

Article

Model Simplification on Energy and Comfort Simulation Analysis for Residential Building Design in Hot and Arid Climate

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Abstract: Accurate building physics performance analysis requires time-consuming, detailed modeling, and calculation time requirement. This paper evaluates the impact of model simplifications on thermal and visual comfort as well as energy performance. In the framework of dynamic zonal thermal simulation, a case study of a residential building in hot climate is investigated. A detailed model is created and simplified through four scenarios, by incrementally reducing the number of thermal zones from modeling every space as a separate zone to modeling the building as a single zone. The differences of total energy and comfort performance in the detailed and simplified models are analyzed to evaluate the grade of the simplifications' accuracy. The results indicate that all simplification scenarios present a marginal average deviation in total energy demand and thermal comfort by less than 20%. Combining rooms with similar thermal features into a zone presents the optimal scenario, while the worst scenario is the single-zone model. Results showed that thermal zone merging as a simulation simplification method has its limitations as well, whereas a too intensive simplification can lead to undesired error rates. The method is well applicable in further early-stage design and development tasks, specifically in large-scale projects.

Keywords: Model simplifications; Thermal and visual comfort; Energy performance; IDA ICE; Residential building

1. Introduction

High consumption of energy is unavoidable at a global scale [1–6]. It measures the economic success of a given country. The operation of residential and commercial buildings attributes one third of the world's energy consumption [7]. Thus, there is great potential for decreasing global energy consumption through improving the building design [8]. All advanced countries concerned on building-energy problem in various ways to preserve the energy sources and to use energy in a rational way [9]. Based on the U.S. Department of Energy report, buildings are attributed to the

majority of total annual energy consumptions and greenhouse gas emissions by the range of 40% to 50% [10,11], and similar results are shown in Europe [12]. Thus, different supranational and national initiatives, regulations, and different programs of private sectors such as CASBEE, LEED, BEEAM, DGNB, and others identify the parameters and standards to assess buildings' sustainability level and to minimize energy use. The role of appliances and residents' behaviors of users should be taken into account in sustainable building design as this role is strictly connected to energy savings and indoor comfort [13,14]. Becherini et al. [15] suggested and modeled several scenarios through which occupant behavior and thermal coating can contribute to the thermal performance of the building. Proper implementation of the framework, materials, knowledge, and system from design stage to construction and operation stages is required to obtain efficient buildings. The "Integrated Building Design" approach [16] is one of the possible solutions to integrate all these elements in the building sector.

Building-energy simulation is an essential support tool to design and commission green buildings. Many available, validated building-energy simulation tools, as Energy Plus, IDA ICE, TRNSYS, BLAST, ESP-r, Radiance, DOE-2 and eQUEST promise high accuracy level and effectivity for comprehensive simulation of building designs [17,18], but they require detailed input for model analysis, composing of zero thickness partitions or walls between thermal zones [19]. The operation and input of building-energy simulation parameters are quite complex [20], including geometric modeling, division of thermal zones, software selection, and selection of meteorological data. Geometric modeling represents the first stage of simulation and often consumes about half of the time of the simulation procedure [21]. Thus, simplification of geometric modeling is considered to be one of the most crucial way to enhance the simulation process. Converting a detailed model back to the spatial model is a complex task for the user and represents some of unfortunate challenges [19]. Despite the proliferation of several building-energy analysis tools in recent years, architects still face difficulties to use the basic tools of energy analysis [22]. The outputs confirmed that the majority of energy simulation tools are not appropriate for the working needs and methods of architects [23–25]. Usually, simplifications occur during translating real building geometry into an energy simulation model due to the lack of modeler software, or model simplifications serve the reduction of computational effort and calculation time. Though some previous studies such as Liu and Henze [26], Westphal and Lamberts [27] and Capozzoli et al. [28] investigated the effects of simplifications on the energy analysis of buildings, it is often underestimated or neglected. Therefore, it is essential to develop a simplification methodology of building physics modeling tools to reduce time and costs of thermal and lighting building simulations, without adverse impact on the quality of results. Complex building geometries are often simplified to perform energy performance simulation [29]. Zhao et al [20] identified three common types of geometric model simplifications as follows:

- (A) Calculating the load for one floor and multiplying it based on the number of floors,
- (B) Simplifying the fenestration of modeling (e.g., merging windows in one space's façade),
- (C) Reducing the number of internal thermal mass and thermal zones of the building.

Several studies have examined the effect of model simplification on the result accuracy. Amitrano et al. [30] investigated the effect of the level of detail on the accuracy of the energy simulation in office buildings. Their study concluded that more detailed geometry can enhance the reliability of simulation by 5 to 15%. Picco and Marengo [16] assessed the effect of different simplifications in building construction types, thermal zoning, and building obstructions, for instance. The findings showed that strong simplifications on the building geometries do not make significant change on the outputs, compared to the detailed model. Bosscha [31] applied a sensitivity analysis by varying the material properties, geometry, and heating, ventilations and air conditioning (HVAC) settings to compare the accuracy of the calculations with the detailed model. The results concluded that the increase in accuracy obtained by more detailed zoning and geometry is highly relying on the HVAC simulation type. Korolija and Zhang [32] compared the predicted annual energy use of the detailed model in which every room was modeled as a separate zone with a simplified model, in which each floor is was modeled as a single

zone. The output results showed that thermal zoning simplifications decreased the simulation time by 30% and the mean absolute error of annual heating demand was 10.6%. Klimczak et al. [33] explored the effect of model simplifications on the quality of energy simulation results of a residential building case. The simplifications consisted of the reduction of thermal zones and internal walls, removal of shading elements, and calculations were carried out in different iterations. The findings showed that the exclusion of the shading devices on the south façade had a considerable effect, thus, in future studies this simplification should not be applied. Heo [34] estimated the impacts of internal load, scheduling, and thermal zoning simplifications for domestic buildings in the United Kingdom. They concluded that the differences in annual heating demand are 26% and 17% in the simplification with one single zone for the entire dwelling and one thermal zone per floor, respectively. Dipasquale et al. [35] studied the impact of defining the physical and geometric characteristics of buildings, such as the presence of internal walls, thermal capacity, thermal bridges, the gross or net surfaces, and the number of zones during the modeling stage for heat load assessment. The findings of these results concluded that the reduction of the number of zones has the highest effect on the loads, almost 22% in the cooling demand and 12.5% in heating demand. Chatzivasileiadi et al. [19] explored the impact of simplifying the complex geometries through a systematic analysis of different test cases on the accuracy of energy performance simulation results. The results concluded that orthogonal prisms as simplified surrogates for buildings should be avoided where it is possible, as it showed the worst-case scenario. Akkurt et al. [36] concluded that the simplification of geometry is often unavoidable for use in building-energy performance simulation, but inaccuracies resulted from oversimplification in some geometrical characteristics must be avoided. Zhao et al. [21] investigated the appropriate level of geometric modeling simplification through thermal zone, typical floor and fenestration in energy analysis for office buildings and they found that the more accurate case is modeling the exterior wall in regarding to internal edge. Samuelson et al [37] assessed the accuracy of 18 design-phase building-energy models to enhance the simulation predictions compared to measured energy data.

Despite the valuable results of the aforementioned studies, they just evaluate the impact of model simplification on energy simulation in residential buildings or in office types. The impacts of modeling simplification on the thermal comfort analysis are usually not investigated properly. A study of Korolija and Zehan [32] analyzed the effect of modeling simplification on thermal comfort analysis, but with a different method and focus as they considered one simplification scenario of treating each floor by a single zone and they assessed the thermal comfort performance through annual operation of carbon emission and overheating risk. Consequently, it can be stated that there is no study about the effect of model simplifications on the thermal and visual comfort published yet.

Accurate energy and thermal comfort analysis of buildings requires a lot of time, especially in complex cases it may require up to several weeks. Minimizing the required time of analysis is necessary to be compatible with design duration. Therefore, the main aim of this paper is to assess the impact of model simplifications through different scenarios considering the simulation time, modeling time, and accuracy level of the derived results in both energy demand and thermal comfort in residential houses. The paper evaluates the impact of simplifications by comparing the simulation outputs of the detailed reference model and the simplified models with incremental reduction in the number of thermal zones, until the whole house is modeled as a single zone. Moreover, the investigations explore what level of simplified thermal zoning is required to support energy and thermal comfort analysis of residential buildings. The study is carried out in the simulation framework of IDA ICE, and it also identifies the optimal scenario of the proposed simplification scenarios.

2. Model Simplification Methodology

This study examines the impact of reducing the number of thermal zones on the prediction accuracy of energy and comfort of residential buildings. A thermal zone represents the division of a dwelling for the convenient calculation of the energy and thermal comfort simulation of the building. The thermal properties and parameters are relatively consistent in the same thermal zone. Obviously,

to get more accurate results of energy and thermal comfort, the simulation model should be more accurate regarding the number of modeled thermal zones of the building, but at the same time it would need more calculation time and, as a result, modeling work expenses. Many countries have provided relevant regulations for the division of thermal zones of the buildings. American National Standards Institute / American Society of Heating, Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE) 90.1 [38] reported that multiple spaces can be represented as one thermal zone with the following requirements: the usage of the spaces, the air conditioning and heating systems applied in the spaces and the orientation of the exterior walls and windows should be the same. The Building Research Establishment Ltd. [39] stated that a thermal zone is an area that has the same set points for cooling and heating, identical operating times of the plant, the same ventilation provisions and set-back conditions. In addition, they should be served by the same primary plant and terminal device type. The Canadian standard EE4 [40] stipulates that a thermal zone must have the following features: (1) same air conditioning system and heating with similar operations and functions, and similar heating and cooling loads; (2) the surrounding and the internal space should be distributed into different thermal zones; (3) rooms for laundry, equipment, power distribution, corridors, cloakrooms, and stairs cannot be modeled as a single partition.

For the purpose of the model simplifications, a multifamily house as a reference is proposed, representing a generic, typical residential building type in the largest building sector of the world. This reference building model is derived from an existing, common residential house, built in 2005 in New Minia, Egypt at 30.73 E longitude, 28.08 N latitude (Figure 1). The building consists of nine apartments. The ground floor is represented by one apartment and consists of a lounge, dining room, bathroom, and kitchen, with the total floor area of 180 m². Each floor of the repeated floors consists of two identical apartments, with 220 m² net floor area. Every apartment includes reception, master bedroom, two children rooms, bathroom, and kitchen as shown in Figure 1 and occupied by a couple with two children based on the real evaluation from the field. The composition of building elements was used on the basis of the Egyptian standards, as shown in Table 1. IDA ICE has been used to simulate thermal and visual comfort as well as energy performance in a detailed model about the reference building and in several simplification scenarios, whereas the reference model is modified according to the simplification concepts. Table 1 presents an overview of the major parameters and input data.

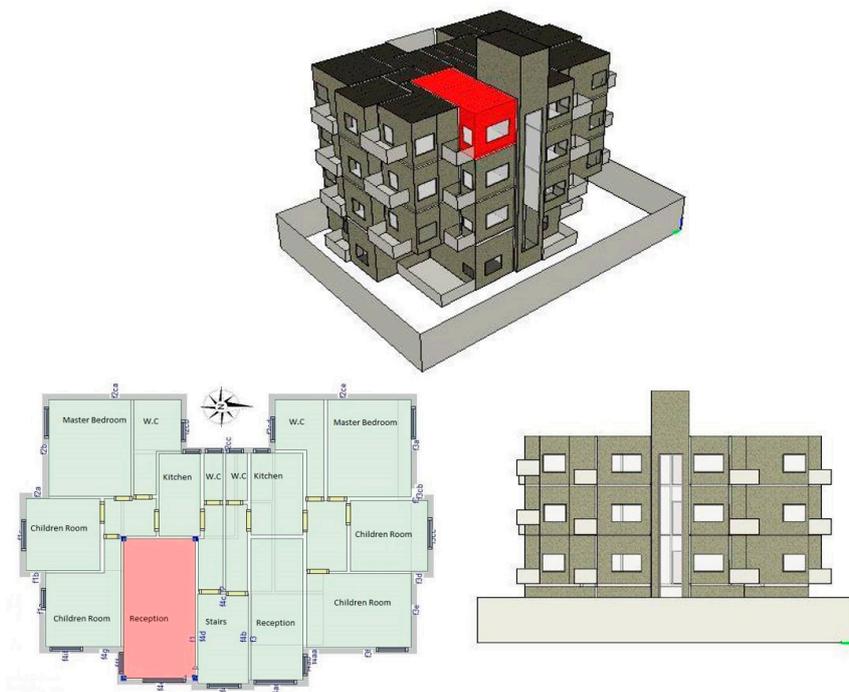


Figure 1. Generic residential building as a reference for model simplification tests.

Table 1. Boundary conditions for the simulation.

Boundary Conditions	Model Characteristics
Location	Minya
Simulation Weather File	EGY_MINYA_623870_IW2.PRN (ASHRAE 2013)
Modeling Software	IDA Indoor Climate and Energy
House Type	Family house
Plot Area	300 m ²
Glazing Type	20 mm single glazed glass, U-value = 5.9 W/(m ² K)
External Walls	5 mm Plaster + 25 mm Egyptian Portland cement mortar + 250 mm Double red brick + 25 mm Egyptian Portland cement mortar + 5 mm Plaster. U-value = 1.546 W/(m ² K)
Internal Walls	5 mm plaster + 25 mm Egyptian Portland cement mortar + 125 mm single red brick + 25 mm Egyptian Portland cement mortar + 5 mm plaster U-value = 2.281 W/(m ² K)
Internal Floors	10 mm concrete tiles + 20 mm Egyptian Portland cement mortar + 50 mm sand + 200 mm plain concrete. U-value = 1.824 W/(m ² K)
Roof	10 mm concrete tiles + 20 mm Egyptian Portland cement mortar + 50 mm sand + 20 mm betomine damp insulation + 150 mm rein force concrete. U-value = 1.707 W/(m ² K)
External Floor	10 mm Concrete tiles + 50 mm sand + 20 mm Egyptian Portland cement mortar + 200 mm plain concrete + 250 mm soil. U-value = 1.172 W/(m ² K)
Basement Wall Towards Ground	5 mm Plaster + 25 mm Egyptian Portland cement mortar + 250 mm double red brick + 25 mm Egyptian Portland cement mortar + 5 mm plaster. U-value = 1.546 W/(m ² K)
Infiltration	7 ACH
	- Occupant: Activity level 1.0 MET
	Constant clothing 0.85 ± 0.25 CLO (clothing is automatically adapted between limits to obtain comfort)
	Occupancy time:
	1- Living room: fully present (1) [7:00–8:00, 17:00–22:00], half present (0.5) [15:00–17:00], 0 otherwise,
	2- Bedroom 0 [7:00–22:00], 1 otherwise (remaining)
	Emitted heat per person 75 W
	- Equipment usage time:
Internal Gains	1- Living room: full intensity 1 [7:00–8:00, 17:00–22:00], half intensity 0.5 [15:00–17:00],
	2- Bedroom: 0 [7:00–22:00], 1 otherwise
	Luminous efficiency 12 lm/W
	- Artificial lighting use:
	1- living room From 1 Jan to 14 Apr all days:1 [7:00–8:00, 17:00–22:00], 0.5[15:00–17:00], 0 otherwise From 16 Oct to 31 Dec all days:1[7:00–8:00, 17:00–22:00], 0.5[15:00–17:00], 0 otherwise From 15 Apr to 15 Oct all days:1 [19:00–22:00], 0 otherwise All days: 0
	2- Bedroom From 1 Jan to 14 Apr all days:1 [6:00–7:00, 22:00–23:00], 0 otherwise From 16 Oct to 31Dec all days:1 [6:00–7:00,22:00–23:00], 0 otherwise All days: 0
Schedules	Independ in different spaces
Daylight	Meteonorm database diffuse and direct radiation (W/m ²)
HVAC	No mechanical ventilation. Generic heating and cooling in the zones to compensate heat losses and loads.

In the following, four different simplification scenarios of the thermal zones are proposed as shown in Figure 2. Summary of the simulated scenarios is presented in Table 2. First, in the base scenario (BS) model, each space is modeled as a single independent zone (Figure 1). Then, scenario S1 combines spaces with similar characteristics (e.g., orientation, operation schedules, same use, etc.) into one thermal zone (Figure 2). Then, scenario S2 combines the same oriented spaces for all of the 4 floors

into one thermal zone (Figure 2). In scenario S3, all spaces on the same floor are merged into one single zone, and scenario S4 models the entire building as one single thermal zone (Figure 2).

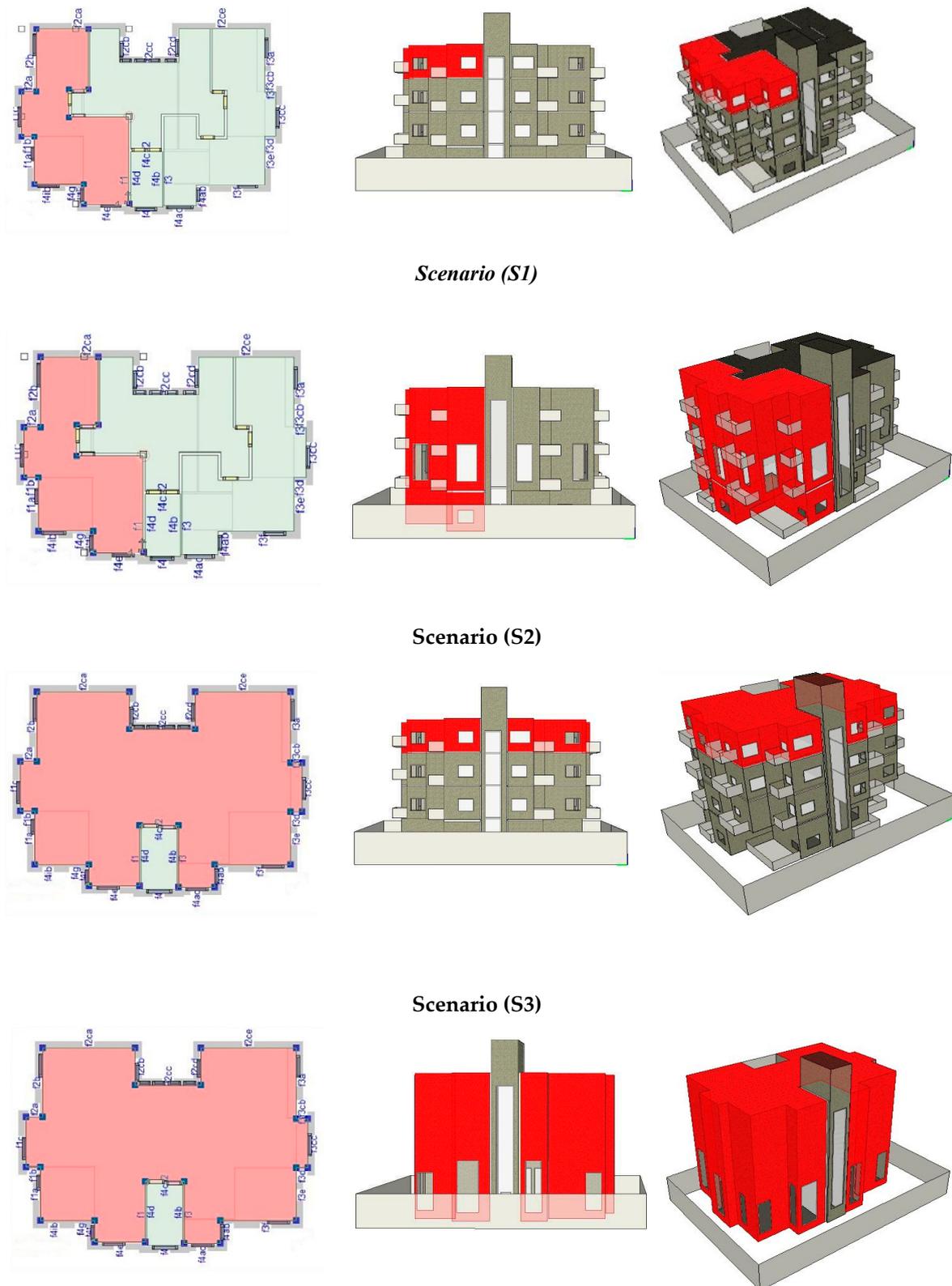


Figure 2. Simplification scenarios—simulation models (plan, side, and 3D view).

Table 2. Simulated simplification scenarios.

Scenario	Description of Investigated Thermal Zones	Number of Thermal Zones
BS	Base model: Each building space is modeled as a single zone.	64
S1	Floor by floor, all identically oriented spaces with the same function are merged into one zone with the same operation schedules, use, etc. The same oriented spaces with the same use for all of the 4 floors are	14
S2	combined into one thermal zone, i.e., bedrooms on ground floor, 1st floor, 2nd floor, and 3rd floor are merged with circulation areas into one thermal zone.	8
S3	All rooms on the same floor are merged into one thermal zone, thus in this scenario the whole building has 4 zones.	4
S4	The entire building is modeled as one single thermal zone.	1

3. Results and Discussion

3.1. Building-Energy Assessment

IDA ICE has been used to simulate energy consumption and indoor comfort performance of the studied building for the BS model and all the simplification scenarios. Figure 3 summarizes the energy results for the BS model and the simplification scenarios in comparison to BS model. The simplification scenarios have minor effect on the lighting, facility, equipment, tenant, and DHW results due to their similar input parameter and cumulated settings. On the other hand, electric cooling and heating show larger differences. In BS scenario, the cooling demand accounts to 67% of the total energy consumption, while the heating demand attributes to 18%, as the case study located in a hot and dry climate. Lighting, facility, equipment, tenant and DHW accounted to 15% of the total energy consumption. In S1, the cooling demand increased by 9.6% and the heating demand decreased by 3.1% with respect to BS (Table A1). S2 and S3 scenarios performed an increased cooling demand by 15.1% and 10.6% respectively, while the heating demand decreased by 3.5% and 0.3%, respectively, compared to BS (Table A1). In scenario S4, the heating demand decreased by 23.6% in respect to BS model, while the cooling demand increased by 12.2% compared to BS (Table A1). Similar reports of the simplification on the energy performance are available in the literature, e.g., Heo et al. [34] and Ren et al. [41] have reported that merging rooms with similar characteristics into one zone (scenario S1) and modeling a single zone for the entire building (scenario S4) underestimated the annual heating demand by 7% and 24%, respectively, in comparison to modeling every room as a separate zone (detail model) for domestic buildings in UK. Picco et al [17] have also reported that cooling and heating loads was underestimated by 9.29% and 8.12%, respectively for scenario S3 (Every floor was represented by one individual zone) compared to the detailed model in an office building built, located in Bolzano, Italy. Picco and Marengo [16] have reported similar finding of simplification on cooling and heating demands. They reported that when the number of thermal zones are reduced to one thermal zone per floor (scenario S3), the annual heating and cooling demand are underestimated by 0.86% and 6.25%, respectively. Consistent with the present result, Dipasquale et al. [35] have also reported that reducing the whole floor to one thermal zone underestimated the annual heating and cooling demand by 12.5% and 22%, respectively with respect to the detailed model. Korolija, and Zhang [32] have also reported that treating each floor of a house as a single thermal zone underestimated the annual heating demand by 10.6%. The change in the total energy consumption evolved in the first, second, third, and the fourth scenarios as follows, +5.8%, +9.5%, +7.1%, +4.0% in respect to the BS model (Table A1). Although the fourth scenario represented the worst scenario considering only the cooling and heating demand individually, it had the smallest change in total energy consumption compared to BS model, because the heating and cooling deviations equaled each other out, resulting in the least difference in total. The thermal envelope is the same in all of the models, hence the fundamental differences can be derived from the complexity level of the actual modeled thermal mass, (walls, slabs) that affect mostly the cooling and heating demand, although the geometrically “missing” thermal mass was added to the model variations as individual mass elements respectively. Case S4’s lowest heating demand is caused by the least floor space to be heated.

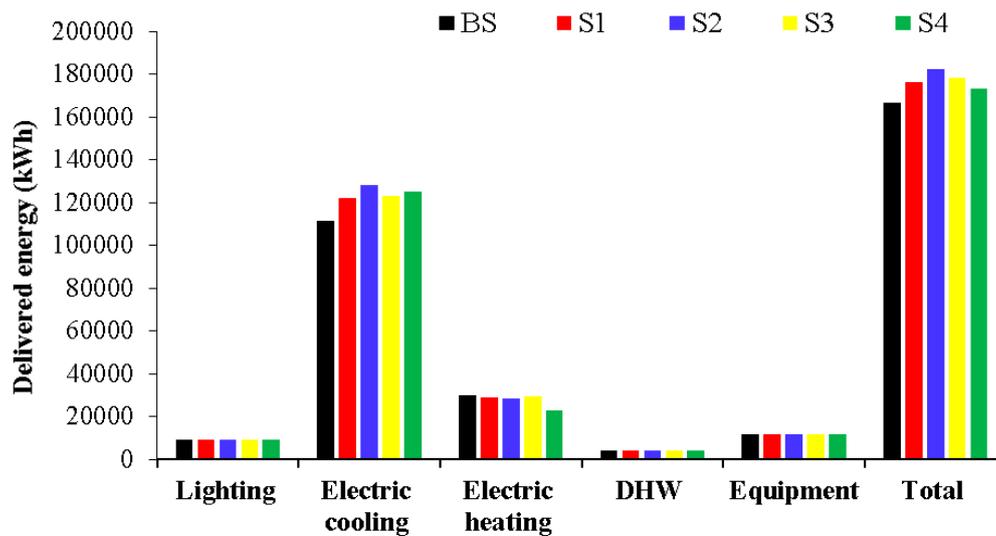


Figure 3. Delivered energy for the detailed and simplified models.

3.2. Simulation Time and Modeling Time

The total modeling time of the BS model was 215 min, while it decreased to 45, 35, 22, and 11 minutes in the simplification scenarios, as shown in Table 3. The most decisive difference in modeling expenditure of time takes place in modeling of one story of a building, since multifamily houses possess a great diversity of apartment sizes, room arrangements and room geometries. After completion of a floor, the typically identic domestic levels can be copied above each other to complete the building model; therefore, this modeling work duration is insignificant. As the number of thermal zones are reduced in a story, the simulation time decreases decisively. Considering the geometry and structure creation as well as the editing and parametrization working time, the required modeling time is approx. proportional—with a rate of 1:1—to the number of zones. At the same time, the total simulation time of the BS model was 86 minutes, and it decreased to 32, 14, 23, and 5 minutes in the scenarios. With a decreasing number of thermal zones, the simulation time decreases significantly. The scenarios saved 79 to 95% of the modeling time and 63 to 94% calculation duration compared to BS, demonstrating a huge potential in model simplification and workflow conservation.

Table 3. Modeling and calculation duration of the detailed and simplified models and respective differences.

	BS	S1	S2	S3	S4
Modeling time (Minutes)	215	45	35	22	11
Modeling time difference (%)	0	-79	-84	-90	-95
Calculation time (Minutes)	86	32	14	23	5
Calculation time difference (%)	0	-63	-84	-73	-94

3.3. Assessment of Building Thermal Comfort

3.3.1. Evaluation of Predicted Mean Vote (PMV)

In this study, PMV was evaluated as one of the main indices to assess the thermal comfort in an occupied zone [42,43]. PMV refers to thermal 7-stage sensation scale [44] through seven points range from -3 to $+3$ as follow $-3 = \text{cold}$, $-2 = \text{cool}$, $-1 = \text{slightly cool}$, $0 = \text{neutral}$, $1 = \text{slightly warm}$, $2 = \text{warm}$, and $3 = \text{hot}$ [45]. Three categories A, B, and C were proposed in ISO 7730, PMV is ranged in the interval of $[-0.2, +0.2]$; for Category A, in the interval $[-0.5, +0.5]$ for Category B and, in the interval $[-0.7, +0.7]$ for Category C [46]. Category B represents the normal level of applicability based on ISO 7730. Figure 4 shows the average number of annual hours of PMV, category B in the detailed

and simplified models' separated as well as merged thermal zones. In the simplified models, the average annual hours of PMV, category B is calculated by an area weighted averaging of the annual hours of PMV, category B for each thermal zone, as presented in Equation (1)

$$N_{PMV} = \frac{\sum_{i=1}^{i=n} N_i \cdot A_i}{\sum_{i=1}^{i=n} A_i} \quad (1)$$

where N_{PMV} means the average annual hours of PMV, category B for the whole model, N_i represents the number of annual hours of PMV, category B for thermal zone i , A_i the total area of each thermal zone [m^2], " n " is the total number of thermal zones of the model. For the complete building in BS, the annual hours of PMV, category B were 7781 h, while 6642 were accounted for S1. The annual hours of PMV, category B increased by 6 hours for S2 and, while the annual hours decreased by 875 and 64 hours for S3 models and one-zone model (S4), respectively compared to the BS model, as shown in Table A2. In S2, the difference in the annual hours of PMV, category B increased by 3.2% in the south side and decreased by 29.3% in the north side, related to the BS model (Table A2). Reason for that: in the south oriented zone, solar gains enabled higher level of PMV, while in the north zone, the contrary effect evolved, because the high thermal zones (3-storey high) are more difficult to heat. In S3, the PMV decreased by 4.7% and 1.7% on the 2nd floor and the 3rd floor respectively, with respect to BS. Reason for that: in the 3rd floor the highest zone is the warmest in summer because of thermal gradient and less thermal mass. However, this greatest deviation is more still at a marginal scale, hence, in general, a consistent calculated thermal comfort sensation was observed in each model.

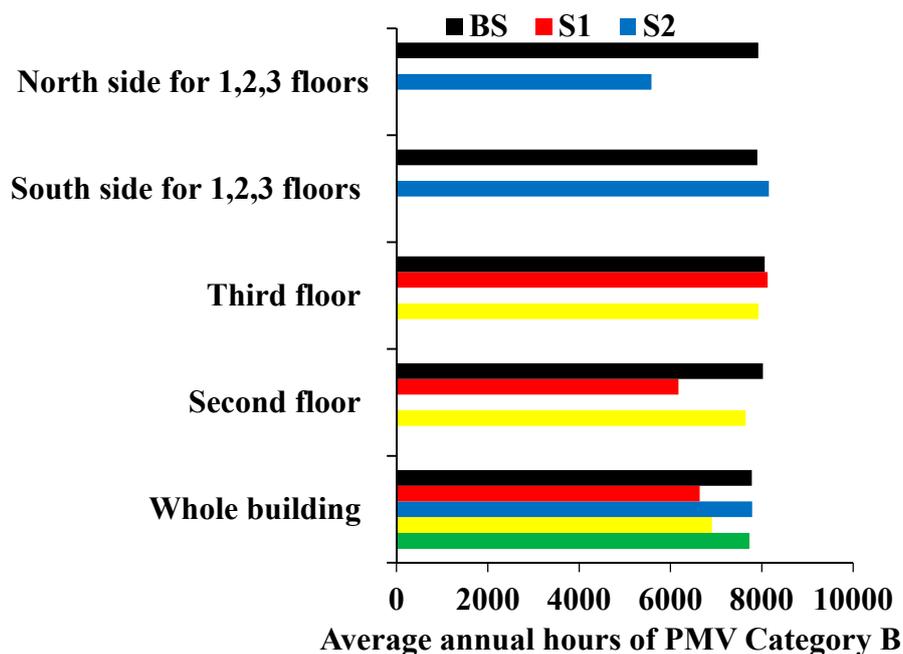


Figure 4. Average number of annual hours of PMV, Category B for whole and some parts of the building in the detailed.

3.3.2. Carbon Dioxide Level Assessment

Concentration of Carbon Dioxide (CO_2) was applied as an indicator of indoor air quality [47]. The connection between indoor air quality and indoor CO_2 concentration originates from the fact that at the same time people are generating odor-causing bio effluents and producing CO_2 [47]. In European Standard CEN-EN 13779:2007 [48], CO_2 concentration is also applied to classify indoor air quality, and the maximum value of CO_2 concentration level is 1500 ppm, while they recommend keeping CO_2 concentration level below 1000 ppm. In this particular study, the number of annual hours is estimated,

when the CO₂ concentration level is above 1000 ppm in the models. The results are compared at three scales (i.e., whole building, 2nd and 3rd floors, south and north sides of the building in all floors). Figure 5 presents the annual hours with CO₂ concentration level above 1000 ppm in the detailed and simplification models. Additionally, an area weighting such as Equation (1) was used to calculate average annual hours of CO₂ concentration level. Regarding to the complete building, the number of annual hours of CO₂ level above 1000 ppm in BS scenario was 2248 h, while S1 was accounted to 2130 h. In the scenarios S2, S3, and S4 this value decreased by 7.2%, 8.4%, and 5.9%, respectively, compared to the BS scenario Table A3. Consistent with the present result, Korolija and Zhang [32] have also reported that treating each floor of a house as a single thermal zone (scenario S3) underestimated the carbon emission by 8%. In scenarios S1 and S3, the differences in the air quality were 0.1% and 21.7% respectively in the second floor, while 48.9% and 8.7%, differences occurred in third floor. In the south side of the whole building (S2 – building high thermal zone), the air hygiene decreased by 17.4% at the north side of the building with respect to the BS scenario while and the south side accounted to the same hours of BS scenario (Table A3). The merged, simplified zones have more space to be window-ventilated, since they include the corridors and secondary spaces (elevator/stairs) as well. That is why they perform higher CO₂ level. Generally, the distribution of CO₂ concentration shows great inhomogeneity in the different sized thermal zones.

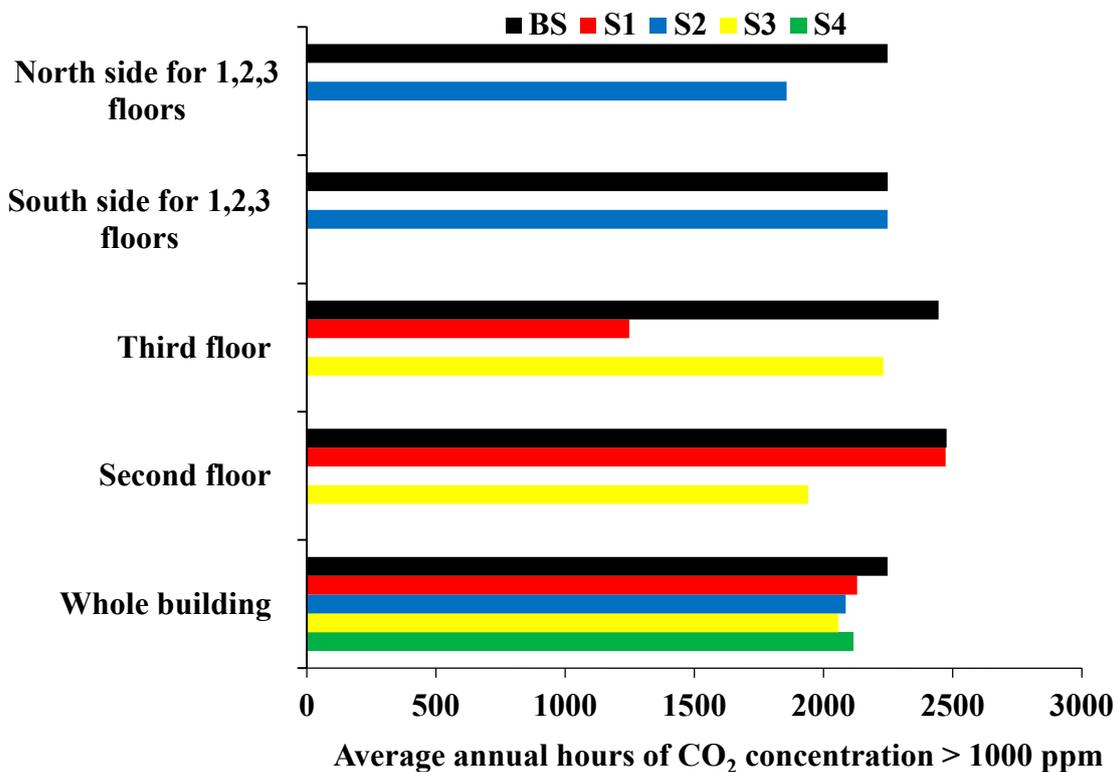


Figure 5. Average number of annual hours with CO₂ concentration > 1000 ppm for the whole and some parts of the building in the detailed and simplified models.

3.3.3. Daylight Factor Assessment

Daylighting as visual comfort is an effective parameter in sustainable and energy efficient building design [49] and it is becoming an essential part of the environmentally friendly building design [50]. Adequate level of daylight is not only important to illuminate all year long and secondarily to heat in wintertime the interior, but it is also an essential source of the occupant's emotional and physiological well-being. Besides ensuring low level of odor and noise, daylight provision is an essential parameter in indoor environment investigations for maintaining the enjoyment of a property. Daylighting performance strongly relies on the illuminance under direct, respectively diffuse sky conditions.

Since the daylight provision under direct illuminance (clear sky conditions) in Minia region possesses high level of daylight autonomy in interior spaces, in this study, the visual comfort assessment focused on the Daylight Factor (DF), representing the illuminance performance of the spaces under mixed sky circumstances, as a kind of ‘worst-case scenario’. Satisfying the minimum required DF limit means a whole year long secured daylighting quality. The DF value is a ratio that represents the amount of illuminance available indoors relative to the illuminance level present outdoors at the same time, under overcast sky [51]. DF at a point of the room is the ratio of the indoor illuminance E_i to the outdoor horizontal illuminance, E_o , [52], expressed as percentage in the following Equation (2):

$$DF = \frac{E_i}{E_o} \times 100 [\%] \quad (2)$$

Calculating Equation (2), the required value of DF for Minia city is 2.1, by applying the required E_i as 300 lx and E_o (median external diffuse illuminance) as 14012 lx according to EN17037 Daylight in Buildings and ASHRAE database. The DF was assessed in all models. Illuminances were computed using meteorological data taken from Meteonorm 7 database [53]. Figure 6 presents the ratio of floor area performing a DF above (corresponding to adequate daylight space partition) and below (equals to inadequate daylight space partition) the DF (2.1) threshold value. In case of BS, 21.3% the floor area is adequately daylight. In S1 and S3 the appropriately daylight floor area increased by 6.1% and 21.6% with respect to BS, while in S2 and S4 delivered significant, 19.8% and 60.3% differences compared to the reference. In S1 the abandonment of all internal walls caused the weaker DF performance and in S3 the additionally merged, deep spaces of the whole story thermal zones indicated the lower level of DF. The reason of the anomalies in S2 and S4 were the different height of the zones in the S2 and S4 models.

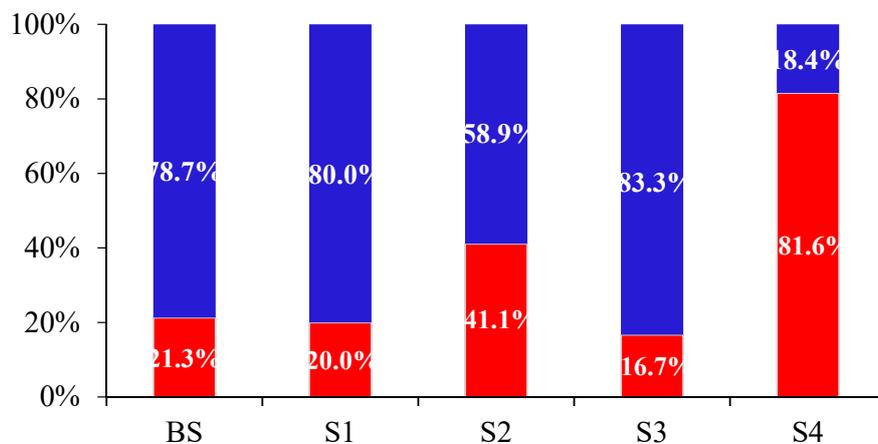


Figure 6. Floor area ratio with daylight factor above (red color) and below (blue color) the minimum DF (2.1%) value.

4. Optimal Scenario of the Proposed Model Simplifications

To determine the optimal scenario of the proposed simplifications, two crucial criteria should be taken into account: the required simulation time and the accuracy of the energy and comfort results. In respect to calculation duration, obviously the single-zone model (S4) represents the fastest model as shown in Table 3, followed by S2 model, S3 model, and S1 model. For the accuracy criteria, Table 4 presents the absolute differences of energy demand (heating and cooling) and indoor comfort (PMV, CO₂ level and DF) in respect to the BS model. More simplification leads to more inaccurate results, as in S4 model the high differences in energy demand and DF distribution demonstrate. In comparison to BS, (S1) presented the optimal accuracy case of the proposed simplification scenarios, resulting in 6.8% average difference of all parameters in energy demand and comfort performance. At the same time, S1 saves over 63% of simulation time. S1 is followed by scenarios 3, 2, and 4. Consequently, the model simplification can be accomplished until the anomalies appear due to the simplified geometry.

Table 4. Absolute % differences of heating and cooling demand, PMV, CO₂ concentration, and DF between the simplification scenarios and BS.

Parameter	Simplification Scenarios			
	Absolute % Differences with Respect to the BS			
	S1	S2	S3	S4
Heating Demand	3.1	3.5	0.3	23.6
Cooling Demand	9.6	15.1	10.6	12.2
PMV	14.6	0.1	11.3	0.8
CO ₂ Concentration	5.3	7.2	8.4	5.9
DF	1.5	20.1	4.5	56.6
Average Differences	6.8	9.2	7.0	19.8
Order	1	3	2	4
% Save in Simulation Time	63	84	73	94

5. Conclusions

Buildings are attributed to a tremendous amount of energy consumption due to their continuous operation and extensive lifetime. Performing Building-energy simulations is an essential part of a decision-making process as it helps designers to assess the energy and comfort effect of different building design options. Since the impacts of building physics simulation model simplifications on the accuracy of the results are not well studied and reported, the proposed simplification scenarios seek to overcome the obstacle of long calculation time and according design costs by providing a simpler and faster way to carry out building-energy and comfort simulations. The main aspect of the methodology is to achieve an adequate level of accuracy that can promote the simulation results of energy demand and thermal comfort analysis by simultaneously minimizing calculation time. The detailed reference building physics simulation model contained all separate rooms modeled as individual thermal zones. The model was then simplified in scenario S1, whereas all spaces with similar use and orientation were merged into one-zone floor by floor. The same oriented spaces for all of the 4 floors were combined into one thermal zone in scenario S2. Every floor was represented by one individual zone in scenario S3, and the whole building was treated as one single zone for scenario S4. Multiple effects of the model simplification methods on energy consumption, CO₂ level, PMV, and DF performance were evaluated in a common residential building in New Minia, Egypt.

A model simplification method that merges all spaces with similar use and orientation into one-zone floor by floor (scenario S1), enables the shortening of the required modeling time of 79% and the acceleration of the required solver calculation duration by 63%. At the same time, the comfort performance values possess 21.4% deviations, while the energy performance results are underestimated by 12.7% in comparison to the detailed model. Combining the same oriented spaces with the same use for all of the 4 floors into one thermal zone (scenarios S2) reduces the simulation time by 84%, while the deviation in total energy demand and thermal comfort are 18.6% and 27.4%, respectively, compared to the detailed model. When the number of thermal zones is further reduced to one thermal zone per floor (scenarios S3), the simulation time is saved by 73%, while the energy and thermal comfort are underestimated by 10.9% and 24.2%. However, modeling the entire building by a single zone (scenarios S4) saves 95% and 94% of the required modeling time and the simulation time, respectively, the energy and thermal comfort are underestimated by 35.8% and 63.3%, respectively. The interdependency of result accuracy and calculation time proved that the optimal simplification method merges all spaces with similar use and orientation into one-zone floor by floor (scenario S1). It is obvious that besides the advantages the geometrical simplifications might carry some limitations as well. Results showed that thermal zone merging as a simulation simplification method has its limitations as well, whereas a too intensive simplification can lead to undesired error rates. Furthermore, the essentially geometry related daylight distribution interpretation can be affected due to the different depth of the merged zones. In addition, the orientation should be considered with consciousness, since the different oriented zones

should not be combined to avoid different solar heat load (summer) or heat gain (winter) effect to be mixed in one greater unified zone to confuse both energy and comfort behavior.

Important to mention that taking only the energy results into consideration during the simplification process is not sufficient to get a truly comparable model version to the original detailed building model, rather it is inevitable to consider all determinate indoor comfort indices as well. Analysis of both comfort and energy results is the only way to identify the optimum on model simplification level. The gained thermal zoning simplification method can imply a high design feedback acceleration effect, offering a great potential for building design optimization. An until now unreached quality level of design optimization evolves, since testing of significantly higher number of design cases in the same amount of available planning time is getting to be possible. The thermal zone geometry simplification's result inaccuracy level should be further reduced by compensation solutions for thermal mass and the central, deeper settled zone sections, which distort to a certain measure the simulation results. The described methodology can help to reduce the duration requirements for a dynamic simulation and it can be seen as a 1st step in a multi-level model simplification strategy, consisting of next stages in simplifications techniques for fenestration, shading, thermal mass, HVAC systems, as well as controlling automation strategies. It can be concluded that the analysis results will be useful for modelers to determine the optimal level of model simplification in the modeling process depending on the achievable accuracy level of energy performance and thermal comfort. The method provided promising results for further applications and it is intended to be further tested in next multifamily projects and office buildings to prove its reliability in building industry standard practice.

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Conflicts of Interest: “The authors declare no conflict of interest.”

Appendix A

Table A1. Delivered energy for detailed and simplified models and their differences with respect to detailed model.

Delivered Energy	BS	S1	S2	S3	S4
Lighting, Facility (kWh)	9199	9209	9213	9205	9205
Difference %	0	0.1	0.1	0.1	0.1
Electric Cooling (kWh)	111,501	122,223	128,313	123,326	125,104
Difference %	0	9.6	15.1	10.6	12.2
Electric Heating (kWh)	29,755	28,824	28,716	29,653	22,723
Difference %	0	−3.1	−3.5	−0.3	−23.6
DHW (kWh)	4246	4246	4246	4246	4246
Difference %	0.0	0.0	0.0	0.0	0.0
Equipment, Tenant (kWh)	11,746	11,764	11,750	11,753	11,761
Difference %	0	0.2	0.0	0.1	0.1
Total (kWh)	166,447	176,166	182,237	178,182	173,038
Difference %	0	5.8	9.5	7.1	4.0

Table A2. Average number of annual hours of PMV, Category B for whole and some parts of the building in the detailed and simplified models and differences of simplified models with respect to detailed model.

	BS	S1	S2	S3	S4
Average Annual Hours of PMV Category B					
Whole Building (hours)	7781	6642	7787	6906	7717
Difference %	0.0	−14.6	0.1	−11.3	−0.8
Second Floor (hours)	8026	6176	-	7646	-
Difference %	0.0	−23.1	-	−4.7	-
Third Floor (hours)	8063	8128	-	7928	-
Difference %	0.0	0.8	-	−1.7	-
South Side for 1,2,3 Floors (hours)	7900	-	8153	-	-
Difference %	0.0	-	3.2	-	-
North Side for 1,2,3 Floors (hours)	7921	-	5585	-	-
Difference %	0.0	-	−29.3	-	-

- = Zero (no value), as there was no simulation in this zone for the given scenario.

Table A3. Average number of annual hours with CO₂ concentration > 1000 ppm for whole and some parts of the building in the detailed and simplified models and differences of simplified models with respect to detailed model.

	BS	S1	S2	S3	S4
Average annual hours of CO₂ concentration > 1000 ppm					
Whole Building (hours)	2248	2130	2086	2058	2116
Difference %	0.0	−5.3	−7.2	−8.4	−5.9
Second Floor (hours)	2476	2473	-	1940	-
Difference %	0.0	−0.1	-	−21.7	-
Third Floor (hours)	2445	1249	-	2232	-
Difference %	0.0	−48.9	-	−8.7	-
South Side for 1,2,3 Floors (hours)	2249	-	2248	-	-
Difference %	0.0	-	0.0	-	-
North Side for 1,2,3 Floors (hours)	2248	-	1858	-	-
Difference %	0.0	-	−17.4	-	-

- = Zero (no value), as there was no simulation in this zone for the given scenario.

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