radiation were continuously measured and recorded. The collector field inclination at the test stand can vary between 0° and 90°, considering this roof and facade systems can be tested closely to their application. The presented measurements in the next section were carried out with an inclination of zero degrees and a collector inlet temperature near the ambient temperature.

4.1 Experimental measurements and evaluation of the results

In order to analyze the performance of the different collectors, collector types 1 to 4 have been tested simultaneously under dynamic conditions. Figure 5 shows the measured global radiation, ambient, inlet and sky temperature during the test period. The corresponding thermal power output for two days in May is presented in Figure 6.

The analysis of the measurements shows that collector type 3 performs best at day-time where the fluid is heated up and collector type 1 performs best at night-time where radiative cooling is dominant. Collector type 2 has the lowest power output at day- and at night-time, which could be explained by the high thermal resistance between the PV and solar thermal absorber caused by the air layer between the PV module and the solar thermal absorber. The thermal efficiency varies between 25 (for collector 2) and 48 percent (for collector 3). The efficiencies are low compared to standard covered flat plate collectors, which can reach efficiencies up to 80 percent during day-time. However, as before mentioned an additional glazing is counterproductive for radiative cooling application.

Figure 5  Measured thermal weather conditions (Stuttgart / Germany 20.05.2014 – 21.05.2014)
4.2 Climatic information for six different climate zones for the heating and cooling potential analysis

Weather data at the specific locations should be analysed in order to draw conclusions about the energy production of PV-T collectors without considering a whole building as a consumer. A common method for the calculation of heating and cooling periods from weather data files is the calculation of heating and cooling degree days (HDD and CDD). The degree-day method can be used to define the time period when cooling demand in a building is needed. The calculation is typically based on daily mean ambient temperatures. However, air conditioning systems are often turned on and off during unoccupied periods, therefore cooling degree hours or cooling degree periods better present the cooling demand. For the calculation of the CDD was obtained from the ASHRAE standard (ASHRAE. 2009) (Equation 1). The weather data for the locations was taken from Meteonorm Software (www.meteonorm.com) and represent long time mean values of the climatic conditions.

\[
CDD = m_k \sum_{k=1}^{365} (T_{e,k} - T_{tc})
\]

(1) 

\[
m_k = \left\{ \begin{array}{ll}
0 & \text{if } T_{e,k} < T_{tc} \\
1 & \text{if } T_{e,k} \geq T_{tc}
\end{array} \right.
\]

Where \( T_{e,k} \) is the mean external temperature at the k period of the year, \( T_{tc} \) is the threshold temperature for cooling (here 22°C). Table 1 shows the calculated cooling season, the \( CDD \), the mean and standard deviation of the ambient and sky temperature for daily occupation periods from 11am-7pm for six different climate zones as defined by Hausladen, Lied and Saldanha (2011).

<table>
<thead>
<tr>
<th>Location</th>
<th>Cooling season</th>
<th>CDD [Kd]</th>
<th>Mean ambient temperature and standard deviation</th>
<th>Mean sky temperature and standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moscow (cold climate)</td>
<td>20 May – 04 Sept.</td>
<td>102</td>
<td>17.9 / 4.5</td>
<td>10.2 / 7.1</td>
</tr>
<tr>
<td>Stuttgart (moderate climate)</td>
<td>11 Apr. – 04 Sept.</td>
<td>155</td>
<td>16.3 / 5.9</td>
<td>7.9 / 8.4</td>
</tr>
<tr>
<td>Shanghai (subtropical)</td>
<td>07 Apr. – 22 Oct.</td>
<td>997</td>
<td>24.2 / 5.1</td>
<td>18.5 / 7.5</td>
</tr>
<tr>
<td>Chennai (tropical)</td>
<td>01 Jan. – 31 Dec.</td>
<td>3803</td>
<td>29.1 / 3.8</td>
<td>23.1 / 4.6</td>
</tr>
<tr>
<td>Dubai (coastal desert)</td>
<td>01 Jan. – 31 Dec.</td>
<td>3617</td>
<td>28.4 / 6.6</td>
<td>18.3 / 8.0</td>
</tr>
<tr>
<td>Riyadh (continental desert)</td>
<td>01 Jan. – 31 Dec.</td>
<td>3843</td>
<td>27.3 / 9.4</td>
<td>8.3 / 10.2</td>
</tr>
</tbody>
</table>

4.3 Simulation model verification and potential analysis of one PV-T collector with different inlet temperatures

This section deals with the quality of the simulation model employed and the potential analysis for heating, cooling and electricity production of collector type 3. The decision to use collector type 3 for the simulation study was based on the available data for this PV module and its better aesthetic for
building integration (see Figure 4b). Type 203 of TRNSYS, which was developed at the Institute for Solar Energy Research Hameln (ISFH) / Germany (Stegmann, M. & Bertram, E., 2011 and Bertram, E. & Stegmann, M., 2011), was used to simulate an uncovered photovoltaic-thermal collector not only for heat and electricity production but also for radiative cooling application. Equation 2 shows the energy balance for the fluid implemented in Type 203 of TRNSYS. The electrical part is modelled according to EN 60904 and the thermal part according to EN 12975.

\[
c_{\text{eff}} \frac{d\vartheta_m}{dt} = \dot{q}_N - E_n^* \eta_0 (1 - b_u u) + (b_1 + b_2 u) (\vartheta_m - \vartheta_i)
\] (2)

Where \( c_{\text{eff}} \) (kJ/m² K) is the effective collector heat capacity, \( \vartheta_m \) is the mean fluid temperature and \( \vartheta_i \) the ambient temperature, \( E_n^* \) (W/m²) is the incident angle-corrected irradiance, \( \eta_0 \) is the conversion factor, \( u \) (m/s) is the wind velocity, \( b_u \) (s/m) is the wind dependence factor for \( \eta_0 \), \( b_1 \) (W/m² K) is the heat loss coefficient, \( b_2 \) (J/m³ K) is the wind dependence factor for \( b_1 \), \( \dot{q}_N \) (W/m²) is the specific thermal collector output power. The parameters for Type 203 were calculated from the measured data shown in the previous section (Figure 5 and 6) and validated against a third day. The identification of the parameters was done by adjusting the coefficients in Equation 2 that best reproduce the measurements. Figure 7 shows the measured and simulated return temperature and power output for the collector type 3.

![Figure 7](image)  
Comparison between measurement and simulation for temperature (l) and power (r)

For radiative cooling applications the view factor toward the night sky of the collector is very important. In this study the angle of the collector was fixed to 0° (full view to the sky), the mass flow was set to 40 kg/(m²h) and the inlet temperature was set to the collector to 25, 35 and 45°C. These inlet temperatures were chosen because they represent typical operating temperatures for systems like cooling ceilings and heat pumps.

![Figure 8](image)  
Simulated absolute cooling potential for the cooling season (left), cooling potential per CDD (right) for the collector Type 3
Figure 8 presents the simulation results of the cooling potential and Figure 9 the solar thermal potential and relative deviation for the PV production depending on the location and the inlet temperature. The results show a strong increase of the cooling potential with the rise of the inlet temperature. This is caused by the increase of the convective and radiative heat losses to the ambient and sky, respectively. The highest absolute cooling potential was calculated for Riyadh and the lowest for Moscow with an inlet temperature of 45°C. However, the highest cooling potential per cooling day could be found for Stuttgart and Moscow. The highest solar thermal potential is in Dubai and the lowest in Moscow, with an inlet temperature of 25°C. The highest increase in PV (electricity) production with 5.8% was found for Chennai and the lowest with 0.1% for Stuttgart.

4.4 Discussion of results

The cooling potential per CDD values presented in this simulation study particularly show high values for cold (Moscow) and moderate climate zones (Stuttgart). However, the highest absolute values can be reached in continental desert zones (Riyadh). Although the cooling season in Chennai is of the same length as in Riyadh, the absolute cooling potential is lower. This could be explained by the lower ambient and sky temperatures of Riyadh compared to Chennai, as presented in Table 1. The new prototypes presented in this paper are uncovered on the top side and uninsulated on the backside. A combination of PV-T collectors with heat pump systems could provide a higher temperature inlet temperature level to the collectors. For the design of a system that includes PV-T collectors, all three aspects, PV production, solar thermal and cooling potential, need to be considered simultaneously. However, the use of PV-T collectors in a system needs to be studied in more detail, especially the integration and the dimensioning of the system. For Chennai, Dubai and Riyadh where heating is not necessary, further research might be directed to find suitable applications for the gained energy during day-time.

5. CONCLUSION

First results show a good match between the simulations and measurements for the analyzed collector. Results prove the potential of the described PV-T collector approach to provide thermal, electrical and cooling applications, which is different from the common application of current or historical use of PV-T products on the market today. Large differences exist in the usage potential in different climatic zones as it has been described and reflected in the PV-T collector design with regard to its technical detailing and its costs, which are highly dependent on the materials, components and manufacturing technology. It is expected that a low-cost approach focusing on an optimum performance on the cooling side has the highest applicability in the areas with the highest overall performance. Another issue will be the integration of these PV-T collectors in buildings with regard to an appropriate supply system (e.g. cooling and heating incl. storage, DHW, electricity) with robust control systems and architectural design requirements.
ACKNOWLEDGMENTS

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Parametric Analysis Method for Urban Energy Transformation Projects

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ABSTRACT
In tandem with industrialization, migration from rural to urban has caused unstructured and unplanned cities. On the other hand the needs of people in the cities have begun to change according to overpopulation, new technologies and life styles. This change results in growing energy demand at the cities and the governmental authorities and municipal services has to respond it. Urban transformation projects are given as a solution for struggling with these problems and reshaping the cities. Energy, one of the main topic on the urban transformation projects, contains the efficient resource and energy management, minimization of the energy consumption as far as possible and capacity enhancement for renewable energy sources. While developing urban transformation projects, the optimal and effective solutions should be investigated for the project area having regard to applicability, environmental impact, and economical feasibility. In this research, the energy demand profiles of generic residential urban blocks for two city locations in Germany and Turkey are simulated using EnergyPlus to identify the site density and physical properties effect moreover the significance of site design on future renewable energy integration opportunities. The research shows that 10-20% energy demand can be saved by an energy aware site planning and the urban transformation projects also have a big potential to supply more than 30% of the energy used with renewable energy sources.

INTRODUCTION
At the end of the 19th century with industrialization, many people began to live in the cities which are the centre for trade, industry and transport. Migration from rural to urban area has gained accearlation with education and business opportunity in middle of 20th century. Today half of the world population lives in cities and it is predicted to increase to more than %65 by 2050 [UnitedNations, 2008]. Nowadays, cities are the overpopulated sharing place of all networks such as transportation, services, finance, social spaces, cultural links, etc. Therefore management of all networks in cities is concerned with configuring, efficiently and equally supplying of the resources to the citizens and ensuring the continuity of the cycles for sustainability.

Especially in Europe, cities have been developed over hundreds years ago. Zonning, structure and network systems were consisted with industrialization but nowadays the European cities are transformed to management centers with head quarters of many firms so cities have to be globalized with sharing network and they need additions or refurbishment for information age [Thorns, 2002].Another point worth mentioning is that new poor citizens (not in Western Europe but rest of the World) who came to city with hope of job placement, solve their residence problem by ownself and living area capacity of the

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city has been increased many times without planning or structuring the new development areas. It is estimated that by the year 2035 half of the world poor population will live in this unplanned areas [Horwood, 2007]. It means that this population will begin to live in unstandardized building blocks with lack of infrastructure and with insufficient supply mechanism. It is big challenge to struggle with this problem for city managers.

Besides that, life style in cities and the technology has metamorphosed the demand of people. Industrial production and modern-day consumers with increasing wealth require more energy for daily needs. Basically all international and national governmental or local authorities deal with this energy management problem. On the other hand authorities have an important role on reducing green gas emissions and climate change mitigation. There is a big opportunity to make a cost effective saving in the energy demand of city building stock and provide the sustainable environment development for cities. At this juncture, sustainable urban development becomes even more important for future of urban life. Sustainable development first appeared in the literature during the 1970s and 1980s and early 1990s the issue of sustainable development gained momentum. After the United Nations’ Rio Conference’s Agenda 21, sustainable development is preferential as policy for every urban authority (Beatley and Manning, 1997). Many projects and programs are going on for sustainable or energy efficient cities on the world and especially European Union level (Concerto, Civitas, Urbact, Energy Cities, etc.) [http://www.eumayors.eu/about/related-initiatives_en.html]. Reconstruction, renewal or transformation projects can be the solution for urban quarters.

One of the most common sustainable urban development strategies is transformation of the city’s quarters. Urban transformation projects are kind of solution for unplanned or unusable urban areas. It is physical transformation for existing building stock with new standards and also it provides better structure to public space and supply network. For developed countries like Germany, it is way to alter the unusable area with new technology integration and to mitigate the impact of climate change. For developing countries like Turkey, urban transformation projects change the physical environment and especially urban spatial structure and begin to control building standards. After having lost thousands of people in earthquake in the past, before even worse disasters hit the country, unplanned cities with buildings out of keeping standards should be transformed in Turkey. Transformation projects are significant for integrating strategies and aspects for energy management of authorities. It has big potential to integrate efficient resource and energy management principals, to minimize the urban energy consumption and to adapt the renewable energy sources. Chief point for this energy transformation acts is that affordable and adaptable solutions should be determined for the urban sites. Sustainability of the developing areas has to be considered for present and future users.

In urban projects, the steps and strategies are important for implement and handle the project as a result of the largeness of the area. If the project developer has an approach for different sites and it is applicable for different area, it can be used for various places. This research takes the common points for all urban transformation projects such as density, building property and possible renewable energy sources. It clarified the steps for this urban energy transformation project and prose a practicable approach for the projects.

**FACTORS AFFECTING THE URBAN ENERGY IN TRANSFORMATION PROJECTS**

In the urban scale studies, to know the patterns of energy consumption is important for the management of supply. In the energy management works, it is easy to get information from supply but it is hard to define the requirement for different energy sources and the nature of users’ requirements. This kind of energy information is significant for sustainable urban energy planning, for the reason that the energy supply needs to be on meeting energy users’ needs in the best way possible. Urban design pattern mainly draw the city line and it shapes the inhabitant’s comfort requirement or requests. On this level architecture or city planning doesn’t have a comprehensive model which can be applied to every place and can take all factors on the account for developing sustainable cities or settlements. But we can define the main factors that affect the urban energy consumption and shape with urban design decision. These
factors can be categorized as follows:

**Urban density**

Rapid population growth brings with it, a growing need for built-up area which is one of main problems of the cities. Most of the time, this need is proved with high-rise buildings or compact settings, instead of expanding the boundaries. This brings the term of “urban density” which is used in urban planning and urban design to refer to the number of people inhabiting in a given urbanized area [Sokido and Bhaduri, 2013]. The urban density can affect the total energy demand of a city with different ways and these effects are complex and conflicting [Givoni, 1998]. Density sometimes can bring the benefits but it also creates extra loads and undesirable conditions. It affects the thermal performance, the natural lighting and ventilation possibilities of the buildings and these effects can either be positive or negative according to dominant climatic condition. On the other hand, the density supports to the district energy systems and besides that, the infrastructure facilities are shorter so it reduces also the energy requirement for pumping. Controversially, the energy requirement for pumping on the vertical direction is getting higher in the high-rise cities [Eicker et al., 2010]. The effect of density on heating, cooling and lighting energy demand of the areas is different and their influences are changing according to climatic conditions.

**Characteristics of built environment**

Physical properties of buildings and technologies in the building sector have a significant effect on the energy consumption. Insulation properties, windows type and area, the efficiency of technical appliances in buildings such as elevators, escalators, HVAC systems’ equipments are profiled the building for evaluation of its energy. Building envelope, this is interface between outdoor environment and indoor conditions, works as a thermal barrier and serves a function in regulating a comfortable indoor temperatures. It plays a crucial role for reducing the need for heating and cooling of building. Moreover the placement of windows and doors, the size and location in the envelope has a significant role on the control of energy losses. Buildings should always be contemplated in the conjunction with their surroundings. In order to manage the use energy of the built environment in a sustainable way and to minimize harmful emissions, the performance of the city scale must be considered. Building energy condition can be characterized with urban pattern, building stock properties and also infrastructure possibilities. In the terms of shading and reflection, lighting and thermal energy loads are influenced by the architectural form of the urban structures and the neighborhood relationship.

**Possible renewable energy source applications**

Buildings are integrated into networks of overriding technical infrastructures which are water supply, drainage, sewerage, water disposal, electricity system, heating and cooling networks and transportation. The development of more sustainable cities critically depends on a style of urban infrastructure condition that encourages more efficient patterns of resource consumption. District heating or cooling in combination with energy efficiency measures in buildings account for approximately one third of the reduction of emissions [Särnholm et al., 2009]. Therefore, efficient supply system and integration of renewable energy technologies to the network are crucial for sustainable cities. On the other hand renewable energy integration is more meaningful solution at urban scale. Indivual building renewable energy integration is not factual answer for efficiency and feasibility. Renewable energy application on the urban area or district, which is directly connected to the grid so it eliminates transmission loss on the other hand it doesn’t use any other land for application, has better energy performance than the individual applications. Solar PV or solar heating system integration on the roof has high potential with easy application. Façade integration has not easy for the underperformance of panels caused by the inequable shading. Wind trubines are not easy to implement to the urban district for the reason that it is affected from location of the building, wind direction, heights of surrounding buildings, other roof-top structures and so on.
Figure 1  (a) Energy plus model of one storey house (b) Row houses and (c) Apartment block

**METHODOLOGY FOR PARAMETRICAL ANALYSIS**

In the urban transformation projects, especially used for residential areas, highrise apartment form is used for restructuring the land in the furtherance of scaling up the recreation and green area opportunity. In order to limit the complexities related with real urban areas, the archetype was defined according to common typologies for transformation projects and this simplified type is used for energy performance simulations. There is not any survey for common building typology in Turkey but the German building stock was explored on the basis of energy demand properties and main residential building typologies defined by Institute for Housing and Environment-Germany (IWU, 2003). According to this research one storey, row houses and apartment blocks take into account for possible former building types of urban transformation area as shown in Figure 1. According to professionel point of view similar building forms are commonly used also in Turkey.

The apartment block with 10 storeys is chosen for possible new building form for urban transformation projects in Turkey and Germany. Floor area of the building is 24.4m*24.4m and height of it is 30m. Glazed area on the façade is 35% of the full façade area. Three dimensional urban quarter simulation was done for generic urban form as shown in Figure 2. The representative urban quarter constitutes of 9 generic building blocks and the distance between the buildings varies according to site density. The major orientation for the site design is the South. To see the total energy demand of the building, heating and cooling analysis including the annual electricity consumption with daylight responsive control was calculated in the Energyplus simulation program (simulation methodology has been described detailledy in the paper Kesten et al., 2011). Ankara and Stuttgart Energyplus weather data is used for the simulations.

Figure 2  (a) Energy plus model of urban quarter and (b) Energy plus model of urban quarter according site density.

<table>
<thead>
<tr>
<th>Building type</th>
<th>One storey house</th>
<th>Row houses</th>
<th>Apartment block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor area</td>
<td>10.5mx10.5m</td>
<td>7m x10m</td>
<td>20mx14m</td>
</tr>
<tr>
<td>Height</td>
<td>3.5m</td>
<td>7m</td>
<td>10.8 m</td>
</tr>
<tr>
<td>Building unit</td>
<td>1 house-</td>
<td>6 houses</td>
<td>1 block-</td>
</tr>
</tbody>
</table>

*Figure 1* (a) Energy plus model of one storey house (b) Row houses and (c) Apartment block

*Figure 2* (a) Energy plus model of urban quarter and (b) Energy plus model of urban quarter according site density.
PARAMETRICAL ANALYSIS RESULTS

Occupation of the flats was simulated for an identical family scenario, consisting of 4 family members who are not home during the day except on weekends. The usage time of the appliances was configured according to the statistical data. Every house has television, computer, washing machine, dishwasher, oven, and fridge. The usage was determined as the average time taken from the German household statistic (Gruber and Schlomann., 2005) The EN ISO 13791 was taken as an input for internal gains from occupants. The lighting was defined as 13 W/m². Without any shading effect the heating consumption of one storey house is 106.5 kWh/m². While depending on the shading of the area the heating consumption can be 12% higher in Ankara climatic condition. The energy demand of apartment block is less by compare with one family houses. Especially for cooling loads site density was highly affected in Ankara conditions and cooling loads decrease nearly 50% for all type of buildings.

Table 1. U-values (W/m²K) of building envelope according to construction year and building energy standards (LE: Low energy standard, PH: Passive house standard)

<table>
<thead>
<tr>
<th>Building Component</th>
<th>ANKARA</th>
<th>STUTTGART</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior walls</td>
<td>1.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Floor</td>
<td>0.75</td>
<td>0.45</td>
</tr>
<tr>
<td>Roof</td>
<td>0.47</td>
<td>0.3</td>
</tr>
<tr>
<td>Windows</td>
<td>2.7</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Table 2. Dynamic simulation results of former reference buildings (construction year 1984) without surrounding obstructions

<table>
<thead>
<tr>
<th>Reference Buildings</th>
<th>Ankara</th>
<th>Stuttgart</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heating</td>
<td>Cooling</td>
</tr>
<tr>
<td>One Family House</td>
<td>106.53</td>
<td>19.44</td>
</tr>
<tr>
<td>Row Houses</td>
<td>98.63</td>
<td>15.38</td>
</tr>
<tr>
<td>Apartment Block</td>
<td>61.82</td>
<td>19.2</td>
</tr>
</tbody>
</table>
As mentioned before, physical properties of buildings have a significant effect on the energy consumption so the building envelope properties according to energy standards or codes are profiled the building for evaluation of its energy. To understand the effect of energy standards on the buildings, reference buildings are simulated according to different construction years. Figure 4 presents the energy demand of eleven versions of apartment block according to different energy standards in Germany since 1948. The passive standard buildings show the heating demand without heat recovery from exhausted ventilation air. Similar trend is observed for one family house and row houses. It is not possible to mention or calculate for Turkey another building envelope properties because of the lack of the energy standards. We can assumed that the buildings which were built before 1984 are in the worse than these conditions and Germany example can have an idea about the effect of thermal properties of envelope. According to results, building standards in 1994 has given a jump for the energy performance of buildings and we can say that for urban transformation project for both countries, the energy performance of the site can be enhance at least 30% for the buildings constructed in the year before 1994.

It is also important to decide for new construction area density for urban transformation project. Therefore ten storeys apartment block which is constructed with current energy standards (Turkey 2008, Germany 2009) was evaluated according to site density and the results are presented in Figure 5. The heating consumption of the blocks is 53 kWh/m² and cooling demand is 10 kWh/m² in Stuttgart. The heating consumption of the blocks is 55 kWh/m² and cooling demand is 16 kWh/m² in Ankara. Depending on the shading on the site, the heating demand can be 25% higher more and the cooling demand can be 40 % less than the building without shading.
According to the reference building results, it is not easy to compare the site energy performance. Therefore the site performance of the new and former buildings was evaluated according to the same size urban districts and equal densities. Depending on the building typology chosen, the number of buildings, and therefore the number of housing units and their occupancy will vary. For each building type, the heating and cooling demand of the whole site was simulated at a density of 40% for Stuttgart. These figures are presented in Table 3. The average heating demand of ten storeys apartment block for urban transformation project is 60 kWh/m² while the average heating demand of one family house is 105 kWh/m², row houses’ is 98 kWh/m² and apartment block with 4 storeys’ is 68 kWh/m². The urban transformation project can reduce the heating demand up to 43% and it has the similar positive effect on the cooling demand of the site. In Ankara, the average heating demand of ten storeys apartment block for urban transformation project is 58 kWh/m² while the average heating demand of one family house is 114 kWh/m², row houses’ is 105 kWh/m² and apartment block with 4 storeys’ is 72 kWh/m². Reduction on the heating demand by urban transformation project can be 50% and also cooling demand reduction can be seen up to 28%.

In this study, supply scenario an electric heat pump with a COP of 4.0 was chosen as a standard heating system solution, covering 80% of the heat demand, supplemented by a gas condensing burner with 96% efficiency. Cooling was provided by an electric chiller with a COP of 3.0. Also, auxiliary electrical energy for pumping as well as delivery distribution losses of 10% of the heating and cooling demand was added. According to the CO₂ emission factor for natural gas was 0.202 t CO₂/MWh and for electricity 0.539 t CO₂/MWh, per capita CO₂ emissions is calculated. The lowest primary energy demand is ten storey apartment block for urban transformation project but lowest per capita CO₂ is the old apartment blocks.

| Table 3. Heating and cooling energy demands of an urban area with 40% site density for different building types |
|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| Number of buildings | Flats | Conditioned floor area/m² | Total heating energy demand/ MWh | Total cooling energy demand/ MWh | Average primary energy demand (kWh/m²) | CO₂ emission per capita/t CO₂ cap⁻¹ |
| One family house | 88 | 88 | 8800 | 926 | 61 | 115.5 | 176 | 0.5 |
| Row houses | 21 | 147 | 20580 | 2010 | 596 | 107.5 | 378 | 0.64 |
| Apartment block | 31 | 372 | 34720 | 2353 | 202 | 87 | 494 | 0.33 |
| Apartment block (urban transformation) | 14 | 560 | 83342 | 5034 | 283 | 79 | 1291 | 0.58 |
In the urban transformation project to add some renewable energy sources to the site is easier than the implementation to former buildings by reason of orientation, construction conditions, shading and etc. It is possible to add some district heating system for both cities and also this system can be combined with cogeneration plant, geothermal heating or central solar heating system in the urban transformation project. These systems can reduce high amount of carbon emissions and burning fossil fuels. For determining the performance of a PV system for the buildings in Ankara and Stuttgart, it was considered that the whole roof area of the buildings would be used for a free standing PV-installation with a tilt angle of 25°. PV-fields with for this example chosen 44 Sunpower SPR-305-WHT panels each, oriented to South. Each PV field was arranged to 4 strings of 11 PV-panels each which are connected to one inverter. The total collector fields and two inverters with a nominal power of 29.34 kW and a power ratio of 1.18. The average energy yield of the system is 34.2 MWh/a for Stuttgart and 48 MWh/a for Ankara. It is possible to produce 25%-35% of the consumed electricity with these installations.

CONCLUSION

The total energy consumption of the cities is crucially influenced by urban design decisions. This study shows that the site density and physical properties of buildings have significant effects on the site energy performance so this kind of evaluation should be made before the design of refurbishment of old settlements area. It is difficult to make the recommendations for all cities since they have unique characteristic and context but according to building standards and density decisions can provide big key for energy management of the cities. There is notable connection between energy demand and the urban site planning. Definitely instantaneous energy demand of the city is highly affected from the energy usage behavior of citizens and operation of the system but statistic mode of energy consumption may give design criteria for energy management decisions. However in addition to that, the climatic conditions and the population of the area, building typology and the density should be analysed carefully before the urban transformation projects. Detailed dynamic thermal simulations show that 10-20% heating and cooling demand may be saved by an energy aware site planning.

Beside that, renewable energy applications should be integrated in the urban planning process at the beginning in order to maximise the use so the urban transformation projects also have a big potential for integrating the renewable sources. According to this study, there is a big potential to save more than 30% of the energy used with renewable energy integration. This study covers only project site decision for urban transformation projects but better renewable energy integration can be done with district planning.

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Multifunctional Glazing System—Solution for Modern Smart Glazing

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ABSTRACT

Multifunctional glazing combines various glazing, that have potential to control solar heat gain by changing the window transmittance and low heat loss. In autonomous multifunctional glazing its function will be powered by PV layer attached to the glazing. This glazing obviates the necessity for shading devices to control the glare. Glare control for such a small scale south facing vertical surface multifunctional glazing is discussed.

INTRODUCTION

The building sector consumes 41% energy in USA, 40% EU, and 25% in China. At present, low energy buildings are gaining importance to reduce overall energy demand. A near zero energy building combines two concepts (i) the amount of energy supplied to the building must be small and (ii) that energy should be supplied from the renewable sources. In this context, windows are the most important building envelope component contributing to energy use reduction. Windows offers privacy, visual amenity, comfort and control of light and air. In a direct dynamic relation with outside atmosphere, heat gain and heat loss both ensue through a window. In addition to multiple pane glazing that includes low emittance coatings vacuum glazing, aerogel glazing, building integrated photovoltaic (BIPV) glazing and smart glazing are available. Vacuum and aerogel glazing gives low heat loss from room to environment and reducing heating load demand. BIPV glazing introduces daylight and reduces the artificial lighting load demand. Smart glazing like electrochromic (EC), liquid crystal (LC), suspended particle device (SPD) type control the solar heat gain and reduce the cooling load demand.

Vacuum glazing consist vacuum between two glass panes separated by small pillars to withstand the atmospheric pressure and insulated hermetic edge sealing around the periphery of the two glass sheets. This glazing shows total heat transfer coefficient ($U$ value) values between 0.5-0.9 W/m$^2$K (Robinson and Collins 1989; Collins and Robinson 1991; Fang et.al. 2006). Highly insulating vacuum glazing can be achieved using hermetic edge sealing around the periphery of two glass sheets (Collins and Simoko 1998). Addition of transparent low emittance coatings reduces radiative heat transfer between the sheets. Use of two low-e coatings does not reduce the overall heat transfer rate over a single low-e coating layer. Using one layer of low-e coating also reduces the overall system cost as low-e coatings are costly (Fang et.al. 2007). An aerogel is a translucent solid gel that exhibits high thermal insulation, low refractive index, and very low density (Jensen et.al. 2004). This glazing filled with aerogel can achieve a heat loss coefficient less than 0.7W/m$^2$K for 15 mm thick aerogel between two glass panes (Schultz and Jensen, 2008; Schultz et.al. 2005). In BIPV glazing transparent or semitransparent solar cells are placed on the outer facing surface of the glass panes (Miyazaki et.al. 2005, Chow et.al. 2009) which can be used as small scale electricity generation, control solar heat gain.
and transparency of visible light. In case of electrochromic glazing electrochromic material are placed between two glass panes. An electrochromic material is cell which changes its state from transparent to opaque state by redox reaction in the presence of applied D.C. voltage typically 0 to 5 V (Rosseinsky and Mortimer 2001). The optical properties of EC can be reversed by simple inversion of electrical polarity (Lee et.al. 2003, Granqvist 2012). The speed of this colour change process decrease at higher ambient temperatures. The bleaching to colour process take more time than colour to bleach process. EC material has potential to control transmissivity, absorptivity, reflectivity and emissivity of a glazing (Granqvist et.al.2003; Granqvist 2005). Electrochromic glazing controls solar heat gain and daylight through a window by blocking the transmission of near infrared (NIR) and visible light (Pennisi et.al. 1999, Granqvist 2000). SPD and LC both work on AC power. Both types become clear when continuous power supply is available and a switched off condition generates an opaque state. Compare to EC glazing LC and SPD switch on response is very fast, within 2 -5ms. Another advantage of these two glazing are they produce equal transparency all over the glazing specifically when the glazing size is larger (more than 1m²). EC glazing colouration process takes 5-10 min depending on the size and sometimes the coloration is not uniform. The required electrical power consumption for EC glazing is much lesser than the LC and SPD glazing.

Building occupant prefer to live and work in space with good daylight distribution. Daylight in a building is preferable to saves energy from artificial lighting. Discomfort glare arises from a high or non-uniform luminance distribution with high contrast luminance between source and surroundings. Discomfort happens due to glare sources position, the part of sky seen through and the size of glare sources (Galasiu and Atif 2004; Nazzal 2005). Controlling glare while achieving maximum utilisation of daylight is one the most difficult task for present available window and shading devices. Different shading devices such as external shading, internal shading, and louvers are used to control daylight and glare (Ahmed, 2012; Freewan, 2014). Particularly overhang type shading devices cannot control the glare created from low azimuth angle direct solar radiation. Switchable glazings are capable of reducing this glare.

CONCEPT of MULTIFUNCTIONAL GLAZING

Combining vacuum and EC device gives both low heat loss and switching characteristics to get both effects together (Papaefthimiou et.al. 2006; Fang et.al. 2008). An EC /LC/SPD device needs an external supply to change colour which can be supplied by PV added to the EC (Deb et.al. 2001; Huang et.al. 2012; Huang et.al. 2012). Using EC window and overhang shading in combination (Lee and Tavil 2007) has been studied.

A new multifunctional glazing, shown in figure 1 integrates of all these different existing EC/LC/SPD system, Vacuum/Aerogel, and Photovoltaics (PV). PV generates the power necessary to change the colour of smart material (EC, LC, and SPD). Multifunctional glazing can be solution for new fenestration devices that control the direct solar radiation, improve daylight quality, control daylight and glare. The location of PV layer will have an influential contribution in multifunctional glazing. Different positions of the PV layer will produce different PV outputs that will be used to switch the smart material.
Transparency reduces when PV cells are applied to the glass. Organic PV cells have a high transparency compared to inorganic PV cell but durability and efficiency of this type of cells are very lower. Keeping in consideration the cost and durability of the PV cells, silicon PV cells are considered in this study. Figure 2 illustrated two different options of placing PV cells are placed to glazing space to provide a semitransparent glazing. In the figure 2 (a) shows a 20% transparency while figure 2 (b) has 40% transparency. For the multifunctional glazing as shown in figure 1 different transparency level of each and layers are, glass 90%, PV 20% or 40%, EC clear 50%, EC opaque 10%, SPD opaque 5% and clear 58%. Different positions for the PV will result in different PV outputs available for switching the multifunctional window. PV arrays produce maximum power when inclined at the local latitude angle. As windows are usually vertical surfaces most the PV will also be inclined vertically. Depending on the different position of window east west south north the incident solar radiation intensity will also be different. It will be evaluated that how much light and solar radiation will be available for multifunctional glazing and also for different orientation.
Different possible positions of different layers are:
Type 1- Glass, SPD/EC/LC, PV, Vacuum/aerogel, and Glass (here we consider only EC, PV 20% transparent)
Type 2- PV, Glass, EC/LC/SPD, Vacuum/aerogel, and Glass
Type 3- EC/LC/SPD, Glass, PV, Vacuum/aerogel, and Glass
Type 4-PV will be on the frame of glazing, Glass, EC, Vacuum/aerogel, and Glass
This Study considers Type1

METHODOLOGY
Glare index calculation is provided for a 25cm × 25cm multifunctional glazing for a sunny day on 1st of June 2014 in Dublin (53.3478° N, 6.2597° W). The glazing is considered to be on a vertical south façade. Dimension of the room and glazing position and measuring points are shown in figure 3.

![Figure 3](image_url)

**Figure 3** Schematic cross section of a room with multifunctional glazing placed on vertical south facade

The available solar radiation $I_{g_{20}}$ inside the room will be

$$I_{g_{20}} = \tau_{gl} \tau_{pv} \tau_{ec} \tau_{vacuum} \tau_{g2} I_{vinci}$$  \hspace{1cm} (1)

Solar radiation incident on the vertical surface is calculated from horizontal direct and diffuse solar radiation using equation 2 (Liu and Jordan, 1960) for vertical surfaces orientated, east, west, north and south.

$$I_{vinci} = I_{h} R_{h} + I_{d} R_{d} + \rho R_{r} (I_{h} + I_{d})$$  \hspace{1cm} (2)

$$R_{b} = \frac{\cos \theta_{i}}{\cos \theta_{r}}$$  \hspace{1cm} (3)
\[ R_+ = \frac{1 + \cos \beta}{2} \quad (4) \]
\[ R_- = \frac{1 - \cos \beta}{2} \quad (5) \]

Angle of incidence are given by
\[
\cos \theta = \sin \delta \sin \phi \cos \beta - \sin \delta \cos \phi \sin \beta \cos \gamma + \cos \delta \cos \phi \cos \beta \cos \omega \\
+ \cos \delta \sin \phi \sin \beta \cos \gamma \cos \omega - \cos \delta \sin \beta \sin \phi \sin \gamma \sin \omega
\]

Global illuminance from the global incident solar radiation can be calculated from (Perez, 1990)
\[
L = I_{\text{vinci}} \left[ a_i + b_W + c_i \cos(Z) + d_i \ln(\Delta) \right] \quad (7)
\]

Discomfort glare is represented by glare index (GI) described by (Hopkinson and Collins 1970; Hopkinson and Bradley 1960)
\[
GI = 10 \log_{10} 0.478 \left( \frac{L_i^{1.6} \Omega^{0.8}}{L_{ba} + (0.07 \omega^{0.5} L_s)} \right) \quad (8)
\]

The standard glare values are 10 for just perceptible, 16 for just acceptable, 18.5 for borderline between comfort and discomfort 22 for just uncomfortable and 28 for just intolerable.

**RESULT & ANALYSIS**

Vertical surface global solar radiation is illustrated for different orientation in figure 4. It can be seen that receiving solar radiation on multifunctional glazing is possible during all the day in south facing building. East facing and west facing glazing receive more solar radiation before 12 am and after 12am respectively. For an East facing window in the morning variable transmission control of glazing is essential whereas west facing windows needs control in the afternoon. South facing window needs maintenance of glare and daylighting throughout the day.

![Figure 4](image-url) Incident global solar radiations for north east west and south on vertical surface

Glare index (GI) for south façade multifunctional glazing for switch off and switched on conditions
are shown in figure 5. When EC was switched off its 50% transparency allowed excessive light inside the room. It can be seen that after 8am it crossed the limit of intolerable limit range of 28. At 12am it was nearly 50. This excessive glare can be controlled using the switched on EC with 10% transparency rendering the glare acceptable range. At 12 am the maximum glare was 16 just in the acceptable range. In both case the PV transparency was 20%.

![Figure 5](image)

**Figure 5** Glare indices when EC was switched off clear (a) and switched on opaque condition (b)

**CONCLUSION**

Multifunctional glazing has potential to control heat loss and heat gain and generate electricity to switch a switchable material. This glazing has the potential to control glare. Glare control of a particular room has been found to be provided was theoretically calculated using standard glare index equation. It was found that when EC device was switched off condition the glare was nearly 50 at 12 am which was more than intolerable limit of 28. During the switched on condition the glare was nearly the acceptable range 16 at 12 am.

**NOMENCLATURE**

- $I$ = Incident solar radiation (W/m$^2$)
- $\tau$ = Transmittance
- $L$ = Luminance (lux)
- $R$ = Conversion factor
- $\Omega$ = Solid angular subtense for modified position index (sr)
- $\omega$ = Solid angular subtense for source (sr)
- $\phi$ = Latitude angle (deg)
- $\delta$ = Declination angle (deg)
- $\beta$ = Title angle (deg)

**Subscripts**

- $T$ = Vertical
- $b$ = Beam
- $d$ = Diffuse
- $s$ = Source
- $ba$ = Background
- $r$ = Radiative
REFERENCES


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Environmental Performance of Adaptive Building Envelope Design: Urban housing in Seoul, Korea

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ABSTRACT

Since the first construction in 1962, apartment housing represented modernity and quickly became a ubiquitous urban housing typology in the midst of Korea’s rapid economic growth. Prominently influenced by the 1930s rational architecture from Europe, the housing site planning for Seoul systematically multiplied into a linear urban pattern of slab typologies. As the city stepped into the 21st century, the old slab typology—criticized for their lack of diversity and low density, adapted a new housing model from North American urban residential schemes—the mega glass tower. Energy consumption of the new tower typology has doubled from the linear slab model due to the increase in glazing ratio, the application of tinted green double glazing in replacement of clear double glazing, and the irregular orientation of the floor plans. This research analyzes the environmental performance of the new tower typology in comparison to the previous slab typology with the objective to improve the quality of future urban housing design and planning in Seoul.

INTRODUCTION

1930s rational architecture from Europe prominently influenced the housing site planning for Seoul, which systematically multiplied in a linear urban pattern. Consequently, typical urban housing layout in Seoul has the characteristics of expanding horizontally or orthogonally in clusters. These forms of clusters follow a linear, single orientation, slab configuration which conceptually provides a level of equality in housing that is in line with early ideas of modernity in the realm of architecture (Kang, 2004, p. 144-146). From a practical perspective, each unit could receive an equal amount of daylight, cross ventilation, and views outward within this system. This idea of equality, despite its formation of unity in the residential sector, simultaneously erased local identities of neighborhoods to the point where eventually every development appeared the same as the other throughout the entirety of the city.

Figure 1  1960s to 1990s Old slab typology apartment housing in Seoul, Korea.
Quite recently this linear apartment development strategy and residential culture have come under critical scrutiny. As the city stepped into the 21st century, the slab typology has been criticized for their lack of life quality, diversity, and dynamic urbanism. The old slab typology building can no longer provide the high density required by the city and create a healthy urban living environment. Developments from the 1960s to 70s remain in poor condition until the point of demolition (Kang, 2004, p. 143). As a reaction, from the demand for housing supply and its heavy reliance on the market, the scale of developments has increased to the mega glass tower. This residential tower typology of higher density is a model adapted from contemporary North American urban residential schemes. The tower simply as a typology has decreased the quality of residential living furthermore, in terms of creating a variety of housing clusters on a block and integrating with the urban built environment and community. Thus, a successful housing model does not exist yet in the city.

Figure 2  New tower typology highrise housing preconstruction sales in Seoul, Korea.

This research determines to analyze the environmental performance of the new tower typology with the objective to improve its quality in terms of architectural design and energy consumption through the building’s envelope. Further examination of the relationship between the building envelope and environmental impact of the urban layout provides insight for sustainable housing developments in Seoul.

BASE CASE STUDY: SLAB TYPOLGY ENERGY PERFORMANCE

The typical slab housing typology constructed from 1960s to 1990s, were built to the height of 8-10 story as multifamily mid-rises with one or two vertical circulation cores servicing all the residents of the building. This typology allowed for each unit to have a double orientation towards north and south, guaranteeing a sufficient amount of daylight, cross ventilation, and solar gains.

Figure 3  Floor plan of the old housing type used in the base case study and diagrammatic depiction of the enclosed balcony.
An old slab typology flat of 136m² was studied as a base case. It was constructed in the early 1980s and had been planned for demolition in the near future by the developer into new residential buildings. When examining a typical floor plan from the slab typology, two important characteristics of the layout are the open kitchen to living room floorplan and the enclosed balcony spaces to the south and north exposures. The open plan layout is crucial for effective natural cross ventilation during the humid months of July and August. The distribution of internal gains from the kitchen is an insignificant amount according to the occupant, but still a diminutive contribution to the internal temperatures as an auxiliary source of heat.

The enclosed balcony spaces function as buffer zones that control heat loss during the winter and also have the purpose of solar protection in the summer season as overhangs or cantilevers. The balcony of the slab typology is typically a glazed area of 50% to the façade area, detailed with two sliding window apertures that open 50% horizontally. The exposed south vertical surface of this flat in the base case study also has a 50% glazing ratio to the façade. Clear double glazing is used on the apertures to the exterior as well as to the glazed interior sliding partitions that divide the balcony from the interior living room space. The advantages of controlling heat loss as a buffer space, and storing the captured solar gains to the flat is a key factor found in the floor plans of the old slab typology.

**Climate Condition of Seoul**

![Psychometric chart defining the summer and winter comfort zones (Szikolay, 2007).](image)

The comfort band calculated from the equation, \( T_n = 17.8 + 0.31 \times T_0 \), defines the summer comfort band range between 23 °C and 28 °C. The winter comfort band ranges from 17.5 °C to 20.5 °C. From the psychrometric chart, the red points plot the months of July and August. The relative humidity levels are high throughout the entire year but only falls outside the boundaries of comfort when the external temperature starts rising in the summer months of July and August. The yellow boundary defining the summer comfort zone shows that for the majority of July and August are outside comfort limitations. Consequently, cooling load consumption is also the highest during this period of discomfort due to this relative humidity level.

**BASE CASE STUDY: TOWER TYPOLGY ENERGY PERFORMANCE**

Urban housing in Seoul has changed drastically since 2000 in terms of typology, construction, design and not absolutely for the better. The market demanded for housing with significantly higher density as the city became over populated. As a consequence, office-tower type urban residential models found common in North American cities (i.e. New York City, Los Angeles, and Chicago) were adapted...
into the residential sectors of Seoul. These towers satisfied the market’s new density demand and provided diversity in the design of the floor plans (in comparison to the simple slab floor plates), in its irregularity and asymmetry. Each unit found more variety in the layout of the interior spaces and orientation towards the city. But these deeper tower plans have appeared to create new problematic environmental issues. The new tower typology unit which is analyzed closely as a case study is a corner unit of 132m² exposed to both south east and south west. Most of the units within the towers have lost the benefits of natural cross ventilation and north-south orientation of the old slab model. Externally the tower typology has not been able to address its contribution to the urban fabric of the city in providing an improved open space. In fact, the quality of the open space is in greater threat of diminishing due to the height and higher obstruction angles created by these mega towers.

Urban living in a dense city such as Seoul is a constant fight for more space. Due to the desire for maximizing floor sq meters for liveable space, the previous enclosed balconies have been erased for maximum floor sq meter and consequently the envelope has become a 100% fully glazed façade. From the post occupancy evaluation with the family, most discomfort was expressed during the summer months for overheating, weak natural ventilation, and high bills for cooling. In the tower typology base case, poor operable aperture on the glass façade with a small area of merely 0.84m² which tilts outward with a maximum angle of 30°, is a hindrance to the performance of natural ventilation.

**Figure 5** Construction standard comparisons between base cases of the old slab typology and the new tower typology (Jang, 2002).

**Glazing Type and Thermal Performance**

An essential difference between the two typologies is found in the envelope of the building. In terms of construction, the heavyweight construction of the old slab typology has transformed into lightweight construction in the new tower typology. The external wall of the slab typology had a typical U-value of 0.47W/m²K—concrete load bearing wall construction with insulation placed on the inner side
of the wall. In the old slab model, the envelope of the building had a 50% glazing ratio to the façade. This ratio increased nearly to 100% in the new towers. Clear double glazing with a standard U-value of 3.0W/m²K and solar transmittance g-value of 0.707 has been replaced with tinted (commonly green tint) double glazing with a solar transmittance g-value of 0.422. The tinted glass has become a conventional strategy by contractors for urban housing to accommodate the increased glazing area and reduce overheating. In the new tower typology base case, poor operable aperture on the glass façade with a small area of merely 0.84m² which tilts outward with a maximum angle of 30°, is also a hindrance to the performance of natural ventilation.

![Diagram of building layout](image)

**Figure 6** TAS simulation results show that the new tower typology unit has multiplied in annual heating and cooling consumption by approximately 50% in comparison to the old slab model. Previous research data collected from various organizations such as, the Korean Solar Energy Society, Seoul National University of Technology, and Korea Institute of Energy Research Department showed thermostat temperatures set at 20°C for winter heating simulations and 25°C for summer cooling. Both units are 136m² and 132m² in floor area, similar in the layout of the interior spaces, and with the same occupancy.

**Impact of Obstruction by Urban Layout and Energy**

An important issue to deal with is the urban planning of the new tower typology. What environment or context should the tower be in? A repetitive distribution motivated by careless market driven developments will lead to the identical banality created by the old slab typology. Urban planners and city authorities must have a higher awareness to prohibit monotonous, simply cost-saving development. The sheer height of the new typology creates a greater challenge in terms of integrating with the urban fabric at the ground level. Environmentally, the longer overshadowing of neighbour buildings and the open outdoor spaces must be taken cautiously into consideration during the early urban planning stages.
**Figure 7** Aerial photo depicting the urban layout of the old slab vs. the new tower typology. The typical urban canyon of the old slab typology in Seoul was a 1 to 1 ratio of height to width.

**Figure 8** The thermal performance of a 1m² clear double glass glazed area for the two urban canyon ratios-- 1 to 1 and 3 to 1 ratio, maintains a parallel pattern to each other for the entire 12 months.
Three mid floor levels are studied to understand impact of obstruction angles. The balance in kWh/m²·day calculates the difference between amount of solar gain and amount of heat loss over the area of a 1m² glazed vertical surface. At the 3 to 1 ratio urban canyon, the percentage reduction of annual incident solar radiation is already less than half of the available amount falling on the south vertical surface of a 1 to 1 ratio canyon. Corresponding to the different percentage reduction in the annual incident solar radiation, the thermal performance of glazing also shows a similar 50% to 60% difference between the two urban canyons. To take a specific example, in Figure 8, the 5th level floor which has a positive balance of solar gain than heat loss until the month of December in the 1 to 1 ratio canyon; at the 3 to 1 ratio canyon it shows for almost half of the year, there is greater heat loss than solar gain through the glazed area.

Figure 9  The chart studies the thermal performance of different types of glass. Four types are studied: clear double glazing (U-value: 3.0 Wm²/K, solar transmittance g-value: 0.707), double glazing with low-e (U-value: 1.8 Wm²/K, solar transmittance g-value: 0.616), triple glazing (U-value: 1.2 Wm²/K, solar transmittance g-value: 0.64), and green tinted double glazing (U-value: 2.94 Wm²/K, solar transmittance g-value: 0.422).

The conclusion from this study is that, the three glazing types: clear double glazing, double glazing with low-e, and triple glazing, because of it proximity in solar transmittance g-values, perform similarly in the summer climate of Seoul. But for the cold winter months of November through February, the balance between solar gain and heat loss starts to vary according to their different U-values. In terms of thermal
performance for the lowest level floors at the ground, double glazing with low-e appears as a sufficient application for glazing choice to minimize heat loss.

The green tinted double glazing which has been applied to new urban housing construction in Seoul as a substitute or response to higher glazing ratios in the façade performs the worst in the winter season. Due to its lower solar transmittance g-value, the summer performance is stronger than the other options but it is at the cost of an extremely poor winter performance.

CONCLUSION

With an informed building envelope that responds to the climate in Seoul, the performance of the new tower typology is significantly improved. In terms of general strategies for energy saving for the new tower residential typology in Seoul, the most effective measures were found first in replacing the green tinted double glazing (0.422 g-value solar transmittance) with double glazing with low-e. Though the annual cooling consumption increases by 41% with the higher solar transmittance (0.707 g-value) of the double glazing with low-e, the more problematic energy consumption is in heating and this increased cooling amount is reduced again with the application of external shading. The second general strategy is to improve the U-value of the external walls from the standard of 0.47 Wm²/K to 0.28 Wm²/K. The improvement in the U-value of the external wall improves heating consumption by 11%. In addition the application of insulated night shutters and external shading devices to the façade of the new residential tower typology is crucial as an architectural solution in response to the demand for higher glazing ratios. Night shutters with 20mm of insulation with a 0.026 conductivity, can save 30% of heating consumption. The same device which is used as an external shading device can reduce 55.2% of cooling consumption. External shading devices dissipate any absorbed solar energy to the outside air and therefore play a key element for passive cooling. Internal blinds were the least effective in terms of solar control in comparison to external blinds.

To push energy savings to extremely lower values, selective use of the enclosed balcony is necessary in the interior. The final strategy can theoretically achieve values as low as 12.5 kWh/m² for annual heating consumption and 8.1 kWh/m² for annual cooling consumption.

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REFERENCES


Establishing Energy Efficient Building Codes in Developing Nations: 
An analysis of window characteristics suited to hot-dry climates through a study of the residential byelaws of Lahore, Pakistan.

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ABSTRACT
Evidence that windows are responsible for most heat gain through solar radiation into a building underlines the importance of climatically sensitive window design. Many of the recent building practices in the developing world are dismissive of the more environmentally appropriate traditional building forms, adopting instead, an urban form that is neither environmentally sensitive nor sustainable. Such practices demonstrate a lack of understanding between the thermal performance of windows in relation to the urban geometry, yet are in most instances legitimized by inadequate regional building codes. A case in point is that of Lahore Pakistan, where despite a predominantly hot-dry climate there is no mention of suitable apertures within the building code, this situation is exacerbated in residential areas by the byelaw requiring a mere 1.7m distance between the building unit and boundary wall on two sides of the building. Taking Lahore as a prototypical developing world city, this paper addresses the specific spatial arrangements created through the existing building codes and focuses on controlling solar gains through an analysis of the window characteristics that are most suited to the climatic and urban environment. The discrepancy in building codes is investigated through software simulations that evaluate real housing clusters with particular focus on the obstructed facade (by boundary wall or adjacent building) for which suitable window characteristics that balance seasonal natural light and thermal gains are determined. A further set of simulations addresses the effect of modifications in the byelaws regarding the distance of obstruction and the consequent adjustments necessary to window characteristics. The results of these simulations provide the knowledge-base for a critique of the environmental sensitivity and suitability of the existing byelaws, and propose modifications that would optimize both climatically appropriate window design and land use within the urban environment of Lahore.

INTRODUCTION
The twentieth century technologies and universally available materials have greatly facilitated the trend towards homogeneity of the urban built form across the globe. This trend is popular in all aspects of urban built form but is particularly obvious in the form of public and commercial buildings in most city centers the world over.

Traditional building design was perfected over a long period of time, with the construction practices, architectural vocabulary and urban form of a region being sensitive to the climatic conditions and cultural requirements of that region. The result was an urban-scene unique to the place and the people, with the building envelope maintaining comfortable indoor conditions.
However the influence of new materials and technologies has resulted in a drastic shift in the built form which in most instances is far removed from tradition and also the goal of maintaining comfortable indoor conditions. While these changes to the urban form have been somewhat conscientiously undertaken in First World Countries in that desirable indoor conditions remain within achievable limits, the situation within developing countries, particularly those with hot climatic regions, leaves a lot to be desired. The modern urban form in such parts of the world and the accompanying lifestyle is largely reliant on mechanical methods of air conditioning to maintain comfort which is an unsustainable and expensive option. This situation is exacerbated by the unquestioned adoption of design standards that have been developed in colder parts of the world and are geared to satisfying comfort and energy use in developed nations. The extent of this practice can be gauged by the situation in much of South Asia where the comfort standards laid out in ASHRAE guidelines have been incorporated within the national building standards and are legislatively enforced. The irrationality of such practice is reinforced in recognizing that even within regions of the world that are similar in their climatic environment, variations in the comfort parameters will exist due to the differences within the culture and lifestyle choices of the people of the various regions.

The formulation of a robust workable code is rooted in an understanding of the environmental efficiency and behavior of different building types within the particular climatic and cultural environment of that region. Such understanding is typically based upon empirical data, however it appears that not all building types have been given due attention; the urban residential form has been largely ignored in this regard, with the major focus of such research being the traditional building (Oktay, 2002) while the study of modern buildings has remained almost exclusively within the realm of office buildings. It is therefore an imbalanced understanding of thermal comfort and occupant behavior that has been created and on which we continue to base our requirements of comfort.

A robust building code implemented within a well-designed regional energy policy would go a long way toward improving this situation by ensuring the design and construction of all buildings (irrespective of purpose) results in the internal environment being as close to comfort parameters as possible. Comfortable conditions could then be achieved through passive control or low energy measures and if artificial air conditioning were still required, the reduced temperature differential between the desired and existing would result in a significant reduction in energy costs.

In the absence of an accurate database of regionally appropriate comfort parameters the environmental efficiency of the buildings cannot be gauged nor a solid measure of the success of building standards formulated. At the very least, existing inappropriate guidelines can be modified in order to adapt them to the local climatic conditions. Focusing on the hot-dry South Asian scenario, the primary design flaws in the existing standards that render it inapplicable are:

**The glazing ratio:** The design guidelines for window size and placement were developed in climates that design for daylight: providing adequate natural light in to the building. These recommendations were based on the window area to wall area of the room and vary for different climatic zones; the consensus however is that the optimal glazing ratios lies between 25% and 40% providing adequate light while not incurring undesirable thermal gains and avoiding disability or discomfort glare (Muneer et al, 2000, Baker et al, 2000). In a hot climate, however, there is ample sunlight and providing natural light into the building is not of concern. Rather, the glazed surface area needs to be managed in order to control the solar gains in the building.

**Rate of air change:** Traditionally based on standards developed for maintaining desirable internal conditions in a conditioned environment, the rate of air change is not applicable to naturally ventilated buildings in hot climates where the speed of air takes precedence over rate of air exchange purely for the cooling effect of air movement.

The following addendum to the standard requirement of air changes is seen as:

**Wind speed:** The cooling effect of wind speeds between 0.5m/s and 3m/s has been documented however speeds above 1.5m/s are not advised because of the nuisance factor created through the disturbance of paper etc. (Baker, 2000). The cooling effect of re-circulated air through the use of mechanical fans is utilised in most hot climatic regions the world over. This reliance on fan generated
wind speed to counteract the effect of increased temperature has been documented to ‘occurs [sic] at
temperatures of around 26°C’ (Nicol et al, 2014 p.128). The consequent reduced temperature is known
as the Effective Temperature. The cooling effect produced is significant with a wind speed of 1m/s
causing a 3°C reduction in effective temperature at 30°C (Baker, 2000), and 4°C at 40°C (Nicol, 1994).

It is surmised that recirculation of indoor air in hot climates would prove a beneficial low energy
measure and should be accommodated within building standards and guidelines particularly in such
regions where such practice is established.

**Thermal Comfort in a hot-dry environment**

The rigidity of comfort parameters determined through climate chamber experiments does not
reflect the seasonal variations within conventional comfort ranges wherein occupants adapt to the
environment and accept significant deviations in their surroundings. This behavior has been utilized in
the development of the adaptive model for achieving comfort and recently this approach has been
validated by several international standards such as ASHRAE 55-2004 and EN15251 through the
recognition that indoor comfort temperatures are dependent on changing outdoor conditions (Nicol et al,
2014).

One such representation of the relationship between indoor comfort temperature and outdoor
temperature is the 1978 formula developed by Humphreys:

\[
T_c = 12.1 + 0.53T_o
\]  

Where \( T_c \) is indoor comfort temperature and \( T_o \) is outdoor temperature.

This formula has been found to be 95% accurate in predicting comfort temperatures during summer
months for occupants in environmentally controlled buildings in the South Asian country of Pakistan
(Nicol et al, 1995). It is assumed that the range of validity of this formula will have an upper limit of
47°C, (the average high temperature of Multan, one of the 5 cities in the study and with the highest
average temperatures of the sampled cities).

It is to be noted that this equation does not take into consideration the cooling effect of wind speed.
The use of ceiling fans is standard adaptive behaviour in such climatic conditions and the Oxford
Brookes report specifically mentions the cooling effect of ‘about 2°C for average air movement’ in
Multan with ‘an approx 4°C shift between still air and 1m/s’ (Nicol, 1994, p23). A modification of
Humphreys’ formula is thus undertaken to incorporate a conservative 2°C reduction in temperature due
to the effect of re-circulated air movement, giving the relationship for Effective Comfort Temperature
(\( T_{ce} \)):

\[
T_{ce} = 10.1 + 0.53T_o
\]  

**LAHORE, A CASE IN POINT**

The case study undertaken is the city of Lahore in Pakistan, a typical developing world city which
is prone to the issues of conformity to developed world trends in urban form and lifestyle. Located at
31.34°N and 71.20°E, Lahore experiences severe hot-dry summer with a mean average temperature of
over 35°C for five months of the year and remaining over 30°C for a further two months (Weatherspark,
2013). With peak summer temperatures of over 45°C, the control of solar gain was the central design
consideration in indigenous architecture. The modern urban form however has abandoned the dictates of
tradition, with thinner walls (standard construction of 9” load-bearing brick masonry), lower thinner flat
roofs, and significantly larger glazed apertures – where previously apertures were small and were
protected from the sun’s glare by either external open-able shutters or fixed marble/wood jalli.

The situation in Lahore epitomises the unsustainable condition of the urban-scape of many parts of
the developing world with the existing energy regulations based on inadequate research and the local
building codes largely ignoring the issue of thermal performance of residential structures. Lahore falls
within the same climatic region as Multan, and as such the predictive values of Equations 1 and 2 in the
preceding section are applicable. In Lahore where the mean maximum summer temperature is 40.4°C,
indoor comfortable conditions would be at 33.7°C, or at 35.7°C where the environment is supplemented with fan-generated re-circulated air.

The Building Code

Much of the residential development within the city falls under the jurisdiction of two major and several minor building control agencies all of which conform to national recommendations. Through this, residential structures within Lahore are regulated within the same byelaws and guidelines irrespective of their location. Universally the building codes specify mandatory clear areas on the periphery of plots –the depth of which is dependent on the dimensions of the plot, residential units are restricted to two storeys in height with a maximum height of 8m and with the upper storey limited to 75% of the floor area of the ground.

The cultural trend, supported by the high land prices is to construct over the entire area permitted by the building codes. This trend combined with the uniformity of plot sizes, a rectilinear industry standard road network, and building code dictated volumetric conformity produces a high density low-rise urban form which has remarkable similarity with respect to open spaces between buildings and solar shading by adjacent buildings.

Figure 1  Nolli plans of a sample of residential colonies in Lahore. Density of form and compact nature of planning is clearly visible. (OCCO, 2009)

The primary focus of this study is the largest development authority of Pakistan, The Defence Housing Authority (DHA) within which the development typifies the urban geometry of the city both in density and building form. An initial survey of the sample residential units within the DHA confirmed the translation of the building guidelines is taken literally: in most instances the minimal distance required towards the sides (and the rear of all but the largest plot size) of the residential unit, a mere passageway of 1.7m (including boundary wall width) is maintained. Further to this, as the bye-laws limit the height of the boundary wall to 2.13 metres, the facades on at least two sides of all residential units are affected by an obstruction in the form of the boundary wall and close proximity of the neighbouring building.

<table>
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<th>Area (sq.yd)</th>
<th>Dimensions (m)</th>
<th>Front (m)</th>
<th>Rear (m)</th>
<th>Side (m)</th>
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METHODOLOGY: ANALYSIS OF THE EXISTING BUILDING

The current building codes in Lahore have not been designed with a view to develop an environmentally sensitive and sustainable urban form. However an analysis of the buildings created through conformation to the building code will determine a base line of environmental suitability of the code. In order to determine the primary source of uncomfortable indoor conditions, the dissection of the urban form into its basic parts: the building and the urban geometry formed of neighbouring buildings is undertaken.

A random selection of existing residential buildings within the DHA area – providing at least 5
from each plot type, yielded a set of building plans that were then analysed, the significantly atypical disregarded and from the remaining sample pool, a ‘typical’ residential unit selected.

Preference was given to the 500 sq.yd. (418.3m²) buildings as these are representative of approximately 70% of the residential building size in DHA. Furthermore the byelaws applied to this plot size require the minimum distances of 1.7m from the boundary wall on three sides resulting in greater applicability of any analysis.

Figure 2  (a) Building footprint of randomly selected existing residential buildings within DHA limits. Prototypical residential unit used for modelling purposes highlighted. (b) 3D model and floor plans of selected residential building.

The typical residential unit selected above is simulated with the EDSL’s (Environmental Design Solutions Ltd) software Thermo Analysis Simulation (TAS). For the purpose of this analysis, the building is modelled in peak summer conditions for one day (day 180/360) with the number of preconditioned days set to 15 (this equates to the building experiencing the environment for 15 days and analysed on day 16, providing a realistic representation of the environmental sensitivity of typical buildings). The building is simulated as unoccupied and without internal gains so as to provide an unadulterated measure of the effect of the outdoor environmental conditions. The internal partitions are taken to be unopened. The building envelope is true to popular construction materials and the apertures are single-glazed with a U-value of 5.7 which reflects occupant preferences based on empirical sales figures: 65% of occupants opt for single-glazed while 35% opt for double glazed. The primary focus of the study is the ground floor level of the building so as to minimise the effect of thermal gains through the roof.

The contribution of the urban geometry:

The typical residential building was modelled under various exogenous influences that together make up the urban geometry of the area. The building was simulated with each parameter in isolation and also incrementally to determine the effect of the urban geometry as a whole, thereby determining which areas need addressing with regard to environmental sensitivity.

These parameters are: the influence of the boundary wall at 1.7m, the neighbouring residence at 3.4m, and the overall effect of the urban-scape (a residential block of 6 houses, with the central one analysed). These simulations showed an expected increase in the internal temperature of the building unit due the introduction of the boundary wall, however there was no significant change to the internal
conditions due to changes in distance of wall from the building edge. Furthermore it was found the close proximity of the neighbouring residence had a positive effect on the indoor climate possibly through the shading factor of building. Overall it has been determined that the effect of the urban micro-climate is an increase in the indoor temperature of the residence, by a maximum of 0.6°C.

![Figure 3](image)

**Figure 3** Representative plans of the typical residential building as simulated: (a) building in isolation, (b) with 2.13m high boundary wall at 1.7m, (c) with boundary wall and adjacent building at 3.4m., (d) within a typical block of residential units.

![Figure 4](image)

**Figure 4** Simulated temperature for 24 hour period over day 180/365 (30th June). Unglazed apertures. Comparison of effect of urban-scape on the indoor temperature.

**The environmental sensitivity of the building envelope:**

Two preliminary simulations were undertaken for the purpose of developing a baseline for comparison. The first with all apertures opened for 24 hours, with the building unit as an unglazed shell, this simulation showed no significant difference between indoor and outdoor temperatures. The second with the glazed apertures closed for 24 hours where an increase in indoor temperatures by over 3°C signifies the negative effect of the glazed apertures within the building envelope.

In an attempt to mimic typical user behaviour of closing out the harsh intense heat of the day and opening up and airing the inside of the residence during the cooler night, a series of simulations were carried out where the apertures were opened for a few hours of the day. The simulations indicated opening the windows for a period of 12 hours, from 1900 Hrs to 0700 Hrs yields the most significant reduction in internal conditions with the highest indoor temperature (west facing areas) becoming 3.4°C lower than the outside. There is however a time-lag between maximum indoor and outdoor temperature of 4 hours (see Figure 5).

The detrimental effect of glazed apertures on the indoor temperature (3°C) is significantly higher than the increase due to the effect of the urban micro-climate (0.6°C) hence further investigation is directed towards the building envelope. For the purpose of assessing the worst case scenario, all further simulations concentrated on the regions of the building most affected by solar gains: the west facing...
areas. The treatment of the apertures was scheduled as opened for 12 hours: 1900 to 0700.

**Overcoming inappropriate glazing:**

A simulation was conducted to compare the suitability of double glazed with single glazed apertures in a hot-dry climate. It was determined that double glazed apertures are climatically appropriate as they maintained an indoor temperature 0.5°C lower than single glazed apertures.

A series of simulations were carried out where the building was augmented with various shading devices. These included a 1m deep shade, 2.5m shade, and a 2.5m deep veranda (with walls enclosing the veranda space). A comparison of the effect of such shading devices led to the conclusion that while temporary respite may be achieved from direct sunlight and associated glare discomfort, the change to internal temperature within the building is negligible.

A comparison of the simulations undertaken indicate a reduction of the window area by 50% (to 15% glazing ratio) leads to an improvement of the indoor environment by over 2°C bringing the (maximum) indoor temperature down to 34.8°C—which is an acceptable indoor comfort temperature. The smaller window size results in a slower decrease in indoor temperature at night with the temperature remaining 2.5°C higher than outside temperatures (see Figure 5).

**Augmenting passive control: Forced Ventilation**

The passive control of the indoor environment is augmented with a degree of mechanical control through forced ventilation. The introduction of cool outside air into the indoor environment results in a reduction in temperature, however the intrusion of dust and insects necessitates control over the quality of air used for ventilation. A solution to this issue is in the form of forced ventilation whereby outside air may be filtered and forced into the indoor environment. This is a variation of the standard supply system of forced ventilation where outside air is brought in and creates a positive pressure (Szokolay, 2008).

The building is simulated to follow the schedule of apertures open during the evening hours from 1900Hrs to 0700Hrs and adjustments are made for an increased air change rate (as a means of controlling air velocity) during the same schedule to mimic the inclusion of forced outside air. Assuming the outside air speed to be 1m/s (the average air speed in Lahore is approximately 4.5m/s for July) (Weatherspark, 2013) the number of air changes through a 2m² window (at 15% glazing ratio) and a room of 77m³, as simulated, is at 97. A conservatively applied air change per hour value of 50 results in a reduction to the internal temperature by 0.5°C.

![Figure 5](image-url)

**Figure 5** Simulated temperature for 24 hour period over day 180/365 (30th June). Comparison of change in temperature due to change in glazing ratio and with forced ventilation.
A slight modification to the schedule postpones the start of forced ventilation till 2200 Hrs when the outside air temperature has dropped to below 35° with the result of the indoor temperature remaining between the comfortable values of 34.5°C and 28.8°C.

The 1st floor:

The difference between the indoor temperatures of ground floor and a similar space at the 1st floor region is an average of 1.1°C which with the introduction of the passive and mechanical control measures listed above comes down to 0.5°C. The result is a significant reduction in indoor temperatures for both floors and further reductions can be attempted by focusing on the insulating properties of the roof construction.

CONCLUSIONS

This paper has attempted to assess the role of building codes in establishing thermal comfort within the indoor environment. Focusing on hot-dry climates and taking Lahore Pakistan as a case study some shortcomings in the building code are identified, foremost of which is the absence of locally relevant thermal comfort parameters.

Taking the urban geometry and the building envelope as products of the building code, specific contributions of the indoor environment of a typical residential structure were studied through software simulations. The simulations indicated that the urban geometry has both a positive and negative effect on the indoor environment; the effect of the urban micro-climate being an increase in temperature while the close proximity of neighbouring buildings dampening this rise possibly due to their shading effect. The simulations further indicated that the building envelope is responsible for most of the heat gain to the interior of a building and that the primary contributor to uncomfortable indoor conditions are the glazed apertures within the building envelope. It was also determined that through a simple reduction to glazed surface area, augmented with low energy mechanical conditioning (such as ceiling fans and forced night-time ventilation) the indoor environment can be brought to within comfort levels.

The overall focus of the work has been upon the achievement of thermal comfort through the use of passive and low energy measures. The work indicates this is an achievable target for a sizeable section of the population, it thus contributes towards laying the ground work for modifications in building codes to achieve this objective.

REFERENCES


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16-18 December 2014, CEPT University, Ahmedabad