USING SIMPLIFIED GEOMETRY MODEL TO IMPROVE ENERGY MODELING EFFICIENCY AND REDUCE COST

Yiyuan Jia and Fred Betz, PhD.
Affiliated Engineers, Inc., Madison, WI

ABSTRACT

Simplified modeling has been a tried and true approach for energy modelers for years to inform early design. So much so that it has been included in ASHRAE Standard 209 for early stage modeling (Agarwal, Pastore, and Andersen 2019). Indeed, at the early stage of a project, detailed modeling is oftentimes not necessary either because the presence of uncertainties, the lack of information or the context of the decision simply does not demand it (Augenbroe 2019). However, two bigest hurdles that prevent wide adoption of simplified modeling is the continuity and consistency issues between the early simplified models and the destined detailed models. In this paper, we demonstrate a simplified geometry model work flow that tries to address these issues.

This paper first introduces a new tool to create simplifed geometry models for EnergyPlus. A case study of a real world energy modelling project is followed that describes a workflow leveraging this tool for simplified modeling in the early design and makes successful transition to detailed energy models. Finally, a validation study is performed to try to address the "accuracy" concerns related to the simplified modeling.

Discussions and lessons learnt of using workflow in energy modeling project are given. The validation study results shown, in creating simplified geometry for heathcare buildings, priority should be given to space type definitions and program areas and less so for building envelopes. The study has also implied simplified geometry modeling could be a very effective strategy to reduce code compliance and rating system modeling cost while maintain the same level of modeling accuracy if being used properly.

INTRODUCTION

Simplified modeling, aka. model order reduction (MOR) is a technique used in computation domains to reduce the computational complexity of mathematical models. In the domain of building performance simulation, this technique is especially applicable. Indeed, buildings are large and complex physical systems, the governing physics equations abstracting a building and its subsystems could compose of tens of thousands parameters based on the author's experience with large complex building models. This demands huge amount of effort for energy modelers such as preparing model inputs, constructions, simulating and diagnosing models, and writing documentation. Simplified modeling is consequently considered an effective strategy to reduce the computational and labor cost in the context of building performance simulation while retaining the same level of modeling outcomes. Many simplified modeling applications have been reported in building performance domain. (Eduardo, Abril, and Blanca 2019) reported a methodology of using simplified acoustic diffusion model (SADM) for concert hall geometry optimization. (Donghun Kim and Braun 2012) presents a study using reduced-order building modeling for the application of model-based predictive control. (D Kim et al. 2015) report the application of using reduced order CFD simulation to support building control. (Lee, Zhao, and Augenbroe 2013) present two application of using normative reduced-order building energy models for community scale energy network and stake holder behavior modeling. (Heo, Choudhary, and Augenbroe 2012) reports using Bayesian calibration and reduced-order building energy models for retrofit decision making.

Current standard practice in building energy modeling involves high level of granularity in modeling building geometries, constructions, and HVAC systems. Among which building geometry creation is essentially the most tedious and time-consuming task in the authors' opinion. A complex building geometry model may consist of over 1,000 thermal blocks, and over 10,000 surfaces. The coordinates of the surfaces and sub-surfaces need to be defined using CAD tools and stored in a certain data format that is acceptable by the designated building simulation engine. Although many have reported the successes in automating the geometry transformation from CAD or BIM IFC model to an analytical geometry model (BIM to BEM), a consistent workflow that is robust and universal in a broader industry application has not yet been made available. Today, a typical energy modeling workflow still involves recreation of the building geometry through manually tracing and drawing the floor plans and construction of 3D building geometry model that is ready for energy analysis. The model set up time of a complex building geometry therefore could take as long as 100-150 person-hours in energy modeling practice and around 25% of the whole building energy modeling time depending on the complexity of the building geometry.

Simplified geometry modeling is an effective means to address the inefficiencies mentioned above. First, a simplified geometry model would significantly reduce model set up time in the manner of reducing number of zones, simplifying geometry creation workflow, and reducing model simulation and diagnostic time. In addition, as design is constantly evolving, the investment in detailed building geometry modeling may soon lose its value due to the changes of floor plans or building program. Under such circumstances, the early geometry model would need be significantly revised or even recreated from scratch, putting all the efforts of creating detailed building geometry models in vain. Furthermore, in early stage energy modeling, energy models are utilized to evaluate the building energy performance of various design options in multiple design iterations. A lightweight building geometry model is favored in this phase of the energy modeling as it reduces the computational time for the building side heat balance calculations and allow a shorter run time for model diagnosis and improve the model agility for testing and evaluating additional HVAC design options. Figure 1 shows a simplified "shoebox" geometry model.

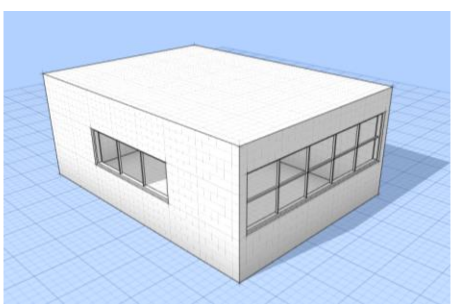

Figure 1. Simple shoe box model

However, challenges of integrating simplified geometry models into a standard energy modeling workflow still exists. Current energy modeling protocols for code compliance and rating system purpose has described explicitly how building geometry and thermal blocks should be defined and created to reflect the design documents. This rejects the option of demonstrating relative performance improvements using simplified geometry modeling in the final energy modeling documentation. Due to the fact, the simplified geometry model would face the destiny of being abandoned at the mid to late stage of a project. A related critic would be as the building geometry models are altered drastically from the early stage model to the final model, would the performance improvements or design recommendations still hold true? In addition, if simplified models are to be discarded, the paramount efforts spent on the non-geometry modeling, such as construction and HVAC system modeling, would be wasted as well.

These concerns about consistency and continuity issues could have introduced by simplified geometry modeling are valid. Although there're no perfect solutions to address these issues yet, further clarifications are needed to be made. First, one needs to recognize that design by nature is a constantly evolving process, with many uncertainties imposed in the beginning. It should be noted that it is the design uncertainties rather than the simplified modeling approach that may have caused the inconsistency in energy modeling results, if it is ever observed. As mentioned previously, in early stage design, detailed floor plans are either not available or constantly changing, using a simplified geometry model has equal or even less probability to be wrong in some instances, according to the law of parsimony, aka. Occam's razor (Wikipedia n.d.). In the sense that, using a simplified model, one has less chances to be wrong since there are less "falsifications" needed in creating a simpler model. In addition, the flexibility of EnergyPlus as simulation engine and modeling environment enables a partial solution to the continuity issue, as many of the IDF objects could be copied and reused between different EnergyPlus models with some level of rework (node connections).

In this paper, we introduce a workflow using simplified building geometry for design support from the early schematic design (SD) phase to the design development (DD) phase energy modeling and the evolve to a detailed model. An in-house simplified geometry tool for EnergyPlus is created to construct simplified building geometry models. The modeling outcomes are evaluated and discussed based on comparisons of SD phase simplified energy models and DD phase detailed energy models. A validation study is also performed to try to address the "accuracy" concerns of simplified energy models.

SIMPLIFIED GEOMETRY MODEL GENERATOR FOR ENERGYPLUS

A big challenge facing by EnergyPlus modelers is there's not efficient interface for creating massive EnergyPlus objects, especially for large scale building energy models. In this case we have 57 simplified thermal zones. Manually input building geometry information through IDF Editor would be a time-consuming task. To address this issue, a simplified geometry model generator for EnergyPlus is developed in a spreadsheet.

Using a spreadsheet tool as building energy modeling interface with a macro program to write EnergyPlus input files has been a common practice in the AEC industry. Many firms have adopted this approach to create their own in-house automated building energy modeling workflow (Rao et al. 2018). The flexible and extensive nature of the spreadsheet makes it a good interface for storing, transferring, organizing and editing building energy modeling input data. Following the same philosophy, the simplified geometry generator spreadsheet works as an interface allowing users to create up to 1,000 thermal zones for this example, each is represented in a single row of the spreadsheet. Figure 2 shows the user interface of the tool.

The tool takes the following inputs to define each simplified shoe box building geometry model:

- Zone Name
- Zone Area [ft2]
- Zone Origin X [ft]
- Zone Origin Y [ft]
- Zone Origin Z [ft]
- Zone Height [ft]
- Zone Length [ft]
- Zone Width [ft]
- Perimeter Zone [y/n]
- Perimeter 1 Normal [0,90,180,270]
- Perimeter 2 Normal [0,90,180,270]
- Roof [y/n]
- Ground Contact [y/n]
- Window to Wall Ratio [0-1]
- Windowsill Height [ft]
- Construction Template [ASHRAE Climate Zone ID]

Each building thermal zone is defined with the above input parameters. Most of the input are self-explanatory. The zone origin x, y, and z are used to define the origin coordinate of each thermal zone. As the adjacency between thermal zones is ignored in the geometry representation, the zone origins input is there to make sure thermal zones are not overlapping with each other.

Zone Name	Zone Area [sf]	Zone Origin X	Zone Origin Y	Zone Origin Z	Zone Height [ft]	Zone Length [ft]	Zone Width [ft]	Perimeter Zone [y/n]	Perimeter 1 Normal (Leave empty if Core Zone)	Perimeter 2 Normal (Leave empty if Core Zone)	Roof [y/n]	Ground Floor [y/n]	Window to Wall Ratio	Window Sill Height	Construction Template
LV00-CORRDR-044	100	0	0	0	3.5	20	10	y	90	270	y	y	0.85	0.2	ASHRAE 90.1 2010 Climate Zone 5
LV00-CORRDR-045	200	400	0	0	3.5	20	10	y	90	270	n	n	0.85	0.2	ASHRAE 90.1 2010 Climate Zone 5
LV00-CORRDR-046	300	600	0	0	3.5	30	10	y	90	270	n	y	0.85	0.2	ASHRAE 90.1 2010 Climate Zone 5
LV00-CORRDR-047	400	800	0	0	3.5	40	10	y	90	270	y	n	0.85	0.2	ASHRAE 90.1 2010 Climate Zone 5
LV00-CORRDR-048	500	1000	0	0	3.5	50	10	y	90	270	n	y	0.85	0.2	ASHRAE 90.1 2010 Climate Zone 5
LV00-CORRDR-049	600	1200	0	0	3.5	60	10	y	90	270	y	n	0.85	0.2	ASHRAE 90.1 2010 Climate Zone 5
LV00-CORRDR-050	700	1400	0	0	3.5	70	10	y	90	270	n	y	0.85	0.2	ASHRAE 90.1 2010 Climate Zone 5
LV00-CORRDR-051	800	1600	0	0	3.5	80	10	y	90	270	y	n	0.85	0.2	ASHRAE 90.1 2010 Climate Zone 5
LV00-CORRDR-052	900	1800	0	0	3.5	90	10	y	90	270	n	y	0.85	0.2	ASHRAE 90.1 2010 Climate Zone 5
LV00-CORRDR-053	1000	2000	0	0	3.5	100	10	y	90	270	y	y	0.85	0.2	ASHRAE 90.1 2010 Climate Zone 5

Figure 2. User interface of the simplified geometry tool in Excel

Parameter zone, roof, ground floor tags are created if the thermal zone has these boundary conditions. Two perimeter normal directions are available to be defined such that to represent a corner zone. The external surfaces are defined with the azimuth angle, where 0 is North, 90 is East, 180 is South and 270 is West. Window-to-wall ratio accept an input ranges from 0 to 1, the spreadsheet macro program would use this ratio to generate external windows at all vertical surfaces identified as external walls. Construction template would be used to create surface specific construction names in the IDF file. The construction names are in synchronization with an external building construction library which contains the actual material and layer information of each construction in a stand-alone IDF file.

The spreadsheet then takes the input data to write an IDF file using a spreadsheet macro program. Three EnergyPlus classes are written following the IDD schema under EnergyPlus v8.8:

- Zone
- BuildingSurface:Detailed
- FenestrationSurface:Detailed

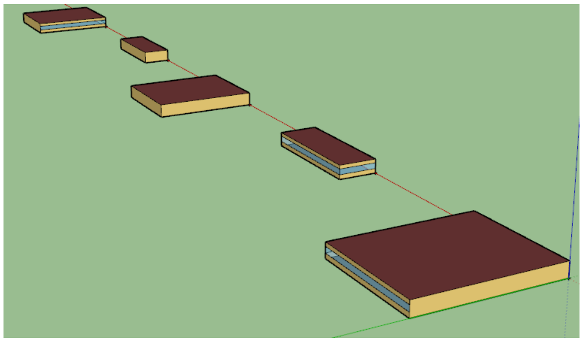

Figure 3. Simple "shoebox" models created by the tool

Figure 3 shows a partial view of the simplified geometry model written using the described spreadsheet tool.

The geometry IDF could be used to construct a complete building energy model using another in-house building energy modeling tool as mentioned in this article (Rao et al. 2018).

CASE STUDY

A real-world case study using the simplified geometry model generator in an energy modeling project is described in this section. The project contexts are briefly introduced. The workflow leverages simplified geometry from early SD stage energy modeling is described. The benefits of the workflow in terms of model run time savings and overall project time savings are presented. The model accuracy is examined by comparing the modeling outputs from both simplified and detailed models.

Building description

The case study building is an 700,000-ft^2 (60,032 m^2) inpatient healthcare facility located in Michigan, USA, climate zone 5A. Figure 3 shows an external view of the building. The 12-story hospital houses multiple high energy and ventilation requirements spaces such as patient rooms, operating rooms, airborne infectious isolation room, imaging and radiology rooms, food service, and IT rooms. The key buildng features are listed below:

- 700,000 square feet of total floor area
- Dual-coil configuration in the AHU serving operating rooms for dehumidification purpose
- Heat recovery chiller with dual cooling temperature setpoints, connecting to two different cooling loops based on summer/winter operation
- 24% Window-to-wall ratio
- High--efficiency water cooled chillers
- 47 space types inlcude patient room, ISO room, operating room etc.

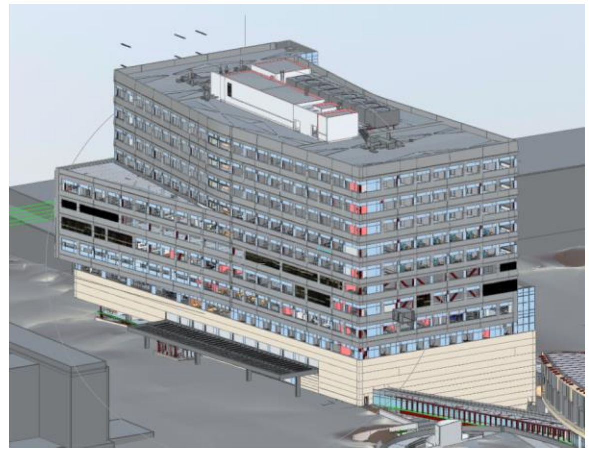

Figure 4. External view of the building

Workflow description

In a conventional energy modeling project, a detailed geometry model is created based on the early available floor plans, building programs and modeler's experiences and best guesses. This introduces a source for potential error due to design uncertainties. In this project, a simplified geometry generator was used to create simplified "shoebox" geometry models based on the building stack diagram and building program information. At the early SD stage of the project these were the only available building geometry information provided, in the meantime, a possible separate cancer center wing were in debate to add on site or within the tower as a floor, bringing more uncertainties to the building geometry. Figure 5 shows the stack diagram of the building in early stage. Given the context, 57 "shoebox" models were created to represent the whole building geometry for the project. These "shoebox" models were then assigned with 9 different space types to represent 57 building thermal blocks. The building geometry model is imported to the in-house space template and HVAC system builder to construct a full energy analysis model. Due to the complex system configuration as mentioned in the building description, no existing HVAC system templates are available to represent the configuration. Additional coil and heat recovery chillers were modeled manually in the IDF Editor.

An ASHRAE 90.1-2013 baseline energy model was created with similar workflow to provide a comparison to the owner's stated performance targets. The relative building performance resulted from the proposed and baseline energy modeling is used as a performance indicator for the added value of additional design options. The energy models were used to drive design conversations and provide a "directionally correct" path for design to progress. Some early stage energy savings measures (ESM) evaluated with the modeling strategies are listed below:

- Improved glazing performance
- High-efficiency lighting
- Low pressure-drop ductwork fan
- Operating room air flow setback
- Perimeter heat
- Heat recovery chillers
- Energy recovery wheels

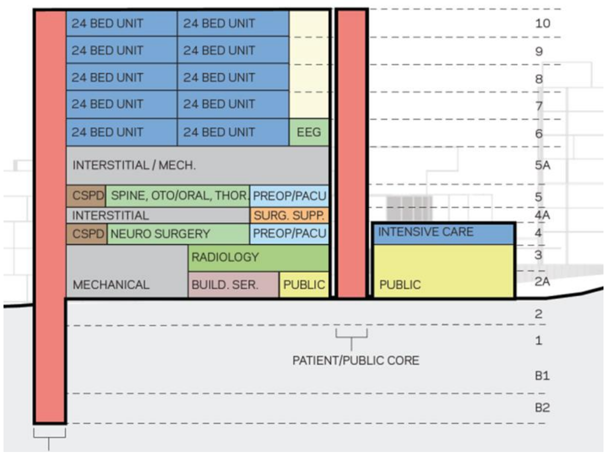

Figure 5. Building stack diagram

After design reached a mature stage at the design development (DD) phase, a detailed building floor plan was also developed by the design partners. Detailed building geometry models were then constructed using the conventional workflow. Figure 6 shows the appearance of the completed detailed building geometry. As the HVAC system models and the ESMs were already tested based on the simplified geometry model, the related IDF objects could be copied and pasted the to the detailed geometry model to construct the full building energy models.

Table 1 Model level of details comparison

Model Features	DD Detailed	SD Simplified
Number of Zone	904	57
Number of Space type	47	9
Window-to-Wall Ratio	22%	40%
Number of AHU	10	3
Total Building Area	689,934 ft^2	543,333 ft^2
Gross Wall Area	224,469 ft^2	123,364 ft^2
Gross Window Area	50442 ft^2	49345 ft^2

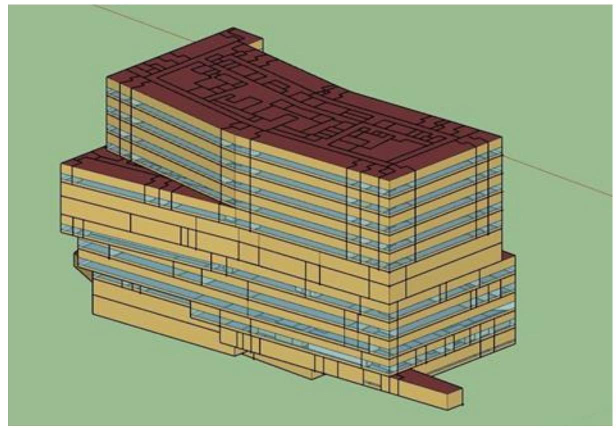

Figure 6. Detailed geometry model for energy modeling

Model Results

Four energy models were constructed from the early SD phase to DD phase of the design, as listed below.

- Baseline DD Detailed
- Proposed DD Detailed
- Baseline SD Simplified
- Proposed SD Simplified

The model run time and accuracy are compared and showed in the table 1. The simulations are performed in a desktop workstation with an Intel(R) Core™ i7-9700K CPU @ 3.60GHz and 32 GB installed RAM. Table 1 shows simulation time improvement of over 90% using the simplified geometry model in comparison to the conventional detailed geometry energy models. The run time improvements were greatly appreciated in the early design phase, where complex system modeling was to be implemented, multiple design options were to be modeled. The simplified model enabled rapid development of the HVAC systems without bogging down in the details of the energy model, which streamlined system development and quality control. An estimated savings of 80 hours of modeling time were reported due to these benefits.

Figure 7 shows the modeled energy use intensity (EUI) from the four energy models. The DD phase baseline model with detailed geometry has an EUI of 319 kBtu/sf-yr., the EUI of SD phase baseline simplified geometry model is 290 kBtu/sf-yr., percent difference is 9.5%. The DD phase proposed energy model and SD phase simplified proposed model have EUI of 235 and 236 kBtu/sf-yr., respectively. The proposed over baseline EUI saving using the simplified geometry model is

26.3% versus 18.6% using the detailed geometry modeling approach.

Table 2 Model run time comparison

Model Type	DD Detailed Runtime	SD Simplified Runtime	Improvement
Baseline	621.6 s	51.6 s	91.60%
Propose	631.0 s	57.9 s	91.60%

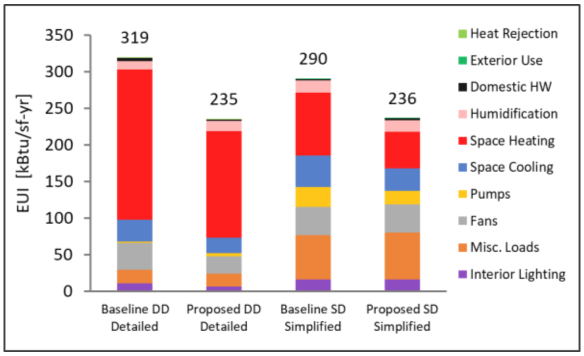

Figure 7. Detailed vs. simplified energy model results

Table 3 Model EUI (kBtu/sf-yr.) comparison

Model Type	DD Detailed EUI	SD Simplified EUI	% Diff.
Baseline	319	290	9.50%
Propose	235	236	0.40%
Energy Savings	26.30%	18.60%	8.60%

Discussions

From the EUI standpoint, the simplified geometry approach seems to be sufficient in capturing the design performance in both absolute EUI performance and a relative EUI performance improvements over baseline models. However, it is noted although the overall EUI differences are very small. The energy end-use breakdown between the simplified and detailed models has shown greater differences as shown in figure 7. There are several factors might have caused the differences. First, the design uncertainties at the early phase of the project, such as floor plan updates, equipment selection, patient room ventilation schedules, lighting and equipment power density, number of full equivalent employee (FTE). Second, the model order reduction approach applied in geometry modeling. Note the limitation of geometry simplification mentioned here is different than the floor plan design uncertainty as noted above, this limitation is not attributed to the unknown or unavailable building geometric information at the early stage but is rather resulted from the model order reduction approach itself. Such as the simplification applied in modeling surface boundary conditions, adjacency, grouping of zones and space types. Third, the energy model quality, such as unmet hours, unmet demand or setpoints and other possible errors in the energy models. In this case study all these factors are mixed, which makes it difficult to draw a conclusion on the sources of the discrepancy, or the validity of the simplified geometry approach. The next part of the article will try to address this issue.

Overall, these results show a positive message on accuracy and efficiency of the simplified geometry modeling approach.

VALIDATION

In order to clarify the potential limitations of the workflow and gain confidence and insights of using this workflow for future projects, a validation study was carried out. Unlike developing simplified and detailed models at different stages of a project as discussed in the case study. This study derives a simplified model from a detailed model. By doing so, the design uncertainties posed on the simplified models at the SD phase of the project were eliminated. The differences between the simplified model and detailed model are the simplified geometry modeling and subsequent model reductions. The model order reduction considerations are described. The model results are compared and discussed. The implications of this study on healthcare building energy models and code compliance energy models at large are presented.

Model order reduction

The detailed model adopted for this study is a modified version of the baseline model from the DD phase energy modeling. To make it simple, the plant side systems are first removed from the detailed model before the applying the model order reduction measures. For model order reduction, the number of zones was reduced by combining zones with same space types and ignoring the internal adjacency between zones. A tricky part with the geometry model order reduction was to maintain the same external boundary conditions and window area for perimeter zones. Some approximation was performed to maintain the model consistency. Another consideration was to create an approximated AHU zoning relationship in the simplified model based on the detailed model, the number of AHUs was reduced because of the combination of zones.

A simplified model was created from the detailed model following the considerations described above. Table 4 lists a comparison of the level of details for each model feature.

Table 4 Model level of details comparison

Model Features	Detailed	Simplified
Number of Zone	904	50
Number of Space type	47	47
Window-to-Wall Ratio	22%	31%
Number of AHU	10	6
Total Building Area	689,934 ft^2	688,467 ft^2
Gross Wall Area	229,286 ft^2	35,756 ft^2
Gross Window Area	50,442 ft^2	11,087 ft^2

The essence of the model order reduction approach was based on a hypothesis that the energy model results are not sensitive to the highly detailed geometry or boundary conditions definitions other than some key metrics such as floor areas per space type with the level of complexity and scale as mentioned for this type of project.

Model results

Figure 8 and table 5 report the detailed and simplified energy modeling results. The modeled EUI of detailed model is 440 kBtu/sf-yr. The simplified model has a EUI of 433 kBtu/sf-yr. Both the EUI are much higher than reported previously in the case study. This is due to the plant systems are removed from both models. The EUI percent difference between the detailed and simplified model is 0.4%.

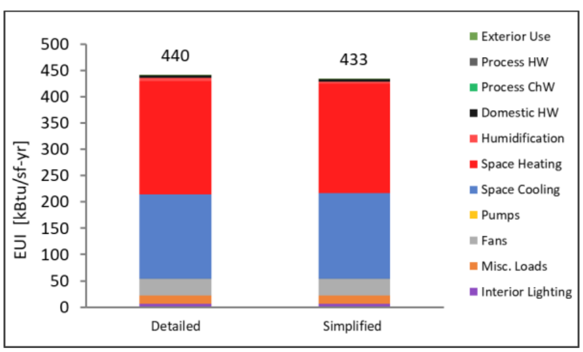

Figure 8. Detailed vs. simplified energy model results

The modeled energy end-uses are reported in table 5. Only space heating and humidification has shown apparent differences of 4.3% and 5.9% between the two modeling approaches, all the rest end-uses are aligned well.

Table 5 Model end uses comparison

End Uses	Detailed	Simplified	% Diff
Domestic HW	5.7	5.7	0.0%
Space Heating	215.4	208.1	0.9%
Space Cooling (purchased cooling)	161.2	162.7	0.2%
Pumps	0.3	0.3	0.0%
Fans	31.5	31.6	0.1%
Misc. Loads	15.9	15.9	0.0%
Humidification	5.7	4.5	5.9%
Interior Lighting	6	6	0.0%
Total	441.7	434.8	0.4%

Discussions and Implications

Compared to the simplified models as mentioned in the case study, the simplification conducted in this study has maintained the same number of space types, program areas for each space type. However, are loose on defining similar envelope geometries, such as gross wall areas and window areas. Both the overall and end use modeling percent differences are smaller compared to the case study. This has implied that given the context of this project, the building energy consumptions are less sensitive to envelope condition than to space type and program areas. This observation is consistent with the authors' experience of modeling healthcare facilities. In designing healthcare buildings, the performance drivers are often not the heating and cooling demand from the envelope heat gain or loss, but rather the stringent ventilation design guidelines, such as ASHRAE standard 170. Therefore, the heating and cooling demand are largely met as a byproduct of providing minimum ventilations. This provides a hint of the proper use of simplified geometry modeling for healthcare buildings, where one should focus more on capturing the level of details on space type definitions and program areas and could spent less efforts on building envelope.

In a broader sense, the study has increased the confidence of using simplified geometry model for early stage design support, the study implies if it is possible to exclude some design uncertainties and model quality factors, the simplified geometry models could be nearly as accurate as the detailed ones. Although in a real energy modeling practice, these two factors would always exist and causing inconsistent energy modeling outcomes throughout the design processes. With this in mind, the authors would suggest energy modelers using the principle of Occam's razor as a heuristic, to always start from simplified models, knowing that it will be equally or less likely to be wrong. However, care must be taken to not oversimplify to the point of the model becoming meaningless. Identify what design questions have to be answered with the model and go from there. Additional work to identify parameters that are most critical and highest priority to get right should be undertaken rather than assuming that all parameters are equally important and must receive the same level of rigor.

Code compliance energy modeling has long been criticized for the overly explicit modeling requirements, long simulation time and the subsequent challenges for model debugging and documentation. The simplified geometry modeling approaches employed in the study could potentially be used to reduce the code compliance energy modeling cost by ignoring less critical and sensitive model features. An uncertainty value might be applied to a simplified model, such as it must be a certain percentage more efficient than the baseline in order to account for the uncertainty.

CONCLUSION

A simplified geometry energy modeling workflow is proposed and implemented in a project of modeling an 700,000-ft^2 (65,000 m^2) inpatient healthcare building. The work proved to have increased energy modeling efficiency and reduced cost from the early stage to design development phase of the project, through which an estimated 80 person-hours were saved. An additional study was performed to further validate and clarify this finding. The study has shown simplified geometry modeling could be very an effective strategy to reduce code compliance and rating system modeling cost while maintain the same level of modeling accuracy if being used properly.

FUTURE

A possible enhancement of the workflow is to create more test cases determined by building type and climate, as well as levels of simplification. From the additional studies more insight and knowledge to form a theory on a model fitness measure. This measure is function of relative model accuracy (in comparison to a high-fidelity modeling outcome) and level of simplification. A detailed model might have a high relative model accuracy but low level of simplification, resulting a low model fitness score. Whereas in the case studies we demonstrated a simplified model have a high level of simplification and the same level of relative accuracy, indicating a better model fitness score.

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