

Sensitivity analysis of building energy models due to the shading effect of surrounding buildings to support building renovation

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Abstract. Building energy simulation is an analytical process to help building owners and designers evaluate the energy performance of the building. Uncertainty in the building energy modelling influences the building renovation from two perspectives: 1) calculating as-built energy consumption, 2) analysing the energy performance of renovation alternatives. Energy models can enhance by incorporating contextual and surrounding data. To this aim, we conducted a systematic study to investigate the effect of surrounding buildings in different distances, heights, and orientations in studying the as-built energy consumption of an example building. The research also investigates the impact of a specific surrounding building on the energy performance of three different renovation alternatives, namely the modification of windows, external walls, and roofs. The results demonstrate that a higher height to distance ratio of the surrounding buildings influences the energy consumption more dramatically. In addition, a surrounding building located in the south direction causes more effect on the energy result than other directions when the building is in the northern hemisphere. For renovation scenarios, if there is a specific building in the south of the building under renovation, the window modification leads to less energy consumption than other renovation scenarios. The paper discusses that for renovation projects, an initial examination of surrounding buildings before selecting the renovation alternative is crucial; since different placements of surrounding buildings can affect the performance of renovation scenarios differently, which can cause a variation in the cost of renovation.

Keywords: Shading effect, building renovation, surrounding buildings, building energy performance, building energy simulation

1. Introduction

The EU Energy Efficiency Directives for 2030 requires EU countries to ensure energy consumption reduction by 32.5%. The energy efficiency of buildings leads to less cost for the inhabitants, protection of the environment, mitigation of climate change effect, and improving the comfort of occupants. Investigating the energy efficiency of buildings requires realistic building energy models, which are expected to be enhanced by incorporating real-life operation complexities.

Energy modelling of residential buildings is affected by many external factors such as occupants' behaviour, the exterior weather condition, and the shading effect of surrounding obstacles. Many studies investigated the impact of urban form, height, and orientation of surrounding buildings in building



energy modelling. Quan et al. [1] reviewed the articles focused on the relationship and extent of impact of urban form concerning the densification and topology in building energy consumption. Most of these studies are focused on new constructions and suggest suitable urban forms to have more energy-efficient buildings in future [1]. To the best of our knowledge, no study provided insight regarding the shading effect of surrounding buildings in building energy modeling of building renovation projects. In this research, we try to fill this gap by exploring and gaining insight into this topic.

Building energy simulation affects building renovation from two perspectives: investigating the as-built situation of a building and examining the performance of the renovation alternatives. To this aim, firstly, we analyze the sensitivity of building energy models of the as-built building situation to the presence of surrounding buildings placed at a specific distance and with a particular height and orientation. Secondly, we demonstrate how including and excluding surrounding buildings influence selections of renovation alternatives and, consequently, their costs. To this aim, we conduct a set of exploratory energy simulations for a real case study in Europe.

This research supports renovation projects from three aspects: 1) it helps to realize how significant the effect of surrounding buildings is in calculating the energy consumption of the current situation of a real case study; 2) it helps to reduce the gap between design and performance by estimating the energy consumption and operational costs more realistically; 3) it suggests improvement in the selection of renovation alternatives, which leads to less cost due to the mitigation of the overestimation of building components.

2. Research background

Many studies investigated the influence of surrounding obstacles in energy consumption of buildings. Ascione et al. [2] investigated the inter-building effect for two buildings in Italy by applying different shading systems. Han et al. [3] measured the impact of shading in a network of buildings systematically. They performed simulations under different climate contexts, and indicated a more substantial impact of shading effect in warmer climate cities [3]. Ichinose et al. [4] performed simulations in five major cities in China to consider different climate conditions and studied the effect of nearby shading on electricity consumption for space cooling and heating. They demonstrated that space cooling demand decreases by 10% to 20%, while space heating demand increases by 20% [4]. Haijing et al. [5] applied a parametric method to estimate shading effect on building energy demand for more than 93000 simulations in seven cities in different climate zones. Based on their findings, cooling loads can be calculated 45% more, while heating loads can be estimated 21% less, depending on the different geographic situations [5]. Nikoofard [6] quantified the shading effect of surrounding buildings and trees on the annual heating and cooling loads of buildings for four cities in Canada, representing major climate regions. Based on their findings, the heating and cooling demand of the building can change by 10% and 90%, respectively, due to the existence, distance, and height and direction of surrounding obstructions. Quan et al. [7] described that urban density is related to urban geometry and urban typology. If it is merely related to geometry, it affects building energy use negatively. When it is related to urban typology, the relation of energy use and density may be more complex. Quan et al. [8] performed more than 1400 parametric simulations to calculate the cooling and heating demand of the buildings in Portland considering urban form. Their results show that energy consumption and density do not always relate negatively. They also believe that building energy consumption can still vary significantly with the same typology. Other studies also investigated the effect of urban form, texture, and morphology in building energy loads [12, 13]. All these studies aim at providing information for developing urban form strategies and constructing new buildings. To the best of our knowledge, no study investigated the shading effect of surrounding buildings in the selection of renovation alternatives. In this research, we use an example building and conduct a systematic study to explore the surrounding building's effect on the building renovation. Firstly, we explore how surrounding buildings can influence the as-built energy demand of the building. Afterward, we investigate the impact of integrating surrounding buildings in the building energy loads of different renovation scenarios. The following section describes the details of our methodology to investigate this topic.

3. Methodology

We performed several energy simulations considering different conditions (with and without surrounding buildings) to analyze the energy demand of the building. When incorporating the surrounding buildings, we included buildings with varying parameters, namely, different heights, distances, and orientations. In another set of simulations, we investigated the effect of including and excluding surrounding buildings in the energy demand of different renovation scenarios.

We performed this research on a residential building in Gdynia, Poland which is one of the demonstration cases in BIM-Speed, an EU research project [9]. The building is a duplex dwelling constructed in 1961 with three stories, and 5.6 m height. External walls are made from full brick with a thickness of 56 cm. The building is partially insulated with expanded polystyrene. The heating system of the building is based on natural gas. The building requires renovation because of its very low energy performance and age of the building (Figure 1).

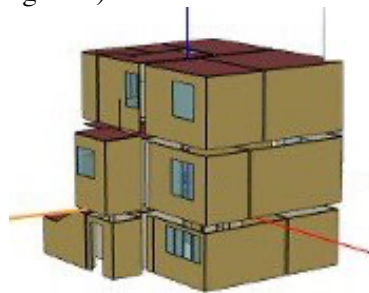


Figure 1: Building Information Model of the case study in Gdynia, Poland

Researchers believe that solar radiation on the building facades has a substantial impact on the building energy demand [10]. To study the sensitivity of the building energy model of the as-built situation to the surrounding buildings, we generated 25 different permutations of shading geometries as surfaces representing surrounding building facades created in different distances, heights, and orientations (Figure 2). For each of the conditions, we calculated the energy consumption of the building. We compared the results of these simulations with the energy consumption of the building, assuming that there is no neighbouring building. This comparison reveals information about the sensitivity of the energy simulation to different parameters of surrounding buildings, namely distance, height, and orientation.

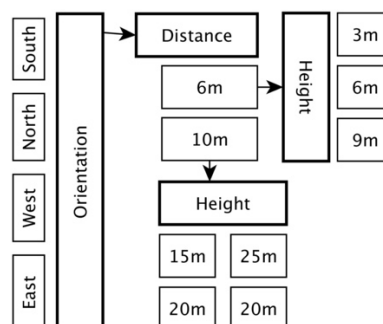


Figure 2: Generation of different permutations of surrounding buildings

Following that, we selected three different renovation scenarios. The alternatives include changing the windows with different U-Values, the thickness, and thermal conductivity in the material used in external walls and roofs. We provided a detailed description of each scenario in an online open data repository [11]. The online repository also includes the building energy models of the as-built situation as well as the three renovation scenarios including information about the indoor temperature range and

heating and cooling systems of the building. We calculated the energy demand of the building considering these renovation scenarios and excluding surrounding buildings. In the next step, we performed the energy simulation for the same renovation scenarios considering that a specific neighbouring building, i.e., a surface in 6 m distance, 9 m height exists in the south of the building under renovation (Figure 3). The result shows the energy demand of the building for different scenarios. We performed all the energy simulations using EnergyPlus™ version 9.1, one of the most prominent energy simulation tools [12].

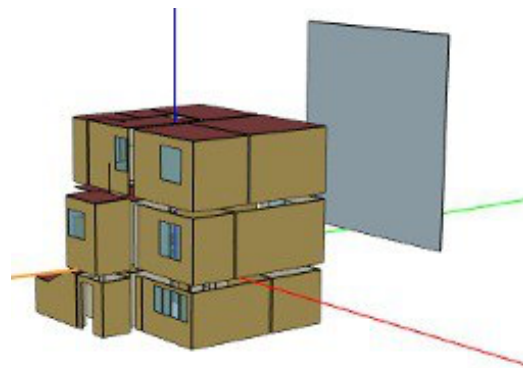


Figure 3: Geometry of a surface in the south of the building in 6 m distance and 9 m height

4. Result

This section summarizes the results of the simulations described in the previous section. By energy demand, in this study, we mean the energy required for building heating.

4.1. Energy consumption of as-built situation of building

Table 1 includes the results of energy simulations without the surrounding buildings compared to the simulation results with surrounding buildings as described in Figure 2. The table includes information about the orientation (O), distance (D) and height (H) of the surrounding building. H/D represents the height to distance ratio. Energy consumption (EC) of the building with and without the surrounding building is shown in the table, and the comparison between them is represented as diff%.

Table 1: Results of energy simulations including and excluding surrounding buildings (*Energy Consumption [EC], Orientation [O], Distance [D], Height [H]*)

Surrounding Buildings				EC (kWh)	diff%					EC (kWh)	diff%	
NA				28047.87						28047.87		
O	D(m)	H(m)	H/D			D(m)	H(m)	H/D				
East	6	3	0.5	28072.3	0.1	10	20	2	28107.77	0.2		
		6	1	28096.5	0.2		25	2.5	28106.86	0.2		
		9	1.5	28108.97	0.2		30	3	28106.3	0.2		
West	6	3	0.5	28048.23	0.0	10	20	2	28047.38	-0.002		
		6	1	28049.04	0.0		25	2.5	28046.36	-0.005		
		9	1.5	28049.31	0.0		30	3	28045.77	-0.007		
South	6	3	0.5	28213.42	0.6	10	15	1.5	28701.03	2.3		
		6	1	28628.59	2.1		20	2	28715.97	2.4		
		9	1.5	28973.94	3.3		25	2.5	28717.8	2.4		
			30	3	28720.02		2.4					
North	6	3	0.5	28048.83	0.0	10	20	2	28068.43	0.07		
		6	1	28060.69	0.0		25	2.5	28068.74	0.07		
		9	1.5	28070.09	0.1		30	3	28068.2	0.0		

Results show a meaningful influence of a surrounding building in the south of the building under renovation for both distances of 6 m and 10 m. In the 10 m distance, having a neighboring building on the west side of the building causes a decrease in energy demand. Results also represent an increase in energy demand by increasing the height of the building in the surrounding. On the other hand, the height to distance ratio (H/D) is an important factor. However, the same H/D ratio created from different heights and distances does not influence the energy result similarly. For instance, we examined neighbouring buildings with H/D equal to 1.5, generated once from a 6 m distance and 9 m height, and another time from a 10 m distance and 15 m height. The result represents an increase of 3.3% and 2.4% in annual energy demand, respectively.

4.2. Building energy performance of renovation scenarios

As discussed in the methodology section, we selected three different renovation alternatives for this study. In each of these cases, we performed the building energy analysis, considering that there is a surrounding building located in the south. This building is 9 m high and is located at a 6 m distance from the reference building. The simulation results are compared with the energy demand of the building using these alternatives and excluding the surrounding buildings (Table 2). Then we compared the energy performance of the alternative with the energy demand of the as-built situation of building.

Table 2: Simulation results for renovation scenarios

Renovation Scenario	Surrounding Building	Energy Consumption (kWh)	diff% from as-built situation
Window	NA	24531.86	-14.33
Window	South D 6m, H 9m	24698.89	-17.31
External wall	NA	25666.27	-8.49
External wall	South D 6m, H 9m	26576.35	-8.27
Roof	NA	27052.82	-3.55
Roof	South D 6m, H 9m	28001.3	-3.36

Renovation scenario I: With installing new windows with lower U-Value and considering no surrounding building, the energy consumption of the building decreases compared to its current situation by around 14%. Considering the surrounding building, the energy consumption of the building will decline by installing this window by about 17%. In this case, the effect of using a renovation component changes by 3% when considering the surrounding building.

Renovation scenario II and III: With changing the external wall and roof, the energy consumption of the building decreases by around 8% and 3%, respectively, including and excluding the surrounding building. Locating the building in the south does not change the influence of these renovation components.

Different decision-making tools are available for selecting among different renovation scenarios. One of the critical factors is economic parameters. Comparing the result of the energy performance of different alternatives considering the surrounding buildings helps to understand the energy cost generated from the building more realistically and compare it with the cost required for installing those renovation components. Similar study considering the Life Cost Analysis (LCA) of building for a large number of varying parameters in design phase has been conducted in NEED4B project [13].

5. Discussion

Results of the simulations support the fact that the position of the building in relation to the surrounding buildings is a critical factor in calculation of building energy consumption. However, the result of the case study depends on its location, which is in the northern hemisphere. In the northern hemisphere, the

sun path in wintertime rises in the southeast, passes the meridians and sets in the southwest [14]. Therefore, it is always on the southern part in the sky. Accordingly, if the south façade of the building is covered with obstructions, the heating demand increases because of the shading effect. This reveals the importance of considering the spatial context when studying the energy efficiency of the building, not only on the urban scale but also on the global scale. Other studies examined the effect of H/D distance [1]. In this research, we argue that, although a higher H/D ratio causes more energy consumption in the building, it is also essential to consider this ratio connected to the height of the reference building and the distance of the neighbouring building.

On the other hand, when selecting renovation alternatives, it is essential to consider the shading effect of surrounding buildings. Among the three scenarios, namely modification of windows and external walls in the south direction facade and the roof (according to the characteristics described in the table and provided online), changing the windows represents more effect in the energy loads of the building. It is essential to consider the shading effect of surrounding obstacles since it can change the cost required for the renovation.

This study has some limitations. Firstly, the investigation requires to be performed on more case studies to confirm the findings. Considering different case studies in different locations may also reveal other information about the effect of the orientation of surrounding buildings on energy consumption. Secondly, including other surrounding obstacles such as trees with their specific characteristics may cause other effects in the energy load of the building. Thirdly, we utilized a limited number of renovation scenarios. Studying other alternatives with other specifications may modify the findings. Lastly, in each simulation, we only considered the surrounding building in one orientation and with a limited number of distances and heights. A more complex combination of different surrounding obstacles in different orientations, distances, and heights may reveal other information.

Future research includes examining other case studies in a different location and with different characteristics such as height, area, and other surrounding building alternatives. On the other hand, we only focused on hypothetical surrounding buildings. A further research task is to study the actual surrounding buildings or a combination of different hypothetical surrounding obstacles, considering the material used in the surface of surrounding buildings. The surrounding buildings do not affect the energy loads of the building only because of the shading effect and reducing the solar gain. Dense urban areas created from tall buildings cause a microclimate effect because of the modifications in the urban temperature and wind circulation. A future research topic is to investigate the shading effect on the building energy efficiency along with the microclimate effect.

We investigated how variation in surrounding buildings can affect the result of building energy models due to the shading effect. The result has uncertainty for two main reasons. Firstly, the surrounding buildings affect the energy model not only because of the shading effect but also due to the microclimate effect. The microclimate effect causes a variation in the weather data, which is one of the inputs in building energy modelling. Secondly, the solar radiation data is available in the modelling from the weather data. The selection of weather data from different sources can affect the energy simulation results considering the shading effect of surrounding buildings. In this research, we only focused on studying the changes in the energy model results due to modest variations in surrounding buildings. Uncertainty calculations is beyond the scope of this research and is therefore, considered as future task. Further research may include describing the entire set of possible outcomes and their probabilities of occurrence, considering all the uncertainties which may happen because of the factors mentioned above. Based on the initial findings in this study, we believe that in renovation projects, the energy expert should examine the urban context and the surrounding obstacles. A comparison of the height of the surrounding buildings with the building under renovation is required to calculate the as-built building energy consumption accurately as also suggested by other studies [15]. On the other hand, although, the surrounding buildings do not influence the selection of renovation alternatives significantly, but the impact is meaningful for window modification. Nevertheless, when selecting the renovation scenarios, it is also essential to consider the neighbouring buildings to ensure the accuracy of the building energy performance and subsequently the selection of the alternatives to avoid extra costs.

6. Conclusion

We investigated the shading effect of surrounding buildings in building renovation. We considered this effect in the renovation workflow from two perspectives: the energy consumption of the as-built situation of building; the energy performance of renovation scenarios. We performed simulations considering neighbouring buildings in different distances, and heights and orientations. The results show that for a case study in Gdynia, Poland, the south direction, and higher H/D ratio causes more influence in calculating the energy consumption of the building.

Moreover, we introduced the specifications of three different renovation alternatives, including modification of windows, external walls, and roof. Assuming that there is a neighbouring building in the south of the building under renovation in 6 m distance and 9 m height, window modification represents more impact in the energy loads of the building in comparison to the two other scenarios.

We highlight that the shading effect of the surrounding buildings influences the energy simulation results. Therefore, to have a more realistic building renovation, which leads to a more energy-efficient process, energy experts should integrate such real-world complexities. In addition, it also helps in controlling extra costs in selecting renovation scenarios.

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