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Identification of Parameters Affecting the Variability of Energy Use in Residential Buildings

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Abstract

Energy use of buildings varies significantly. When aggregating the demand profiles of a group of buildings, the variations of energy demand are critical to determine the aggregated load profile. Especially when dimensioning district energy systems, it is important to know the variability of energy demand that can guarantee the efficient operation of the system. For this reason, it is useful to distinguish the parameters that affect building energy performance the most and to estimate the magnitude of these variations on each parameter.

The aim of the present study is to identify the parameters that lead to the largest variations in energy performance of residential buildings in Denmark. A set of sensitivity analysis has been carried out using an extensive search algorithm. These sensitivity analyses were then applied for modelling a reference building representing Danish single-family houses of the 1940's. The study was able to determine the key variables that affect energy use in old Danish single-family houses using sensitivity analysis and proposes a methodology for parameter optimization. This analysis pointed out that the insulation in external walls and roof lead to the largest variations in space heating demand. Also, the infiltration rate and occupancy behavior play important role on space heating consumption. It was concluded that these findings highly depend on the specific case study and the characteristics of the buildings that are examined. If outdoor climate and location differ from the current case, a different set of parameters should be investigated upon its effect on building energy use.

Keywords – heat demand; variability; sensitivity analysis; building parameters

1. Introduction

Variations in energy use of buildings are considered significant issues for their integration with the overall energy grid. Especially in the framework of Energy Hubs [1] where integrated district energy systems are dominant, the accurate prediction of the operational energy use of a building or clusters of buildings is crucial. According to the findings of IEA EBC Annex 53 [2], these variations are mainly attributed to the following areas: building envelope and equipment, operation and maintenance, occupant behavior and indoor environmental conditions, as well as outdoor climate.

Uncertainty and sensitivity analyses are an integral part of the modelling process [3]. Uncertainty characterizes both passive building parameters (e.g. building structure) and active components (e.g. users, climate). Uncertainty analysis has proven to be the main approach to determine the effect of uncertainty on building energy performance. Moreover, sensitivity analysis is conducted to analyze variations in building parameters and their effect on energy use. Generally, the methodologies found in literature are classified into local and global sensitivity analyses (i.e. regression, variance-based, screening-based and meta-model based method). The main difference between these two methodologies is that the local sensitivity analysis emphasizes on the individual effect that each parameter has on the output, while the global analysis considers the interactions among the examined parameters [4]. However, the local sensitivity analysis is easily applied and often requires less simulation runs than the global one.

Previous studies have extensively used sensitivity analysis in building energy analysis such as [5], [6]. In particular, [7] showed quite early that variation of inhabitants' has a much higher effect on energy use than variation of outdoor climate using Monte Carlo technique. [8] identified the most important parameters affecting the total energy use of sustainable buildings to be lighting control and ventilation rate during winter. When heating demand was examined, the authors concluded that ventilation plays the most important role. In another study by [9], the most critical parameters on heating consumption were found to be thermostat set points and ventilation flow rate followed by the properties of windows. [10] concluded that the biggest factor in heating loads was fabric properties (insulation, glazing, infiltration) followed by floor area, heating set points and orientation, while occupancy behavior and lighting had a very low impact. Therefore, results from previous studies vary quite a lot depending on the reference case and on the purpose of analysis.

First, the present study aims at identifying the parameters that affect the variability of building energy use and specifically space heating demand focusing on residential districts. Second, it aims at estimating the changes in heating demand that the variations of these parameters lead to. In the case of district-level energy systems, the variability of building energy use makes it difficult to estimate the aggregate demand and then, dimension the systems accordingly. Thus, it is very important to determine the parameters that highly influence energy use in buildings when aggregated to specific districts or cities.

2. Methodology

A typical Danish single-family house of the 1940's was used as a reference building. Information about the building was collected by the TABULA Webtool [11] and [12]. The building model was created in IDA ICE using one single zone. The model properties are presented in Table 1. The building was connected to the local district heating system, while no mechanical ventilation or cooling system was installed in the building. The location of the building was set to Copenhagen and it was simulated using the Danish Design Reference Year (DRY) weather file [13].

The parametric analysis was made with the open source software MOBO [14]. MOBO is originally meant to handle multi-objective optimization problems with constraint functions. It provides the possibility to be coupled to building performance simulation tools, while selecting different algorithms to perform the calculations. For this study, no optimization was needed but a sensitivity analysis was carried out instead. An exhaustive search method was selected, namely Brute-force algorithm to conduct a local sensitivity analysis. Brute-force is a very simple straight-forward approach that can sample the whole solution space. For this reason, it is very computationally expensive and not very fast. However, it is very accurate and for the simple case examined in the present study the computation time did not exceed 15 minutes for each parameter.

First, the parameters were identified. It was decided that properties of building envelope and occupancy behavior would be investigated for their effect on heating demand. Outdoor climate was not studied hereby because the purpose of the analysis is to emphasize on residential buildings that are located in the same location (district, city) so they share the same climatic conditions. Moreover, no mechanical ventilation was installed in the building since it is very uncommon in older Danish single-family houses.

MOBO requires setting the initial and final value of each parameter to restrict the spectrum of calculations, as well as the steps. These are illustrated in Table 2. The steps were defined such that 50 simulations are executed in every case. The range of each parameter was very important because it determined the variations in heat demand. Thus, it was selected so that it is realistic for Danish single-family houses based on the TABULA database, as well as on Danish Statistics. More variables were examined, but the ones with the most significant effect are presented in the following.

Since the range of each parameter differs, a dimensionless impact factor had to be defined to indicate the changes in heating demand the variations of parameters caused. So, this was defined according to (1), where output is the space heating demand in kWh.

$$I = \frac{\max(output) - \min(output)}{average(output)} \tag{1}$$

Table 1. Properties of reference building

Properties	Value
Model floor area	90.9 m^2
Model volume	236.2 m^3
Model ground area	90.9 m^2
Model envelope area	282.6 m^2
Window/floor area	16%
Average U-value	0.82 W/K m^2
Number of occupants	2.9
Infiltration rate	0.4 ACH
Orientation	50 deg

Table 2. Examined parameters for sensitivity analysis

Parameters	Type	Min. value	Max. value
Orientation (deg)	Continuous	0	350
U-value of glazing (W/m^2K)	Continuous	1	3
Insulation thickness in ext. walls (m)	Continuous	0.001	0.32
Infiltration rate (ACH)	Continuous	0.1	1
Number of occupants	Continuous	0	6
Insulation thickness in roof (m)	Continuous	0.001	0.32
Insulation thickness in floor (m)	Continuous	0.001	0.35

3. Results and Discussion

The results of the parametric simulations in MOBO are illustrated in Figure 1. The blue curves in the graphs represent the variable that was changing while the red ones represent the respective annual space heating demand that was calculated for these changes after 50 simulations.

It can be observed that for many parameters the influence on space heating demand is almost linear. This means that the impact does not differ significantly depending on the parameter range. Orientation has a more complicated correlation to energy use, since solar gains change dramatically with the positioning and orientation of the building. Increase of insulation thickness of walls and roof, as well as occupancy behavior, result in a decrease of energy use and specifically space heating demand. In particular, the more these parameters increase, the lower the heating demand of the building is, as it was expected. The effect of floor insulation thickness on heating demand had a similar trend with the roof insulation and it is not presented in Figure 1 for brevity. Specifically, the curves of the roof and external wall insulation thickness show a hyperbolic behavior. It was also found that increase of infiltration rate results in a linear increase of the heating demand. Moreover, the U-values of the windows were investigated. It was observed that heating demand increased linearly with the increase of the U-value of the windows. It is evident from Figure 1 that the range of heating demand differs significantly depending on the investigated parameter.

Thereafter, the impact factor of all the afore-mentioned parameters on space heating demand was calculated for the reference building according to (1) representing their magnitude on the variability of heating demand. These results are presented in Table 3. The positive values indicate an influence to increase the heating demand, while the negative ones indicate a diminishing impact on the heating demand. It can be observed that the most influential parameters for the reference building, for the given ranges corresponding to Danish houses, were the insulation thickness of external wall with an impact factor of -1.021. The roof insulation followed with an impact factor of -0.242. Then the infiltration rate followed with an impact factor of 0.141. The influence of occupancy on heating demand was found to be -0.101. The impact factor for glazing U-values was calculated to be 0.058. Lastly, variations of floor insulation thickness and orientation were found to lead to the smallest changes in annual heating demand. Specifically, the impact factor of floor insulation was found to be significantly lower than the one of wall or roof insulation. This is attributed to the fact that the heat losses through the ground are lower for the floor, since the ground layers below the floor slab have thermal resistance and operate as a buffer for heating.

Figure 2 presents the distribution of annual space heating demands for each parameter. The reference line corresponds to the annual heating demand of the reference building which was found to be 14,135 kWh, having the properties as presented in Table 1. Many variations in heating demand are pronounced, the biggest factor being wall insulation thickness with a total range of 8,178 kWh, a mean heating demand of 8,011 kWh and a median heating demand of 7,232 kWh. Variations in roof insulation thickness result to lower changes in heating demand with a total range of 3,410 kWh, a mean value of 14,066 kWh and a median value of 13,759 kWh. Both wall and roof insulation thickness have five or four outliers, meaning that these lie an abnormal distance from the rest of the values. This was expected from Figure 1 due to the hyperbolic shape of the curve, and the low values for minimal insulation thickness. Infiltration and occupancy follow with a total range of 2,039 kWh and 1,423 kWh respectively. Lastly, the total range of heating demand for the variations in glazing U-value, floor insulation thickness and orientation are 844 kWh, 414 kWh and 178 kWh, respectively. This means that orientation and window U-values have minimal impact on the annual heating demand, with glazing U-values having greater influence.

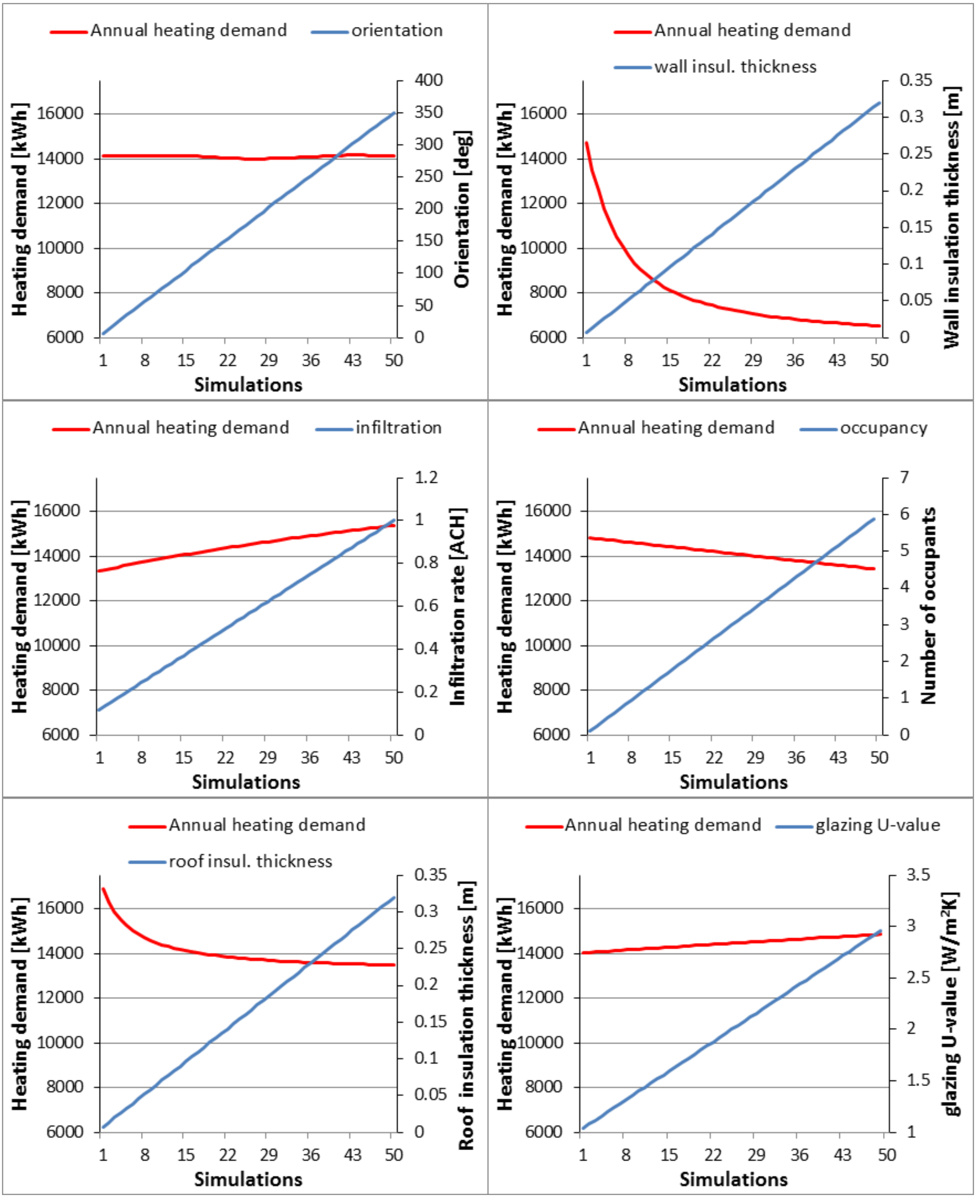

Figure 1. Annual space heating demand for each parameter after 50 simulations in MOBO

Table 3. Results of impact factor for each parameter

Parameter	*I*, Impact factor
Orientation	0.013
U-value of glazing	0.058
Insulation thickness in ext. walls	-1.021
Infiltration rate	0.141
Number of occupants	-0.101
Insulation thickness in roof	-0.242
Insulation thickness in floor	-0.030

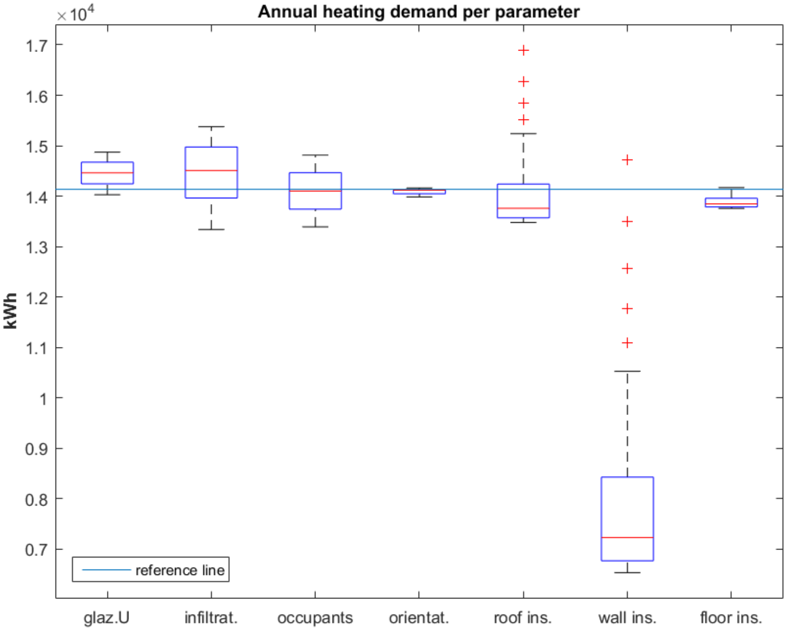

Figure 2. Distributions of annual space heating demand for each parameter. Box plots present the median (red line), quartiles (blue box) and extremes (whiskers). The red crosses indicate the outliers.

The structure of the reference building affects significantly the findings described before, so they cannot be generalized for every single-family house. It has to be pointed out that the reference building representing an old Danish house of the 1940's was poorly insulated with an average U-value of 0.82 W/m^{2}K. Specifically, the external walls and floor of this type of houses are very poorly insulated and only the roof has undergone some energy refurbishment concerning the addition of insulation [12], [15]. The poor insulation of the reference building determined the large impact of insulation thickness of walls on heating demand. At the same time, it affected the impact of secondary parameters such as orientation and occupancy, which were calculated to be significantly lower. If a very-well insulated building was examined instead, the impact factor of these parameters would have been much different. However, the purpose of this study was to propose a methodology for the estimation of magnitude of parameters affecting the variability of energy demand in buildings. In general, homogeneity characterizes most houses built in the same period in Denmark. Variability in occupancy was only accounted for through the number of occupants in this study. Nevertheless, stochasticity in occupant profiles may result in significant differences in similar buildings. So, probabilistic profiles accounting for stochasticity should be considered in the next step.

The weight of the building envelope properties (insulation thickness, infiltration) on the energy use is outlined in the present study. This is also due to the cold Danish climate that causes increased heat losses during the winter period and subsequently increased heating demand. If a warmer climate was applied, the results would be much different. The parameters that affect cooling demand would be more in focus in that case, such as windows g-value and ventilation. The interactions of parameters could be considered through implementing global sensitivity analyses. These interactions are even more important in cases where total energy use is examined because internal heat gains from solar radiation, occupants, appliances and natural ventilation interact highly with each other. Moreover, if the total Danish building stock was to be investigated, the combination of variations in parameters would be necessary to conduct sensitivity analysis.

4. Conclusions

A local sensitivity analysis was applied in the present study through an exhaustive search algorithm. The reference building representing an old Danish single-family house of the 1940’s was modelled in IDA ICE and parametric simulations were run in MOBO. The reported results of the sensitivity analysis indicated that the parameters resulting to the greatest variations in space heating demand were the insulation thickness of external walls and roof. The infiltration rate and number of occupants had significant although lower impacts on heating demand. These findings are highly dependent on the structure of the examined reference building, which in this case was poorly insulated. Different occupancy profiles were not examined in the study. Even if a district containing the same types of buildings would be studied, variations in occupant behavior may result in significant variations in total energy use. To be able to determine the total variations of heating demand in Danish houses, the combination of the aforementioned parameters is suggested to cover the whole range of Danish buildings' properties.

This study has aimed at proposing a simple methodology of estimating the impact of building parameters on energy use focusing on specific building typologies. Nevertheless, more sophisticated approaches should also be investigated and compared with regard to the accuracy of their results. The next step will be to apply this methodology to housing stock models considering any sources of uncertainty, such as heterogeneity and parameter uncertainty.

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