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.

$$\Delta T_c = |T_{op} - T_c|$$

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.

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**Figure 1.** Building case study, plans and construction specifications
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.

$$\Delta MC = C_f - C_i$$ (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.

$$T_n = 17.8 + 0.31 T_m; \quad T_c = T_n \pm 3.0$$ (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; \(T_m= 9.8˚C\)), 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.

INFLTRATION 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.
Table 1. Comfort Indices for the Building Case Study

<table>
<thead>
<tr>
<th></th>
<th>∆Tc (Degree-hours)</th>
<th>∆Tc (%)</th>
<th>T0 min (°C)</th>
<th>T0 avg. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter Bedroom</td>
<td>9,976</td>
<td>67</td>
<td>5.9</td>
<td>15.6</td>
</tr>
<tr>
<td>Winter Living room</td>
<td>8,943</td>
<td>71</td>
<td>7.9</td>
<td>15.6</td>
</tr>
<tr>
<td>Summer Bedroom</td>
<td>3,228</td>
<td>49</td>
<td>36.3</td>
<td>26.3</td>
</tr>
<tr>
<td>Summer Living room</td>
<td>785</td>
<td>36</td>
<td>33.1</td>
<td>23.8</td>
</tr>
</tbody>
</table>

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</th>
<th>ΔMC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B 1</td>
<td>C1</td>
<td>D1</td>
<td>E1</td>
<td>515</td>
<td></td>
</tr>
<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 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>B3</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](image)

Figure 3 (a) Optimized building performance on a typical winter day and (b) on a typical summer day.
Table 3. Comfort Indices of the Improved House

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th></th>
<th>Summer</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>∆Tc</td>
<td>To min</td>
<td>To avg.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Degree-hours)</td>
<td>(°C)</td>
<td>(°C)</td>
</tr>
<tr>
<td>Bedroom</td>
<td>205</td>
<td>8.1</td>
<td>14.8</td>
<td>21.0</td>
</tr>
<tr>
<td>Living room</td>
<td>144</td>
<td>7.8</td>
<td>15.7</td>
<td>20.5</td>
</tr>
<tr>
<td>Bedroom</td>
<td>70</td>
<td>6.9</td>
<td>28.6</td>
<td>23.2</td>
</tr>
<tr>
<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 W/m²K). 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.](image_url)
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

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