

Aggregating building energy demand simulation to support urban energy design

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ABSTRACT

Designing energy efficient cities and in particular designing buildings as well-thought components of the urban fabric and active components of the urban energy system requires reliable information on the current demand in energy within buildings, its distribution in time and space and the possibility to impact on this demand.

In this article we present a methodology developed to produce this information by aggregating the simulation results of a very large number of buildings. The methodology relies on the use of an existing simulation tool (bSol) and of selected default parameter values corresponding to pre-defined building typologies as well as data from existing weather and GIS databases for calibrating the tool. The core challenge being the adequate choice of default parameters related to the building's environment (weather conditions and surroundings), its fabric (mass and envelope), its equipment and its occupants' behaviour, we pay special attention to producing a sensitivity analysis of the tool's results in relation to these parameters. This leads us to define a database structure for required default values and to start populating the database with robust values.

We apply the methodology to recognise typical urban typologies relevant to energy planning and the parameters defining them, such as building typologies, mixity of use, urban density and morphology, existing energy infrastructure, potential for renewable energy production. For each urban typology we attempt to propose typical solutions at different levels of spatial resolution, ranging from decentralised solutions to more centralised solutions at neighbourhood, district or city level.

While the methodology presented was developed within a Swiss project it can just as well as be applied to the challenge of planning and implementing energy efficiency in rapidly growing cities of developing countries, in particular to the regeneration of existing and planning of new city districts.

INTRODUCTION

It is widely accepted that an integrated multi-energy approach covering energy demand, supply, distribution and storage applied to a cluster of buildings (neighbourhood, district or whole city) is required for the optimal planning and design of urban energy systems. One of the main challenges in this field is being able to simulate the energy demand (in particular heating and cooling requirements) of large numbers of buildings at an acceptable level of accuracy.

While building simulation tools are currently capable of simulating single buildings within a reasonable level of accuracy provided a great amount of information is made available to calibrate the tools used, simulating a large number of buildings and their aggregated demand profiles with very little input data remains a core challenge. With increasing computational power the issue is no longer computational run time but rather a reliable estimation of the discrepancy between simulated and real demand profiles (and the reduction of this discrepancy). This information is vital if we wish to rely upon

building simulation for the detailed design and operation of urban energy supply and distribution infrastructure. We present in this article a methodology to address this issue consisting in proposing well defined building typologies with a minimum amount of significant input parameters that can be used to calibrate an existing building simulation tool.

STATE-OF-THE-ART

Previous efforts to model a large number of buildings have been made in particular to support cities in their energy planning. Projects worth noting, for example in Switzerland, are EnerGIS [Girardin et al., 2010], MEU [Rager et al., 2013] and Zernez [Orehounig et al., 2013]. In the case of EnerGIS the energy demand from the building stock of the city of Geneva was represented by a set of 80 building typologies each corresponding to a thermal signature. The two latter projects use the CitySim [Robinson et al., 2009] simulation tool to produce hourly energy consumption profiles of buildings in either the neighbourhoods of the cities of Lausanne, Martigny, La Chaux-de-Fonds and Neuchâtel in the case of the MEU project or the alpine village of Zernez.

At the European level the introduction of compulsory European Performance Certificates has generated a large amount of data on the annual energy demand of buildings as well as a variety of national calculation methods to estimate these. The TABULA project (and its follow-up project, EPISCOPE [Episcope, 2014]) proposes national building typologies typically based on the year of construction and on the size (with categories “single-family”, “terraced”, “multi-family houses” and “apartment blocks”) of the buildings, mostly limited to residential buildings, for each of the 13 countries involved. While the main objective of the project is to inform users regarding the potential for energy demand reduction in “normal” and “ambitious” scenarios of refurbishment and the associated costs it represents an extremely valuable dataset of default values that can be used for parametrizing dynamical simulation tools.

METHODOLOGY

The methodology presented in this article was produced in the on-going Smart Heat project [Smart Heat, 2014] whose objective it is to propose to the energy utilities of Verbier and Sierre a preliminary solution (system design and operation strategy) for meeting the thermal loads of the buildings of each town in line with their urban energy plan. OSMOSE, a tool for the design and analysis of integrated energy systems developed by the Ecole Polytechnique Fédérale de Lausanne (EPFL) [Fazlollahi et al., 2014] is used within the project to define the best possible energy conversion system for the use case, combining centralized and decentralized solutions, by using its thermo-economic optimization functionalities. In order to produce this output OSMOSE requires the knowledge of the dynamical behavior of energy demand of all buildings. For this we use the bSol software [Bonvin et al., 2007] to simulate single buildings or building zones. bSol produces a profile of hourly heat requirements to compensate for heat losses over the previous time step, but does not model the buildings’ energy production and distribution (HVAC) system. It calculates losses based on the thermal balance of heat transferred through the building’s surfaces, heat transferred via air exchanges and internal heat gains due to solar radiation, occupant presence and use of appliances. This calculation requires the user to input parameters related to the building’s fabric (e.g. U-values of the building’s envelope elements, thermal capacity, glazing ratio and g-value of windows), its use (e.g. occupant presence profiles, installed capacity of electrical appliances, temperature set-points, air exchange rates, use of blinds) and meteorological data (extracted from the METEONORM database [Meteonorm, 2014] for the site in question) such as outdoor temperature and solar radiation (taking into account the topography of the site).

bSol has the advantage of existing in a stripped-down server-based version capable of treating, within seconds, batches of simulation runs containing values for the input parameters and returning simulation outputs for each building. This version was used to simulate the energy demand of large numbers of buildings in order to determine the energy demand of neighbourhoods, districts or the whole

town. This approach transfers the problem of large-scale energy demand simulation to that of 1) defining the right inputs parameters for a large set of buildings and 2) aggregating the results of single building simulation to produce realistic energy demand profiles at various levels of spatial resolution.

The problem of producing input parameters for large sets of buildings is best solved by defining building typologies that can be easily related to statistical information available on a building by building basis. The Swiss federal office of statistics [Federal land registry office, 2014] provides geo-referenced information for each building in the country. The Centre de Recherches Energétiques Municipales (CREM) combines this information with other sources of information (e.g. from the trade register) to provide their own geo-referenced database named PlanETer [Cherix, 2011], conceived to support municipalities in the development of their energy masterplan and that is gaining in widespread use amongst municipalities in western Switzerland.

We use the following information for each building: location, year of construction, year of refurbishment, building use, building footprint (typically provided as perimeter and surface) and number of stories. On the basis of this information we define building typologies based on the *year of construction* and the *building use*. Categories for the year of construction are defined as:

A - "Previous to 1980",	C - "From 1991 to 2000"	E - "After 2010"
B - "From 1981 to 1990",	D - "From 2001 to 2010"	

Categories for building use¹ correspond to:

1 - "Residential"	5 - "Hotels"	9 - "Administration"
2 - "Residential - seasonal" ²	6 - "Hotels - seasonal"	10 - "Industrial"
3 - "Restaurants"	7 - "Commercial"	11 - "Sports halls"
4 - "Restaurants - seasonal"	8 - "Schools"	

This allows us to represent the great majority of buildings to be simulated with 55 building typologies. To each of these typologies we associate the full set of input data required to run a bSol simulation (see figure 1). While some inputs are currently fixed for all typologies the values of the following input parameters depend on the typology:

- for the building fabric: U-values of the roof, facade, floor, windows and window frames, glazing ratio of each facade, g-value of windows, total thermal capacity;
- for the building use: temperature set-point, installed maximum heating capacity, occupancy profile and installed electrical appliance capacity (for the calculation of internal heat gains).

The choice of numerical values for these parameters has been made to coincide with national building regulations (e.g. SIA 380/1, SIA 2024) when possible and based on the authors' expert knowledge when not. Each building is simulated as a rectangular polyhedron facing southwards with no obstruction other than the topography of the site (i.e. not considering neighbouring buildings). The choice of intervals for years of construction was based on the authors' expert knowledge; its pertinence is assessed in the sensitivity analysis.

¹ Buildings not covered by these categories (e.g. churches, farms) are currently considered individually but can also be added to the list of typologies.

² The distinction between "seasonal" and "non-seasonal" categories is intended to account for the significant seasonal dependence of building use in touristic resorts, such as Verbier.

Year of construction	Building Use		Thermal coefficients						Glazing ratios				
			U Roof	U Facade	U Floor	U Window pane	U Window Frame	α	Thermal capacity MJ/K.m ²	North	South	Est	West
<=1980	Residential	A1	0.80	1.10	1.50	3.00	2.00	0.80	0.50	15%	30%	20%	20%
	Residential - seasonal	A2	0.80	1.10	1.50	3.00	2.00	0.80	0.50	15%	30%	20%	20%
	Restaurants	A3	0.80	1.10	1.50	3.00	2.00	0.80	0.50	15%	30%	20%	20%
	Restaurants - seasonal	A4	0.80	1.10	1.50	3.00	2.00	0.80	0.50	15%	30%	20%	20%
	Hotels	A5	0.80	1.10	1.50	3.00	2.00	0.80	0.50	15%	30%	20%	20%
	Hotels - seasonal	A6	0.80	1.10	1.50	3.00	2.00	0.80	0.50	15%	30%	20%	20%
	Commercial	A7	1.00	1.10	1.50	3.00	2.00	0.80	0.50	15%	30%	20%	20%
	Schools	A8	0.80	1.10	1.50	3.00	2.00	0.80	0.50	15%	30%	20%	20%
	Administration	A9	0.80	1.10	1.50	3.00	2.00	0.80	0.50	15%	30%	20%	20%
	Industrial	A10	0.80	1.10	1.50	3.00	2.00	0.80	0.25	15%	30%	20%	20%
	Sports halls	A11	0.80	1.10	1.50	3.00	2.00	0.80	0.25	15%	30%	20%	20%

Figure 1 Sample of the inputs associated to 11 of the 55 building typologies and required to run a bSol simulation of a building.

DISCUSSION OF RESULTS

It was not possible to acquire energy demand profiles of the buildings being modelled within the Smart Heat project. The application of statistical analysis on measured data to validate the methodology presented here will be done in further research. In the meantime we have focused our efforts on carrying out a sensitivity analysis of our model to 1) confirm our choice of typologies based on *year of construction* and *building use* and in particular our choice of categories for these parameters, 2) understand which input parameters associated to each typology have a significant impact on the simulation results. This latter analysis is important as it will also highlight which data needs to be collected in the future to validate the model and to improve the values of input parameters.

In order to confirm the choice and number of typologies we produced an analysis of variance (ANOVA) to assess whether the year of construction and the building use are indeed decisive factors allowing one to distinguish between simulations of annual energy demand. Each category of *year of construction* is associated to a unique total U-value of the building envelope (A – 1.36W/m²/K, B – 0.89W/m²/K, C – 0.65W/m²/K, D – 0.46W/m²/K, E – 0.32W/m²/K). Each category of *building use* is associated to a unique occupancy profile, value of installed capacity (of electrical appliances) and value of air exchange rate.

The ANOVA was applied to the results of 165 simulation runs, i.e. 3 runs per typology corresponding to three states of temperature set-point: 19.5, 20 and 20.5°C. This corresponds to the typical precision of a building's thermostat, independent of its year of construction and building use, and allows us to introduce a common variability to the simulations of each typology. A two-way ANOVA was applied on the variability of energy demand for each couple (year of construction, building use). This produced an F-test value of 11.29 that has a probability smaller than $2 \cdot 10^{-16}$ of following a distribution of Fischer-Snedecor with $\nu_1=40$ and $\nu_2=110$ degrees of freedom and confirms our assumption that the couple of parameters (*year of construction*, *building use*) is relevant in classifying the simulated energy demand of buildings and a reasonable choice of building typologies.

In order to visualize the impact of the *year of construction* and the *building use* on our simulation outputs of interest (annual energy demand, peak and average power demand) we also analysed the probability distribution of annual energy demand as a function of these two parameters separately. Figure 2 shows the boxplots of these distributions for categories A to E in the case of a residential building. The parameters shown are the median and average power demand (over one hour), the number of hours of heating over a year and the 95th percentile of the distribution representing a reasonable estimate for the “maximum power demand” that should be used to size the heat production system. The

average power demand of each category lies beyond the inter-quartile range of the previous category confirming our assumption that these distributions are distinctly different from each other that this choice of categories was appropriate.

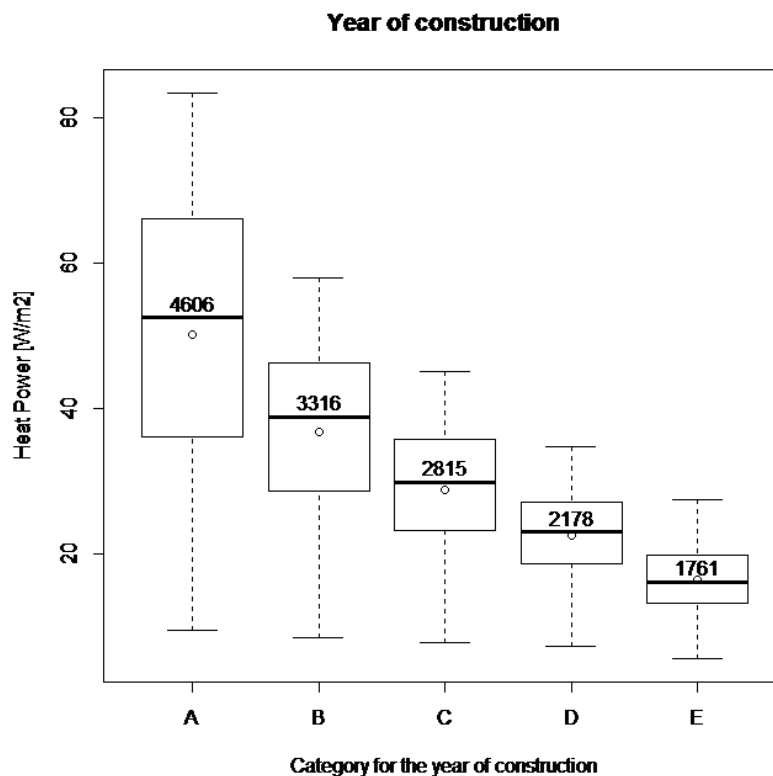


Figure 2 Distribution of power demand for categories A to E including the total number of heating hours, average power (circle) and 95th percentile (upper tail of the boxplots).

We then run, for each category A to E, simulations corresponding to the 11 different building uses. The annual energy demand³ value of each building use is represented by a symbol in the graph of figure 3. The average (mean) and standard deviation (sd) of the distribution of the 11 values per category of year of construction are given in the table on the right. The first observation is that the order of results stays the same for each category A to E. This proves that there is a systematic dependency of annual energy demand related to building use, in other words that the heat gains and losses associated to a specific building use are not affected by the building fabric in such a way that results could be interverted. They are therefore distinguishable from each other; the question is whether the spread due to other input parameters (discussed below in the design of experiments displayed in table 1) overwhelms the spread related to building use. Aside from outdoor obstruction building use proves to have the highest impact on simulation results. Also this impact (the ratio between “sd” and “mean”) increases for newer categories of buildings for which distinguishing between building use becomes essential. We conclude that distinguishing between building use is necessary for most years of construction and should not be limited to newer buildings but be applied to all categories A to E. In addition to determining the way a building is used, building use categories also determine the building fabric elements typically associated to a building use, confirming even more so the need to consider all 11 categories for each year of construction.

³ Values for mean power show similar results. Values for maximum power were not representative due to the fact that the 95th quantile corresponded, for a large number of building use categories, to the nominal power entered as an input into bSol.

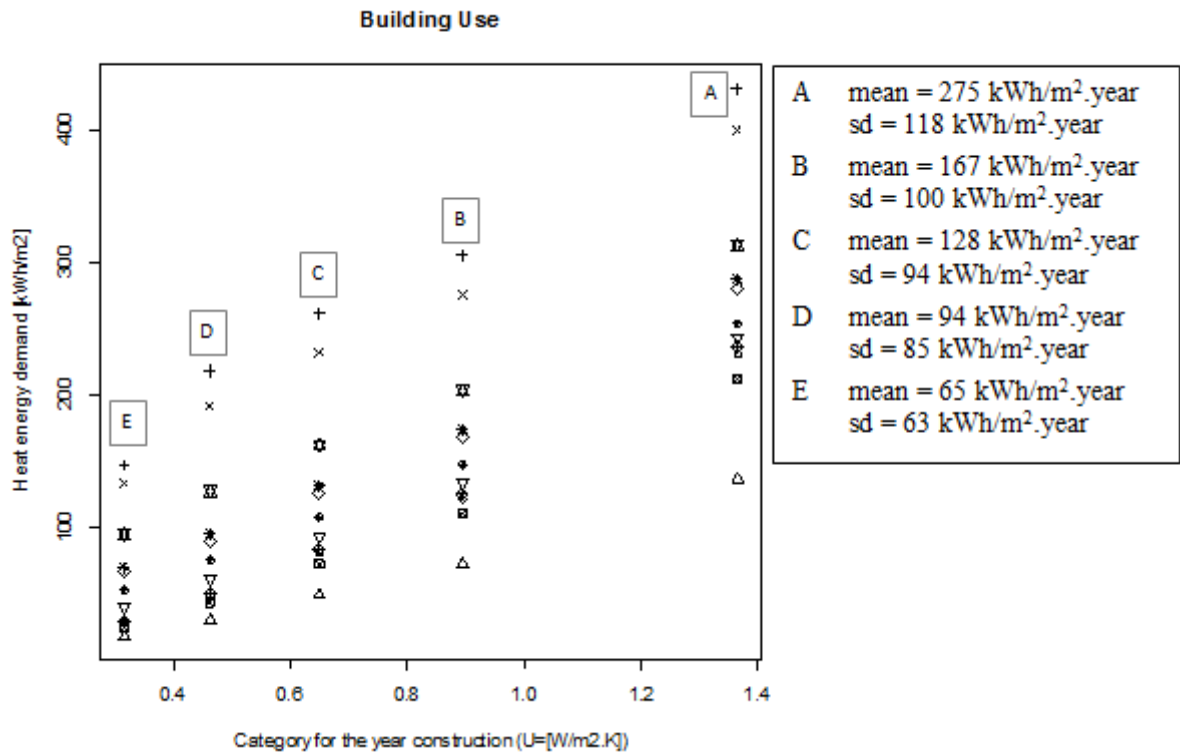


Figure 3 For each category A to E (represented by its total U-value) the left figure represents the annual energy demand of each building use (11 symbols) with the average and standard deviation over all 11 values given in the table on the right.

In order to confirm the choice and number of input parameter associated to each typology we produced a sensitivity analysis in the form of a design of experiments (DOE) for the following 6 input parameters: temperature set-point (over the interval⁴: 18, 19, 20, 21 and 22°C), total thermal capacity (0.1, 0.25 and 0.5 MJ/m²), glazing ratio (from 0 to 50% more than the default values given in figure 1), building orientation (from -90° to +90° relative to the default value of 0°, i.e. facing south), outdoor obstructions (obstructions on the horizon ranging from 0 to 90°) and weather conditions (“cold”, “average” and “warm” years corresponding respectively to Meteonorm data for Verbier for an average year over the period 1961-1990 – with an average temperature of 5.4°C, for an average year over the period 2000-2009 – average of 6.4°C, and for Meteonorm’s forecast for 2030 – average of 7°C). Table 1 displays the results of the design of experiments for categories in the unique case of a residential building use. It shows, for each category A to E, the percentage change (bottom row) relative to the reference value (top row) for annual energy demand, average power demand and maximum power demand for all 6 input parameters⁵. The sign of the percentage indicates whether increasing the value of the input has an increasing or decreasing impact on the simulation output with respect to the reference value.

The results clearly highlight the significant impact, for all categories A to E, of the temperature set-point, glazing ratio and outdoor obstructions on simulation outputs while weather conditions show little impact and building orientation none at all. The glazing ratio has the interesting property of significantly increasing heat demand for older buildings (due to high heat losses) while significantly decreasing heating demand in new buildings (thanks to increasing solar gains). Similarly thermal capacity is most

⁴ The underlined value corresponds to the reference, i.e. the default value used for the typology.

⁵ Non-representative values marked N/A result from the fact that the maximum power demand was limited by the nominal power entered as an input.

important for new buildings.

Table 1. Design of experiments for estimating the impact of input parameters on annual energy demand (E), average power (P) and maximum power (Pmax) demands.

	Temperature set-point			Total thermal capacity			Weather conditions		
	E [kWh/m ² /a]	P [W/m ²]	Pmax [W/m ²]	E [kWh/m ² /a]	P [W/m ²]	Pmax [W/m ²]	E [kWh/m ² /a]	P [W/m ²]	Pmax [W/m ²]
A	231	50	83	231	50	83	231	50	83
	20%	6%	7%	-9%	6%	2%	-5%	2%	-2%
B	122	37	58	122	37	58	122	37	58
	22%	5%	7%	-16%	8%	2%	-8%	-3%	-2%
C	81	29	45	81	29	45	81	29	45
	23%	7%	7%	-17%	10%	2%	-9%	-3%	-2%
D	49	23	35	49	23	35	49	23	35
	24%	9%	9%	-20%	9%	3%	-8%	0%	-3%
E	29	16	28	29	16	28	29	16	28
	28%	6%	11%	-21%	6%	4%	-10%	0%	-4%

	Glazing ratio			Building orientation			Outdoor obstruction		
	E [kWh/m ² /a]	P [W/m ²]	Pmax [W/m ²]	E [kWh/m ² /a]	P [W/m ²]	Pmax [W/m ²]	E [kWh/m ² /a]	P [W/m ²]	Pmax [W/m ²]
A	231	50	83	231	50	83	231	50	83
	N/A	N/A	N/A	0%	0%	0%	45%	-6%	-2%
B	122	37	58	122	37	58	122	37	58
	30%	70%	N/A	-1%	0%	0%	76%	-11%	-3%
C	81	29	45	81	29	45	81	29	45
	31%	83%	N/A	-1%	0%	0%	95%	-14%	-2%
D	49	23	35	49	23	35	49	23	35
	4%	83%	N/A	-2%	0%	0%	131%	-13%	-3%
E	29	16	28	29	16	28	29	16	28
	-31%	63%	N/A	0%	0%	0%	166%	-13%	0%

Based on these observations one could conclude that:

- i. detailed information regarding the three dimensional layout of buildings within a city is of real importance in providing reliable simulation results (although the orientation of each building is of little significance and buildings can be simulated as facing southward with no significant loss in relevance of simulation results)
- ii. as well as is information regarding the amount of glazing on exposed facades and whether buildings are attached or not,
- iii. as the choice of the temperature set-point is significant this input parameter should take on a variety of values whose distribution needs to correspond to surveys of real values,
- iv. the thermal capacity of a building should be well estimated (although three values representing “light”, “average” and “heavy” are enough) in particular for new buildings,
- v. using averaged weather files of a particular site seem to suffice in providing reliable simulation results.

CONCLUSION

We present in this article a simple approach to simulating a large number of buildings at the level of a city neighbourhood or whole city based on the use of building typologies (characterised by periods of construction and by building use) used in combination with a dynamical building simulation tool. The resulting hourly energy demand profiles can be used in combination with an energy production and distribution modelling tool (e.g. OSMOSE) or alone (e.g. when modelling building refurbishment measures) to propose a solution (system design and operation strategy) for meeting the thermal loads of

an urban area in line with targets of the municipality's energy plan.

The success of this approach relies greatly on the appropriate choice of values for the simulation tool's input parameters. The sensitivity of the approach's results relative to the choice of periods of construction and building use in characterising the building typologies as well as to the input parameters associated to the typologies highly depends on the case study to which it is applied, in particular on its climatic conditions, construction practices, typical building use (density of occupancy, profile of occupancy, installed electrical appliances) and the national building regulations that impact on these. We propose in this article a general methodology that the user can apply in order to fine tune the approach to their needs. For our specific case study, an alpine ski resort in Switzerland, we can conclude that our typologies – 5 categories of years of construction and 11 of buildings use – were well chosen. In addition we are able to recognize which input parameters require most attention. In our case study providing detailed information regarding outdoor obstructions, glazing ratios is paramount. Entering temperature set-points as well as information related to building use (internal heat gains and air exchange) that are consistent with real values is also important. Finally information related to the thermal capacity and (off average) outdoor temperatures are mostly relevant for newer buildings with lower heating requirements.

OUTLOOK

We have not discussed the clustering of single-building simulated energy demand profiles as this research is still in progress. A successful methodology will need to integrate the variability of real annual energy demands around the simulated average and the stochastic nature of energy demand. The research presented here will allow us to determine for which parameters an uncertainty analysis needs to be done. Stochasticity of demand will be integrated a posteriori by modifying simulated profiles of energy demand.

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