The Effect of Reducing Geometry Complexity on Energy Simulation Results

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Abstract
Accuracy and time are metrics inherently associated with the design process and the energy performance simulation of buildings. The accurate representation of the building is an essential requirement for energy analysis, which comes with the expense of time; however, this is in contrast with the need to minimise the simulation time in order to make it compatible with design times. This is a particularly interesting aspect in the case of complex geometries, which are often simplified for use in building energy performance simulation. The effects of this simplification on the accuracy of simulation results are not usually reported. This paper explored these effects through a systematic analysis of several test cases. The results indicate that the use of orthogonal prisms as simplified surrogates for buildings with complex shapes presents a worst-case scenario that should be avoided where possible. A significant reduction of geometry complexity by at least 50% can also be achieved with negligible effects on simulation results, while minimising the time requirements. Accuracy, however, deteriorates rapidly below a critical threshold.

1. Introduction
The availability of sophisticated digital design tools has ushered in an era of architectural complexity (Stevens & Nelson 2015). Accuracy and time are metrics inherently associated with the design process and the energy performance simulation of buildings. The accurate representation of the building is an essential requirement for energy analysis, which comes with the expense of time; however, this is in contrast with the need to minimise the time intensity in order to make it compatible with design times (Picco & Marengo 2015) . This is a particularly interesting aspect in the case of complex geometries consisting of curved surfaces, as predicting the energy performance of buildings with complex forms presents several challenges.

First, abstracting building information models (BIM) so that they are suitable for energy modelling is “currently a heuristic process requiring experience and skill” (Dobbs & Hencey 2012). The U.S. General Services Administration (GSA) BIM Guide states: “the greater the complexity of a geometric model, the greater the risk for errors in translating that geometry from a BIM to an energy analysis tool” (U.S. General Services Administration 2012). In this respect, one of the recommendations for research in building performance simulation from the IBPSA Focus Group on Emerging Trends and Needs of Building Simulation (IBPSA-USA Emerging Simulation Technology Research Subcommittee 2016) was that research should “inform best practices for the level of complexity appropriate to each phase of design”. This includes identifying the impact from the adoption of different levels of model fidelity, including single zone, core and perimeter, and detailed multi-zone models. The results from this meeting therefore identified the need for the investigation of the sensitivity of building energy simulation to geometric fidelity.

Second, some conversion processes create a high-fidelity model that may be too complex and too time-consuming to analyse. This may result in reducing the number of analysis iterations and thus increasing the possibility that an optimal design solution is missed. To attempt to solve these problems, some may substitute their complex building form with a simple prism of the same approximate volume. However, the effect of using substitute simple prisms on the accuracy of the simulation is unknown. This paper aims to address this problem.

2. Previous studies

Complex building geometry is often simplified for use in building energy performance simulation (Smith et al. 2011). Several studies have been undertaken regarding the accuracy of energy analysis results after model simplification has taken place. For example, Picco and Marengo (Picco & Marengo 2015) studied the impact of various building model simplifications, such as those regarding building construction types, building obstructions and thermal zoning, on the outputs of the dynamic energy simulations. Their study showed that strong simplifications on the building geometry do not correspond to a strong deviation of the energy analysis results compared to detailed models. The strongest impact on the results was found to occur due to simplifications that strongly change the thermal zone definition of the model depending on the complexity of the building. Bosscha (Bosscha 2013) also performed a sensitivity analysis comparing the level of detail and the accuracy of building energy simulations, by varying the geometry, the material properties and the HVAC settings. It was concluded that the increase in accuracy gained by more detailed geometry and zoning is highly dependent on the type of HVAC simulation used to simulate the building. The 'Building Energy End-Use Study' by Amitrano et al. (Amitrano et al. 2014) explored the impact of the level of detail on the accuracy of the energy model using a benchmark office building. They concluded that detailed geometry can improve a simulation's reliability by 5 to 15%. Moreover, Klimczak et al. (Klimczak et al. 2018) analysed the impact of simulation model simplifications on the quality of simulation results in a residential building case. The simplifications included the removal of shading elements, the reduction of internal walls and thermal zones, performed in different iterations. The results showed that a considerable impact was incurred by the exclusion of the shading devices on the south façade (while on the northern hemisphere), so this simplification should not be considered in future studies.

All the aforementioned studies dealt with sensitivity analyses on the impact of model simplification on energy simulation results in office or residential building types, presenting valuable results. However, they all addressed simple box-shaped buildings with planar surfaces, presenting no sophisticated geometry. Consequently, there was no mention of a geometry simplification process with regard to complex geometry consisting of curved surfaces. Curved building geometry needs though to be post-rationalized as planar elements given the planar constraints associated with energy simulation tools (Chatzivasileiadi et al. 2018). More specifically, one of the geometrical requirements for energy analysis based on these constraints is that if curved surfaces are to be used, the segment count should be as low as possible (NREL 2017). Using the lowest segment count though might result into an over-simplification of complex models, which might jeopardise the accuracy of the results. This paper therefore addresses this shortcoming and presents a suggested range for the number of segments considering the accuracy of the derived results and the time required for energy simulation based on three experiments.

3. Reducing Building Geometry Complexity

In order to better understand the effects of reducing geometry complexity on energy analysis time and accuracy, we devised three experiments. The first experiment focused on the effects of reducing the complexity of the plan (footprint) of a single-story circular office building while keeping the elevation simple and constant. The second experiment focused on the effects of reducing the complexity of the plan (footprint) of a single-story cross-shaped office building. The third experiment focused on the effects of reducing the geometrical complexity of the overall three-dimensional shape of a tall office building. The area and the volume remained constant in all tests. The cooling loads were derived and compared, as simplifications seem always to have a greater impact on the estimation of cooling loads, compared to heating loads (Picco & Marengo 2015) . The simulations were conducted using a 64-bit Microsoft Windows 7 enterprise operation system with 2.00GHz Intel Core i5-4590t processor and 8GB RAM memory. We used the Grasshopper plug-in in Rhinoceros 3D to model the test cases and the Honeybee plug-in with EnergyPlus v. 8.5.0 (Crawley et al. 2000) to perform the energy simulations. The simulation time was derived from the EPlus results. We ran the same experiment several times and did not notice any significant variation in simulation times between runs. Thus, the reported data is from one run. All experiments contained an internal core and perimeter spaces. The number of perimeter spaces are proportional to the number of floors for each experiments. Therefore, for the first two experiments, there is only one perimeter space (since the test models are all one-story ones), while for the third experiment several perimeter spaces are created along the height of the building, according to the number of segments included. In addition, the buildings in the first two experiments do not contain any interior walls, floors, or ceilings, while in the third experiment they do. These configurations result to one thermal zone for the first two experiments and to multiple thermal zones for the third experiment. In the simulations the midrise apartment zone program is used, the zones are conditioned with an ideal air loads system and the default construction in Honeybee library for Energy Plus were used.

3.1 Experiment 1: Reducing the complexity of the footprint

The experiment involved the creation of 45 single-story circular office buildings each with a floor height of 3m, with windows along the whole perimeter, a window-to-wall ratio of 50%, and a floor area of 100m^2. The only variation was in the number of wall sides of the buildings which were varied from 48 to 4 sides with a decrement of 1 side per iteration. A matrix including a representative sample of these models is presented in Figure 1.

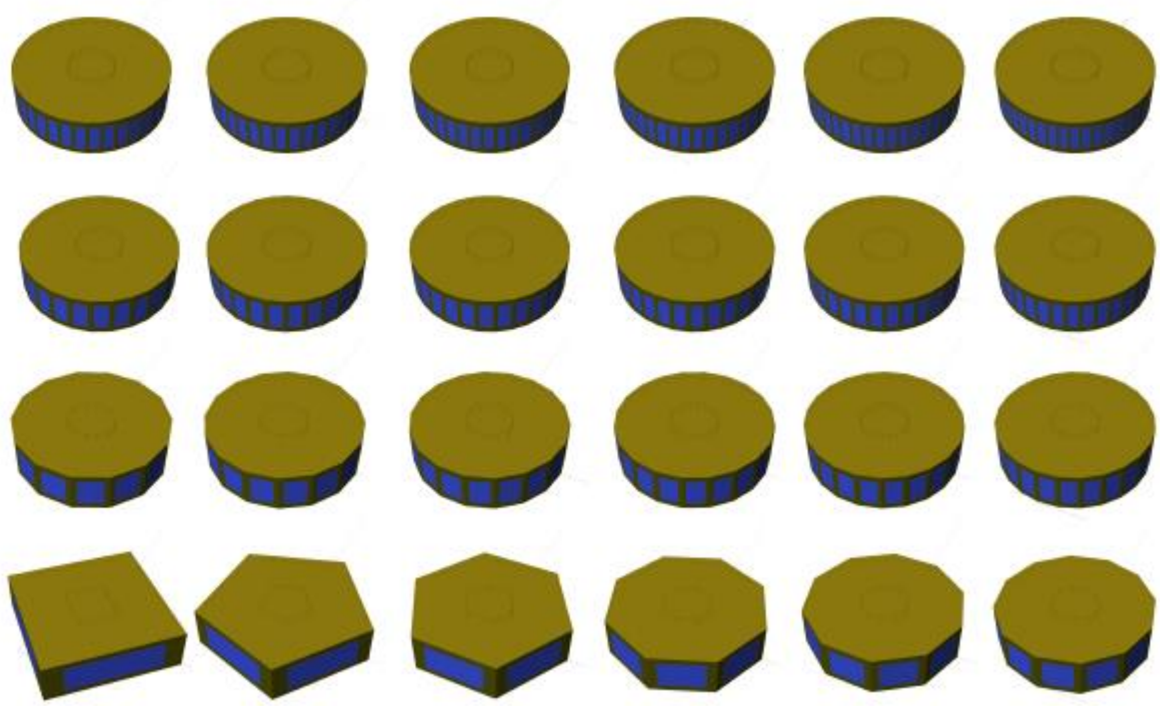

Figure 1. A matrix of 24 *buildings with identical floor area, floor-to-ceiling height, and window-to-wall ratio, but with varying number of sides (*representative sample of models used in Experiment 1, 27 *sides* upper right *to 4 sides* lower left*).*

The floor area of each building was kept constant by increasing the radius of the circumscribed circle around the polygon according to an equation that computes the radius R of a regular polygon with n sides and an area A (Figure 2).

$$R = \sqrt{\frac{A}{n \times \left(\sin\left(\frac{180}{n}\right) \times \cos\left(\frac{180}{n}\right)\right)}}$$

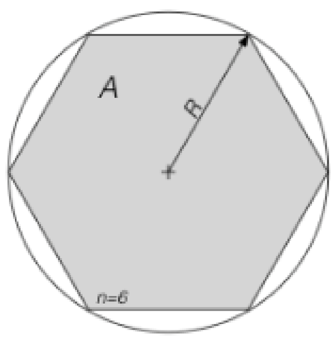

Figure 2. The equation and geometry of a regular polygon with area A, number of sides n and inscribed in a circle with radius R.

We considered the building with the largest number of sides (48) to be the ideal and most accurate representation of an actual building. We then compared it to the simulation time required and the cooling load results of the remaining 44 buildings. The chart below reports the number of sides, the simulation time in seconds, and percentage of deviation of cooling load results when compared to the ideal case – i.e. the building with 48 sides (Figure 3). The chart shows that the accuracy deviation remains relatively stable or presents a slight increase as the number of sides is reduced, and then it reaches a point when it increases sharply. By setting a 1% accuracy threshold, after which the sharp increase occurs, we identified the suitable cases with regard to the extent by which the complexity of the footprint can be reduced without a significant accuracy deviation. In the model with 12 sides, which barely reached this threshold, the simulation time is reduced by 75%, while there is an insignificant accuracy deviation of 0.97%. A building with 12 sides consumes 32 seconds to simulate compared to a building with 48 sides that would consume 2 minutes and 7 seconds (127 seconds) to simulate.

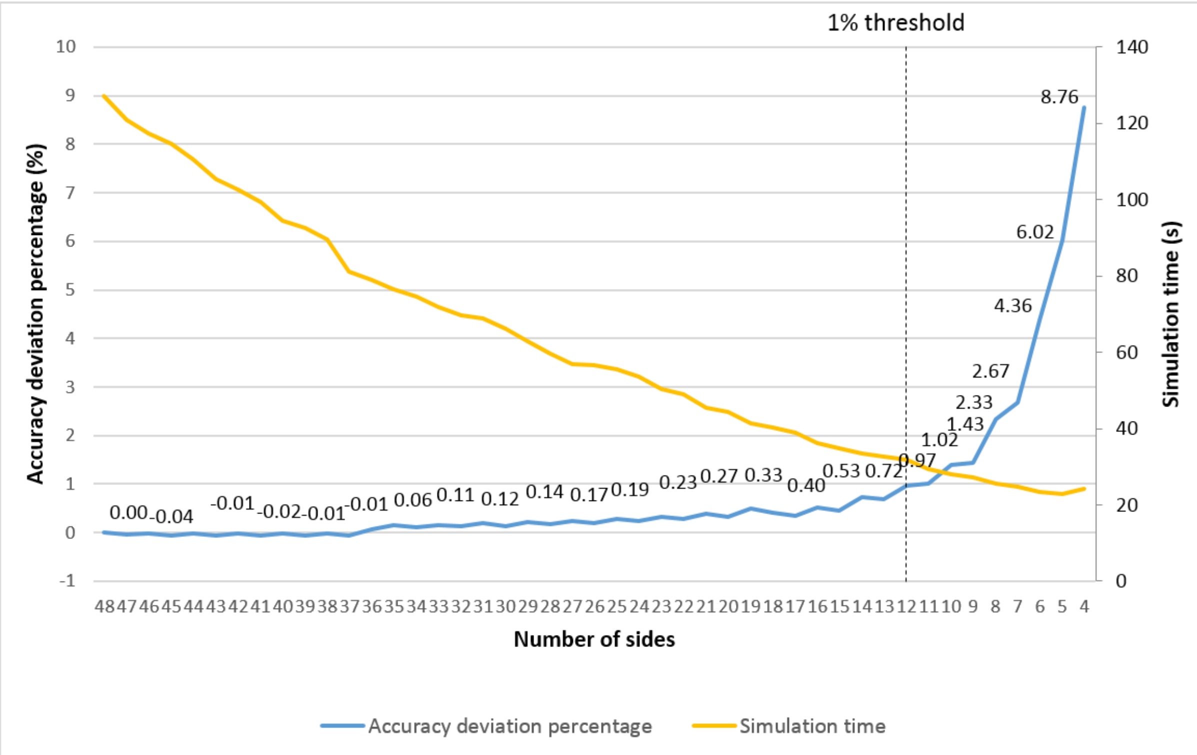

Figure 3. Line chart showing the effect of reducing geometry complexity on simulation time and percentage of accuracy deviation.

3.2 Experiment 2: Reducing the complexity of the footprint of a cross-shaped building

The experiment involved the creation of 22 single-story cross-shaped office buildings each with a floor height of 3m, with windows along the whole perimeter, a window-to-wall ratio of 50%, and a floor area of 100m^2. The floor area of each building was kept constant using the same equation as in the first experiment. The only variation was in the number of wall sides per arc at the endings of the cross shape, which were varied from 22 to 1 side with a decrement of 1 side per iteration. A matrix including a representative sample of these models is presented in Figure 4.

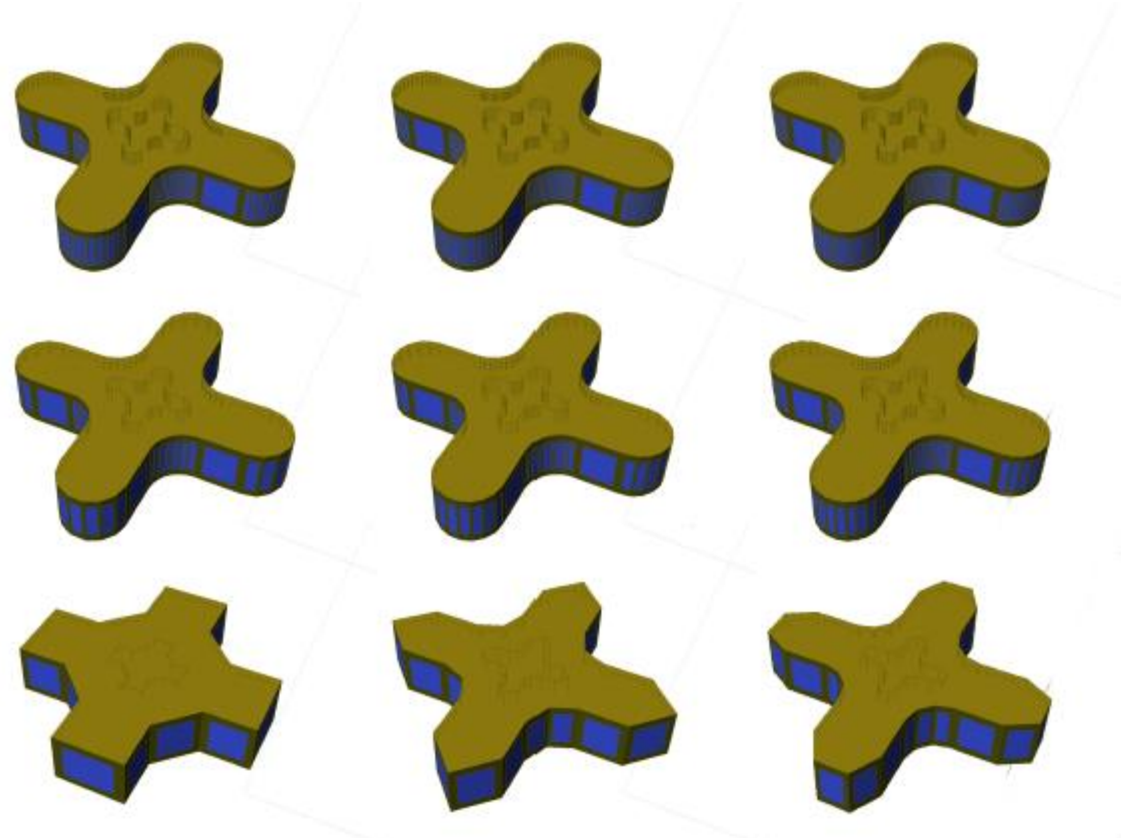

*Figure 4. A matrix of 9 interval buildings' examples with identical floor area, floor-to-ceiling height, and window-to-wall ratio, but with varying number of wall sides per arc (*representative sample of models used in Experiment 2, *9 sides upper right to 1 side lower left).*

We considered the building with the largest number of sides (or faces) per arc (22) to be the ideal and most accurate representation of an actual building. We then compared it to the simulation time required and the cooling load results of the remaining 21 buildings. The chart below reports the number of faces per arc, the simulation time in seconds, and the percentage of deviation of cooling load results when compared to the ideal case – i.e. the building with 22 faces per arc (Figure 5).

Similarly to the results for circular building, the chart shows that the accuracy deviation remains relatively stable or presents a slight increase as the number of sides is reduced, and then it reaches a point when it increases sharply. By setting a 0.2% accuracy threshold, after which the sharp increase occurs, we identified the suitable cases with regard to the extent by which the complexity of the footprint can be reduced without a significant accuracy deviation. In the model with 3 faces per arc, which barely reached this threshold, the simulation time is reduced by 97%, while there is an insignificant accuracy deviation of 0.17%. A cross-shaped building with 3 faces per arc consumes 1 minute and 8 seconds (68 seconds) to simulate compared to a building 22 sides per arc that would consume 40 minutes and 42 seconds (2442 seconds) to simulate.

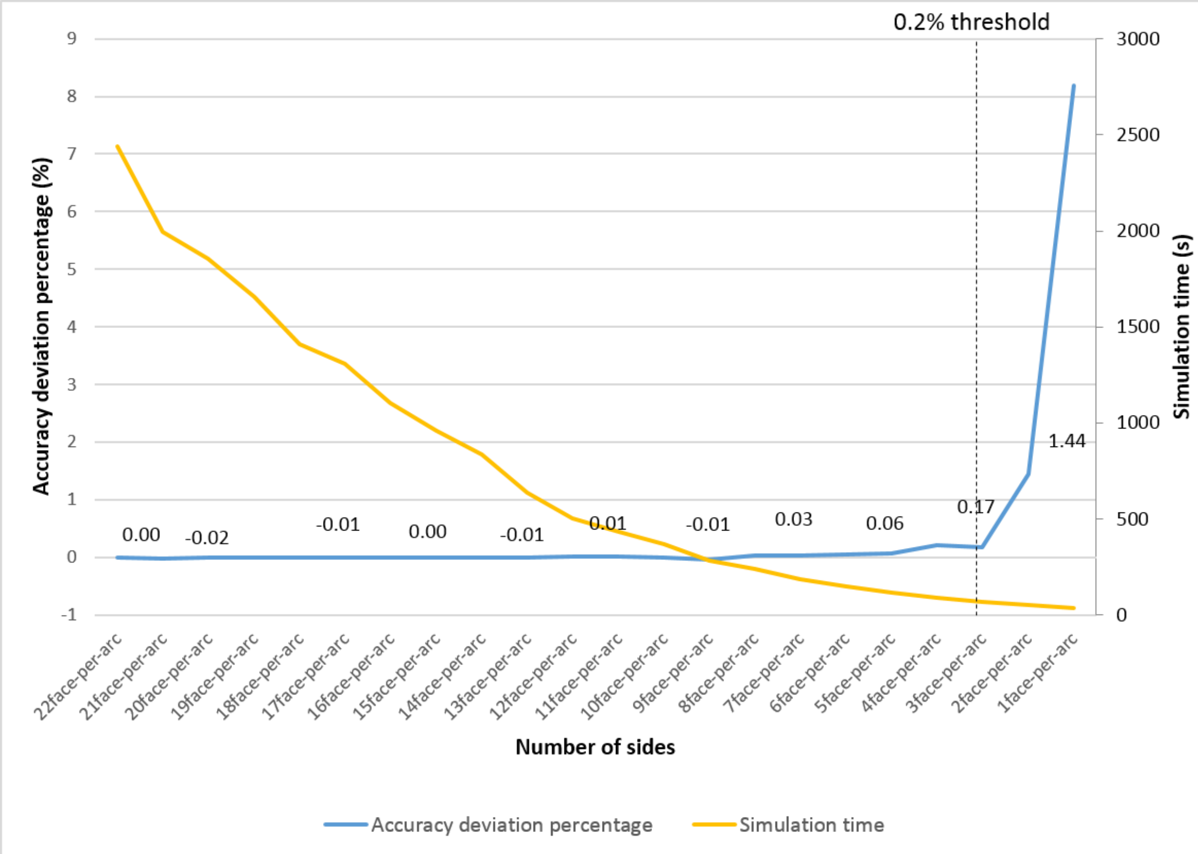

Figure 5. Line chart showing the effect of reducing geometry complexity on simulation time and percentage of accuracy deviation.

3.3 Experiment 3: Reducing the three-dimensional complexity of a tall building

The experiment involved the creation of 20 tall buildings each with windows along the whole perimeter, a window-to-wall ratio of 50%, and a volume of approximately 8,000m^3. The only variation was in the number of segments along the height of the buildings which were varied from 22 to 3 segments with a decrement of 1 segment per iteration. Due to modelling limitations using the loft component with a straight option in Grasshopper, the results for models with 1 and 2 segments were neglected, as there was a considerable deviation in volume compared to the rest of the models. For this experiment, as Energy Plus does not accept non-planar surfaces, we needed to depend on Honeybee's internal meshing processes, which automatically translated the curved tower representation to the analytical model that was then exported to Energy Plus. All buildings were scaled appropriately to ensure the same overall interior volume (Figure 6).

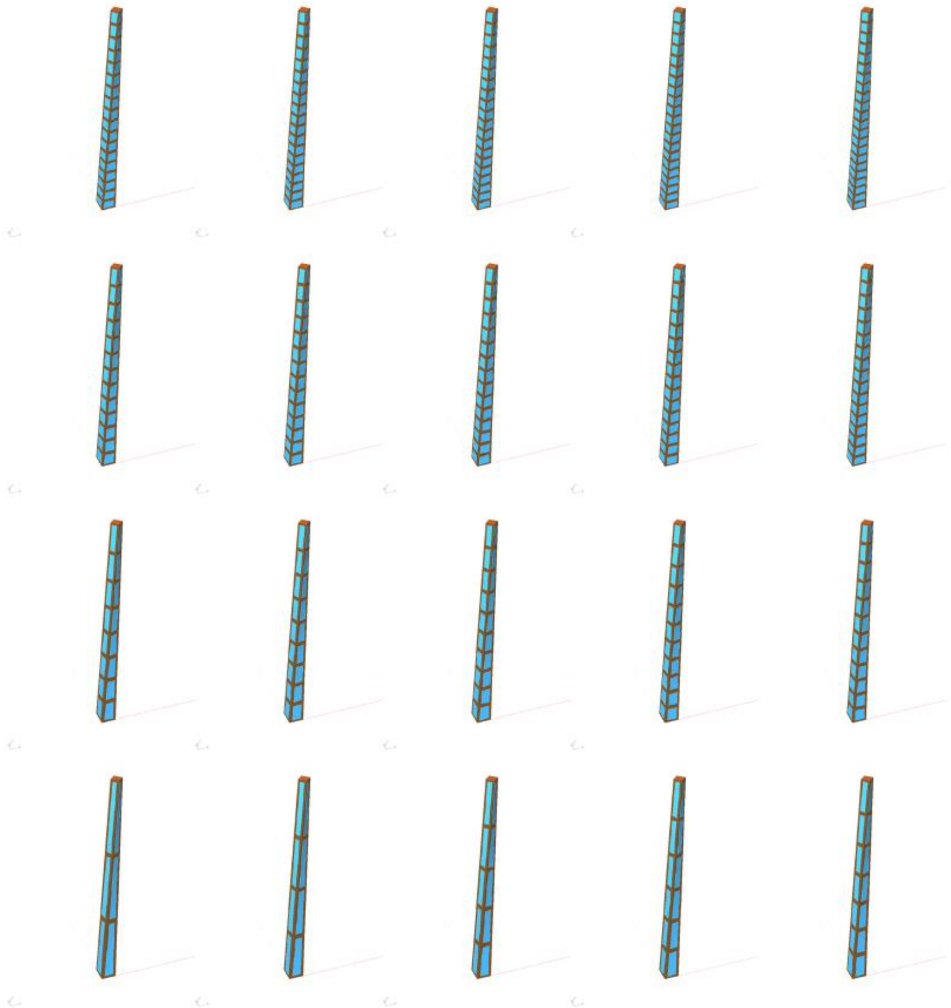

Figure 6. A matrix of 16 buildings with identical interior volume and window-to-wall ratio, but with varying number of height segments (16 segments lower left to 1 side upper right).

We considered the building with the largest number of faces (90) to be the ideal and most accurate representation of an actual building. We then compared it to the simulation time required and the cooling load results of the remaining 19 buildings. The chart below reports the number of segments along the height of each building model, the simulation time in seconds, and percentage of deviation of cooling load results when compared to the ideal case – i.e. the building with 90 faces (Figure 10). Similarly to the results for circular and cross-shaped buildings, the chart shows that the accuracy deviation remains relatively stable or presents a slight increase as the number of sides is reduced, and then it reaches a point when it increases sharply. By setting a 1% accuracy threshold, after which the sharp increase occurs, we identified the suitable cases with regard to the extent by which the complexity along the height of the buildings can be reduced without a significant accuracy deviation. In the model with 7 segments along the height of the building (30 faces in total), which reached this threshold, the simulation time is reduced by 63%, while there is an insignificant accuracy deviation of 1%. A building with 7 segments consumes 2 hours 5 minutes and 17 seconds (7,516 seconds) to simulate compared to a building with 88 faces that consumed 5 hours 36 minutes and 28 seconds (20,188 seconds) to simulate.

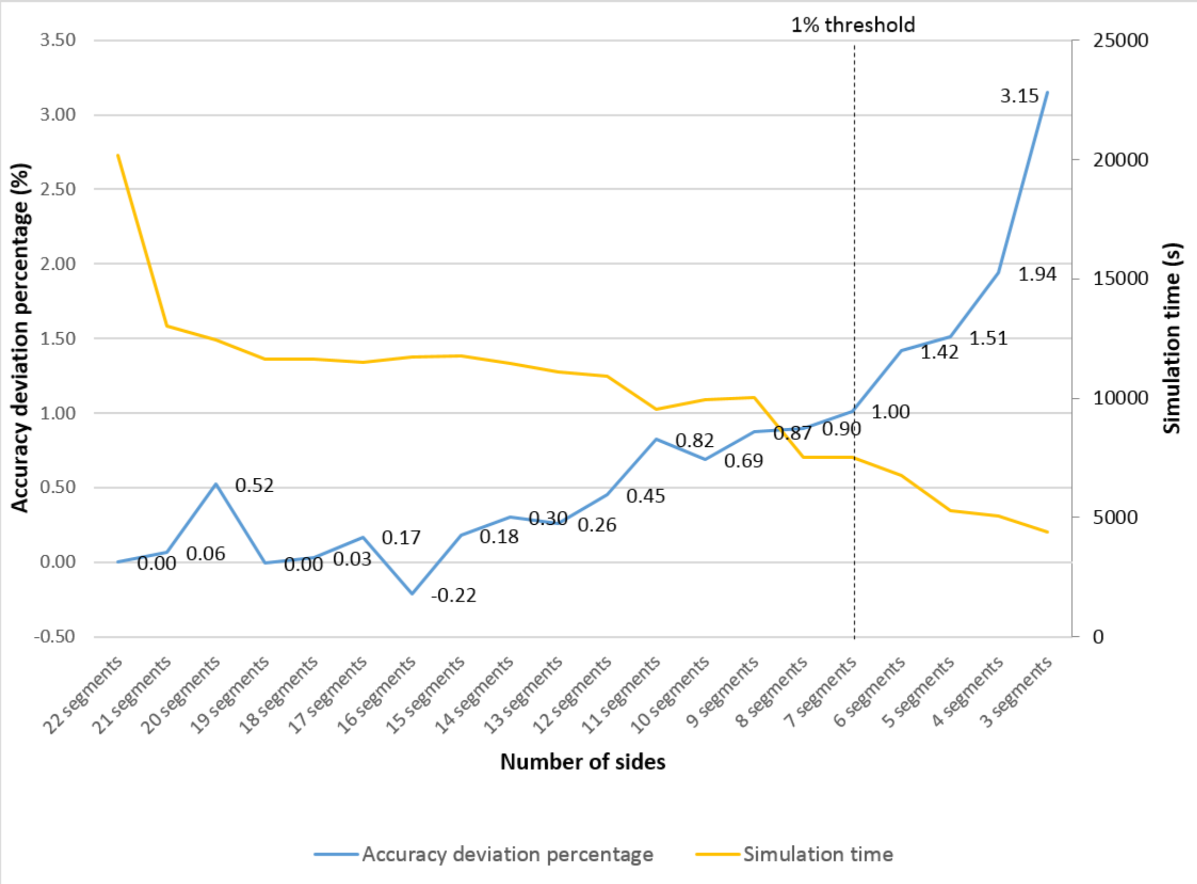

Figure 10. Line chart showing the effect of reducing geometry complexity on simulation time and percentage of accuracy deviation.

Discussion

The systematic analysis presented in this study addressed only geometrical aspects of several test case buildings, including a circular-plan building, a cruciform building and a tower. Different iterations in terms of the simplification of the geometrical complexity were pursued by reducing the number of surfaces of the buildings, which were then simulated in EnergyPlus. The results indicate that a significant reduction of geometry complexity can be achieved with negligible effects on simulation results, while significantly minimizing the time requirements. Accuracy, however, deteriorates rapidly below a critical threshold.

An important finding of these experiments is that the accuracy deviation rose sharply for simple prismatic buildings. In the first experiment, the building with 6 sides had a deviation percentage of approx. 6% and the one with 4 sides has a deviation percentage of approx. 10%. In the second experiment, the building with one face per arc has a deviation percentage of over 8%. In the third experiment, the building with 14 faces has a deviation percentage of approx. 3.2%. Therefore, despite the many energy simulation tutorials where simple orthogonal volumes are used, the use of orthogonal prisms as simplified surrogates for buildings with complex shapes presents a worst-case scenario that should be avoided where possible. While more studies are needed, one conclusion of this limited experiment is that the geometry complexity of a building can be reduced by at least 50% without significant loss of accuracy in energy simulation results. This is in contrast with what has been claimed in an earlier study, i.e. that detailed geometry can improve a simulation's reliability by 5 to 15% (Amitrano et al. 2014), so further investigation is required in this respect. A significant gain in reduction of simulation time was also demonstrated, in the range of 75% for the first experiment, 97% for the second one and 63% for the third one.

In order to consider the full impact of reducing geometry complexity on energy simulation results, there needs to be a comprehensive sequence of experiments leading to studies integrating as large a spectrum of parameters as possible. Further systematic studies considering more complex geometries, different building types and sizes, a bigger number of thermal zones, any shading impacts from neighbouring structures or other aspects including construction, building services and different climate zones could enhance these preliminary results presented in the current paper. These could contribute to the development of a framework regarding the extent of the impact of a range of geometry or other simplifications on energy analysis results.

Conclusions

Complex building geometry is often simplified for use in building energy performance simulation. The effects of this simplification on simulation results accuracy is not usually reported. This paper explored these effects through a review of the literature and a systematic analysis of several test cases. The results indicate that a significant reduction of geometry complexity can be achieved with negligible effects on simulation results, while significantly minimizing the time requirements. Accuracy, however, deteriorates rapidly below a critical threshold. An important finding of these experiments is that the accuracy deviation rose sharply for simple prismatic buildings. In the first experiment on the circular-plan building, the building with 6 or 4 sides has a deviation percentage of approx. 6% or 10% respectively. In the second experiment on the cruciform building, the building with one face per arc has a deviation percentage of over 8%. In the third experiment on the tower building, the building with 6 faces has a deviation percentage of approx. 3.2%. Therefore, despite the many energy simulation tutorials where simple orthogonal volumes are used, the use of orthogonal prisms as simplified surrogates for buildings with complex shapes presents a worst-case scenario that should be avoided where possible. While more studies are needed, one conclusion of this limited experiment is that the geometry complexity of a building can be reduced by at least 50% without significant loss of accuracy in energy simulation results and significant gain in reduction of simulation time.

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