Energy simulation in early stage building design: simplified models and impact on results

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Abstract

The paper stems from the benefits of the application of energy analysis in the early-stage building design combined with the difficulties that prevent this integration due to the complexity of the needed simulations. The most common solution to overtake this obstacle is to simplify the building energy model, but not enough attention is paid to understand or predict the consequences of this action. The paper focuses on discussing the difference in results evaluated comparing the simulation of a detailed building model, based on all information available on the building during operation, and a simplified one, suitable for the application in early stage design. This result is achieved by defining a methodology, which consists in developing a simplification protocol and applying it to a suitable number of case studies starting from a detailed model and ending in the simplified one after the application of said protocol. The protocol is based on the use of EnergyPlus software both to develop a detailed model of the building, under various system hypothesis, and the simplified models. Three different case studies, featuring large non-residential buildings each with specific peculiarities, are discussed in this paper and simulated under three different system hypotheses each, resulting in nine different simplified models. Simulations are performed for the duration of a solar year, the differences registered between a fully simplified model and the corresponding detailed models are discussed both in term of total energy needs and peak loads, both for heating and cooling. Lastly, based on the results of the case studies, the possibility of integrating the presented simplification protocol into a simplified simulation tool is evaluated, discussing the possible advantages said tool would bring to the integration of energy simulation in early stage building design.

1. Introduction

The building energy problem concerns all the advanced countries in different ways, not only in terms of air pollution or emissions but also with regard to the preservation of energy sources and the rational use of energy itself. According to reports from the U.S. Department of Energy, buildings are responsible for a large portion of total yearly energy consumptions and greenhouse gas emissions, ranging from 40% to 50% (Chen, 2009), and Europe shows similar results (Economidou, 2011). As a result, various national and supranational initiatives and regulations, and various programs are flourishing in the private sector, such as LEED, CASBEE and others; defining standards and parameters to evaluate the level of sustainability of buildings and reduce their energy use, both voluntary and mandatory.

The framework, knowledge, materials and systems to achieve high levels of energy efficiency in buildings and strongly reduce energy consumption are readily available and can make a positive impact, but they need to be properly implemented from design to construction and operation of buildings. A possible solution to incorporate all these elements in the building sector is the implementation of the “Integrated Building Design” approach, or more in general an Integrated Design Process (IDP), shifting design decisions upstream in the project’s process, when the occasion to influence positive outcomes is maximised and the cost of changes minimised (Aziz, 2011). In this context, the use of building energy simulation could provide invaluable help to the IDP, providing information otherwise unavailable. Building performance simulations can

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help to reduce emission of greenhouse gasses and to provide substantial improvements in fuel consumption and comfort levels, by treating buildings and their thermal systems as complete optimized entities, and not as the sum of a number of separately designed and optimized sub-systems or components (Hensen, 2004).

Many existing energy simulation tools for buildings are very sophisticated and promise a high level of accuracy. Popular tools such as EnergyPlus and DOE-2 are quite effective at simulating final building designs and are typically used for demonstrating compliance with performance standards such as LEED. However, despite the proliferation of many building energy analysis tools in the last ten years, architects and designers are still finding difficult to use even basic tools (Punjabi et al., 2005).

Although a building energy simulation is a useful tool for predicting performance and comparing design options, most of the energy simulations occur too late in the design process. In the traditional design process, the energy engineer carries out simulations, if at all, as a tool for equipment sizing and code compliance only after the architect has completed the architectural design. Part of the problem is that existing simulation tools are not practical for the design process; however, experiences with real buildings have shown that low-energy design is not intuitive and that simulation should therefore be an integral part of the design process (Hayter S.J., et al. 2001; Torcellini P.A., et al. 1999).

Needs related to the design process can be easily identified in time and accuracy. Accuracy is an essential prerequisite to every analysis used to support decision-making in every field. But accurate energy analysis requires time, up to several weeks in more complex cases, and the more accurate the analysis must be, the more time it will require. This is in contrast with the necessity to minimize the time requirements of the analysis so that it can be compatible with IDP times, but to do so simplifications of the building model and simulation tool are needed, with the drawback of a loss in accuracy. It is therefore essential to devote some research effort in trying to quantify the effects of simplifications applied in simulation practice to evaluate, if and when those assumptions can be considered acceptable, and eventually to identify possible solutions to minimize the differences obtained between detailed and simplified models of the same building. A simplified building model still delivering useful results could drastically decrease the amount of information required to perform a simulation and the time requirements to implement the model itself. In addition to this, if the simplified model allows it, the implementation of such a model in a simplified building generation tool able to generate the model from a limited number of numerical inputs and database selections could greatly help in the integration of building simulation during IDP and early stage design. This paper discuss the application of such a simplified model to various case studies compared against a detailed modelling in term of accuracy of the results.

2. Methodology

To evaluate the impact of simplifications on simulation results in building model descriptions both a detailed model and a simplified model of each analysed building are implemented. Results of the two simulations are compared in terms of total energy needs and peak loads for both heating and cooling season; for this study peak loads are represented by the maximum heating/cooling load encountered during the whole year simulation. For the purpose of this paper, a detailed model is defined as a complete and exhaustive building model able to adequately represent the real behaviour of the building, implemented with full knowledge of the building itself and its use, such as a model developed during building operation. The simplified model is instead obtained through the application of a simplification protocol previously developed by the authors and discussed in other publications (Picco et al., 2014). For each model, simulations are performed in EnergyPlus software for the duration of a solar year, and the differences registered between each pair of models, detailed and simplified, are then calculated and reported.

2.1 Simplification Protocol

To obtain the simplified models a simplification protocol is applied.

The simplification protocol itself is defined as a series of consecutive simplification steps starting from a detailed model and culminating in a simplified model with the objective of evaluating the impact of simplifications on simulation results.

The simplification protocol is defined in eight consecutive steps concerning the model description including, primarily, all the most common simplifications used during the practical application of dynamic energy simulation. Later steps perform heavier and less commonly implemented simplifications.

The result of the application of the protocol is an extremely simplified model of the building representative of a simulation model deployable during early design stages based only on information, at least in some form, already available at each design stage and easily obtainable. Due to the lack of complexity, the model also requires a limited amount of time to be implemented, compatible with time requirements during the first stages of design. Also, due to how it is defined, the simplified model can be easily integrated into a simplified interface able to automatically generate the model starting from a limited number of numerical input and database selections. For the purpose of this paper, we will focus on this final simplified model and compare it with the detailed model before the application of the protocol. The simplification protocol in all of its steps and its application to the building description model is further detailed in a previous paper published by the authors (Picco et al., 2014).

2.2 Case studies

Three case studies are presented in this paper to evaluate the accuracy of results of the simplified models in comparison with detailed ones. For the purpose of this work, all case studies are chosen from large non-residential buildings, considered the ones that could benefit the most from early integration of energy simulation in the design process and the most difficult to do energy simulations on, especially during early stage design, due to the lack of information needed. Starting form this restriction, the single case studies are chosen with varying energy performances and occupational behaviours, to evaluate if those aspects have an effect on the impact of simplifications.

An office building, identified hereinafter as CS1, represents the first case study analysed; the structure was originally built in 1954 and fully renovated in 2007. During the renovations two storeys were added to the existing three and major improvements to the energy efficiency of the building were added, resulting in a highly insulated structure with a 35 cm EPS shell (thermal transmittance of 0.08 W/(m^{2}K) for external walls) and 3-pane type windows (thermal transmittance of 0.781 W/(m^{2}K) and SHGC of 0.466), achieving Klimahaus Gold certification for passive buildings. The structure is characterized by a uniform distribution in term of internal loads typical of an office building with high occupancy levels during the day. Usage and HVAC parameters are similar for the various zones both on the single floor plan and for the elevation of the building, ventilation rates are controlled by a mechanical ventilation system that ensures appropriate air changes during occupancy. The shape of the building is also sufficiently uniform in terms of the floor plan switching from floor to floor.

The second case study is a private clinic, identified hereinafter as CS2, built in 1933 and further expanded in various steps between 1930 and 1970. Due to the age of the building and the nature of the expansions, the structure is characterized by a low level of energy efficiency, with a complete absence of insulation layers in the walls (e.g. thermal transmittance of 1.3-2.1 W/(m^{2}K) for external walls) and low thermal resistance windows (thermal transmittance of 1.96-5.89 W/(m^{2}K) and SHGC of 0.691-0.861).

Being a hospital clinic, the building is characterized by a relatively uniform usage and internal gains for the single floors. However, differences in those properties becomes relevant for the elevation of the building, alternating between floors dedicated to bedrooms, to examination rooms or surgery rooms. Time distribution of internal loads also differ, with examination rooms active during the day while bedrooms are active for the whole 24h. Ventilation is natural for the majority of the building and important infiltration rates are present due to the scarce air tightness of the envelope. HVAC parameters are constant for the entire building with the exception of surgery rooms positioned on the fifth floor. The same floor also constitutes a variation in the otherwise uniform shape of the floor plans.

The third and last case study is a recently built Bingo hall with complementary functions like betting and slot machine rooms, identified hereinafter as CS3. The structure was built in 2010, and therefore complies with current regulations in Italy, granting an adequate level of insulation (e.g. thermal transmittance of 0.363 W/(m^{2}K) for external walls, thermal transmittance of 1.828 W/(m^{2}K) and SHGC of 0.775 for windows) and thermal efficiency. The building has one conditioned floor, with only technical spaces on the second floor and an indoor parking lot underground, but presents a strong lack of uniformity in term of internal loads and HVAC parameters, especially in terms of ventilation air volumes, moving from room to room of the conditioned floor. Internal loads are high, especially due to equipment loads and mainly focused during the night, when the building is fully operating.

For each of those case studies a detailed simulation model has been produced in EnergyPlus based on available design documentation, field surveys and monitored data creating a detailed model characterized by the real usage, internal loads and HVAC parameters of the building during operation. Each model was then associated to three different HVAC system representations to evaluate the impact of simulation results based on the system hypothesis.

The three system hypotheses are summarized as:

- An “Ideal loads” air system, which represents the simplest system possible and operates by ideally adding or removing thermal energy from the air balance of the zones;
- a “Unitary” system in which each single zone is provided with a separate conditioning system comprised of an AHU with direct expansion electric cooling coil and gas heating coil;
- a more detailed system based on the real HVAC system of the building, defining a variable air volume (VAV) system for CS1 and a “Fan-coil” air system, in which conditioning is achieved with recirculating fan-coil units powered by natural gas boilers and electrical chiller for CS2 and CS3.

This adds up to a total of nine pairs of detailed and simplified models, results of which are discussed in this paper. To successfully compare the results obtained by the various simplification steps to the ones of the corresponding detailed models, a number of relevant parameters of comparison are identified.

Simulations are performed for the duration of a full solar year based on climate year Bolzano 160200 (IGDG) for CS1 and Bergamo-Orio al Serio 160760 (IGDG) for CS2 and CS3, depending on their actual location. All weather data comes from the Italian Climatic data collection "Gianni De Giorgio".

3. Results

Based on the results of the detailed and simplified simulations for each pair of models, the difference between the results of the two is calculated. Table 1 shows the percentage differences in results for total energy needs for both heating and cooling loads.

Table 1 – Total energy needs differences for various case studies

		Total Diff. [%]	
		Heating	Cooling
CS1	Ideal	-2.2	12.9
	Unitary	-12.8	-5.1
	VAV	-15.6	-14.6
CS2	Ideal	-2.1	-1.0
	Unitary	11.0	-8.6
	Fancoil	10.0	-1.8
CS3	Ideal	-7.6	-7.9
	Unitary	-10.4	-16.2
	Fancoil	-15.3	-5.4

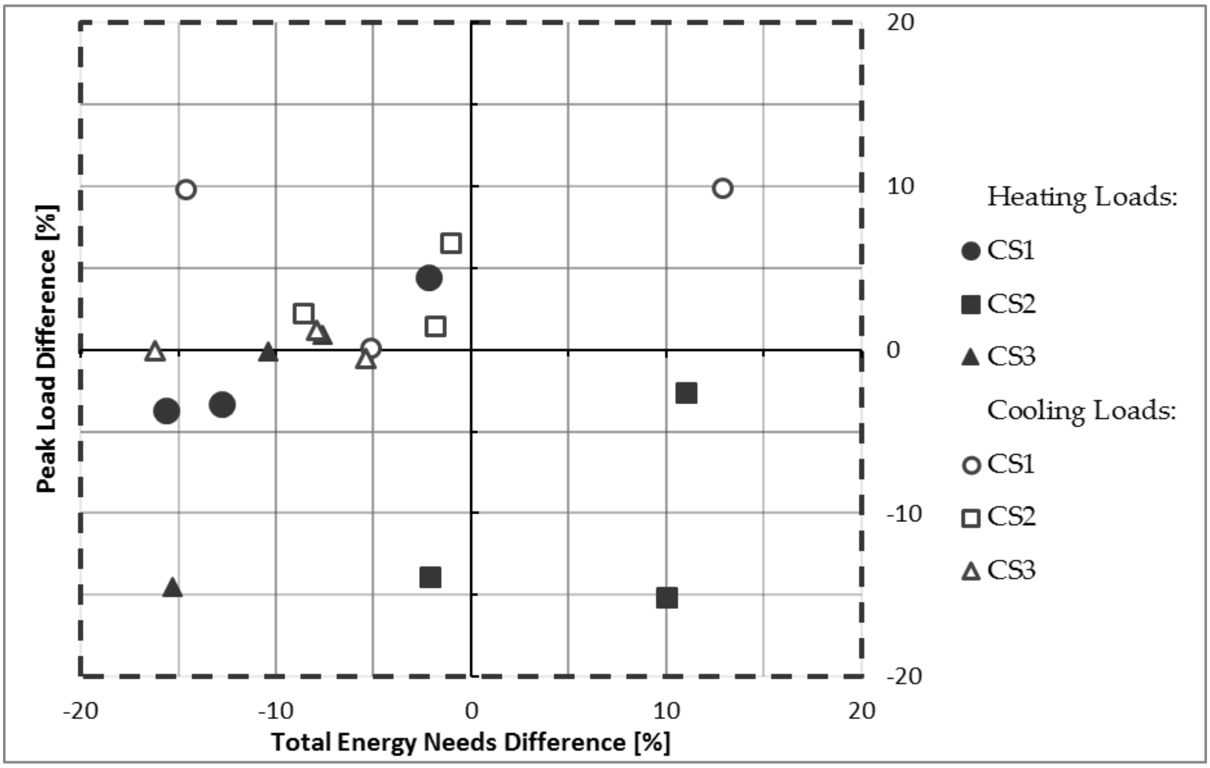

Fig. 1 – Comparison results for all the case studies highlighted based on Case study

Differences vary significantly from one case study to the other and from one system hypothesis to the next, ranging from absolute values of 2.1% up to 15.6% for heating energy needs and from 1.0% to 16.2% for cooling energy needs. In addition, in terms of total energy needs, on average, both heating and cooling needs tend to be underestimated by the simplified models compared to the detailed ones.

Table 2 – Peak load differences for various case studies

		Peak load diff. [%]	
		Heating	Cooling
CS1	Ideal	4.4	9.9
	Unitary	-3.3	0.1
	VAV	-3.7	9.8
CS2	Ideal	-13.9	6.5
	Unitary	-2.6	2.2
	Fancoil	-15.1	1.4
CS3	Ideal	0.9	1.2
	Unitary	-0.1	-0.1
	Fancoil	-14.5	-0.5

This behaviour can be motivated with the ability of the detailed models to detect extreme conditions in selected thermal zones while the simplified model ignores them due to the limited number of modelled zones and associated internal gains.

Table 2 shows the results in terms of peak loads for both heating and cooling seasons. Compared to differences in total energy needs, peak loads seem to show fewer differences from detailed to simplified models, ranging from 0.1% up to 4.4% for the majority of cases and only reaching 9.9% for cooling power in CS1 and 15.1% for Heating power of CS2.

In addition, CS3 shows a difference in peak loads of 14.5% for the fan-coil model. Another interesting, although qualitative, consideration that can be extrapolated from those results is how the simplified models tend to underestimate the heating Peak Power requirement of the buildings while overestimating the cooling Peak loads, with some exceptions.

Results of the comparison applied to all the case studies are also summarized in Figure 1 for more visibility, showing the percentage differences in terms of total energy needs for the simulation on

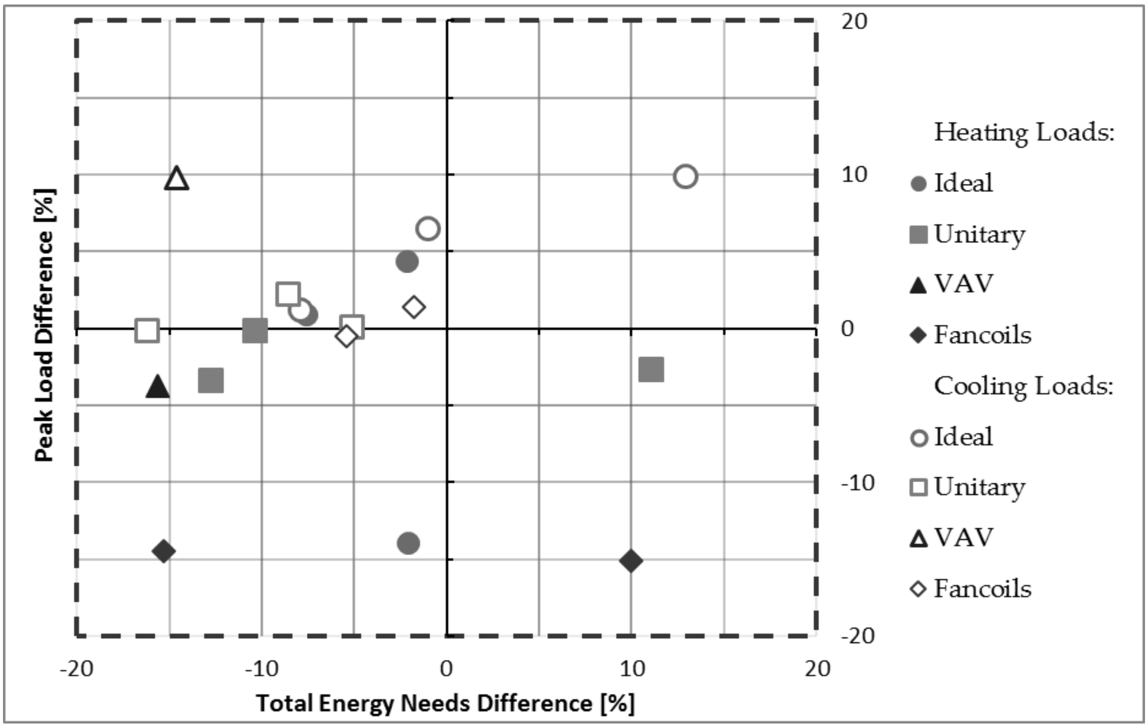

Fig. 2 – Comparison results for all the case studies highlighted based on system hypothesis

the x-axis of the chart and percentage differences in terms of peak loads in the y-axis. Results are visible in terms of heating or cooling loads depending on the filling of the indicator while its shape references the case study as shown in the attached chart. As there is no available threshold, in literature or legislation, to determine if the results of the simplified model are acceptable, through the experience in the field of building design and energy simulation a practical margin of 20% is identified as a reference and considered an acceptable margin of difference between the results of a simplified and detailed model.

As shown in the chart, results of the implementation of the simplified model on all the analysed case studies fall within the aforementioned margin of acceptability both in terms of total energy needs and Peak loads for heating and cooling needs. Results also show how differences in total energy needs are more scattered on the chart while differences in Peak loads are mainly centred in the range from -5% to +5%, showing smaller differences.

For the case studies analysed, there seems to be no major variability in total difference results as a function of the analysed building. Ideal loads system and Unitary system hypothesis are applied to all case studies while Variable air Volume is only implemented in CS1 and fan-coil system is applied to case studies 2 and 3. Figure 2 shows the same results identified in terms of system hypothesis as detailed in the attached chart. From the Figure, it is possible to notice how, in term of total energy needs, the ideal loads system hypothesis seems to be the one showing fewer differences between simplified and detailed models.

In terms of peak load estimation, the Unitary system hypothesis seems to give the best results with all cases inside the ±5% margin. Complex systems such as VAV and fan-coil system hypothesis, featuring modelled plant and air loops linked to distribution terminals in the zones, seem to show more varying results but always inside the 20% margin of tolerance.

4. Conclusions

Of the total energy consumption, a significant portion is consumed by buildings, and the problem is more relevant due to their particularly long lifetime and continued use. Efficient design is critical to reduce those consumptions, even more during its first stages, as poor design decisions can greatly impact the performance of the building and are typically difficult or impossible to rectify. Dynamic energy simulation could significantly increase efficiency in design, especially during early design phases. However, the complexity of simulations models and required detail hinder this integration. To overcome this obstacle, simulation models must adapt to the design process. The results presented in this paper give a new insight into the use of simplified building models and their impact on results.

As expected, different buildings perform differently under various simplifications; nonetheless, general conclusions can be drawn.

In terms of total differences between detailed model and fully simplified model, all the case studies here analysed results in differences never above 16.2% for total energy needs and 14.5% for peak loads. Due to the lack and uncertainty in information provided during early design phases, differences within the practical margin of 20% between the simplified simulation and the detailed model can still be considered acceptable by the authors, meaning those models can still produce useful information to fuel the design process.

The modelling and simulation time of the simplified models are of the order of a few hours, significantly lower compared to detailed models, but enough to allow the integration of building energy simulation in early stage design.

In addition, the simplified model is defined in such a way as to be easily implemented into a model generator tool, able to automatically generate the building model starting from a limited number of numerical inputs and database selections, at the moment 33 inputs are required to define the simplified model, further reducing required time.

Nonetheless, the use of a simplified building model can produce misleading results if used when one or more of the simplifications involved is not acceptable. It is therefore essential for the operator to correctly understand the model and critically evaluate the single instances to determine if the simplified model is suitable for the analysed building.

In addition, the application of the simplified model to a simplified simulation tool would partly result in a black box. In addition, it is possible that the relation of single inputs to the simplified model is not clear, depending on the operator, therefore in this hypothesis, an exhaustive description of the single inputs, also with examples, becomes essential to avoid interpretation errors.

Even so, considering these critical issues together with the results shown in this paper, the authors believe that the use of the simplified model at the beginning of building design can be useful to the design process, at least for non-residential buildings. Furthermore, the application of simplified models during early stage design lessens some of the issues, as, due to lack of information needed, a detailed model would suffer from the same simplifications and hypotheses.

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