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Comparison of EnergyPlus and IES to model a complex university building using three scenarios: Free-floating, ideal air load system, and detailed

Ali Al-janabi[a], Miroslava Kavgic[a,*], Ali Mohammadzadeh[a], Afaf Azzouz[b]

[a] Civil Engineering, University of Manitoba, 15 Gillson St., Winnipeg, Manitoba, Canada, 3RT 5V6
[b] Stantec, 500-311 Portage Ave., Winnipeg, Manitoba, Canada, R3B 2B9

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ABSTRACT

The energy performance gap is one of the most discussed issues in the design community since energy modeling became an integral part of the building design process. Different limitations apply to almost every building performance simulation (BPS) software available today and to have confidence in the predictions of whole-building energy models it is necessary to have a thorough understanding of various features, specific capabilities, and disadvantages of BPS tools. The main contribution of this work is the use of three methods of evaluation with different levels of complexity, free-floating, ideal air load system, and detailed method to analyze and compare the capabilities of EnergyPlus and IES to model complex LEED silver multi-purpose university building. Consequently, this study provides new information regarding capabilities of two extensively used BPS tools to model advanced and innovative buildings, and in particular HVAC systems that are increasingly becoming used in high-performance commercial and institutional buildings worldwide. The difference between the total energy consumptions of the EnergyPlus and IES models developed according to the final construction drawings was approximately 2.1%, whereas differences between the heating and cooling loads of the EnergyPlus and IES models with ideal air load systems were 6 MWh (1.7%) and 0.86 MWh (7.8%), respectively. The high consistency between the models' aggregated predictions are particularly pertinent and encouraging for certification programs such as LEED, which take into account aggregated energy consumption data in their assessments. The findings also emphasize the importance of the modeler's assumptions regarding the modeling of HVAC systems and their impact on the model's predictions.

1. Introduction

Code requirements for the energy performance of buildings are becoming more stringent. One of the most widely recognized rating systems is the Leadership in Energy and Environmental Design (LEED) which promotes a whole-building approach to sustainability through the creation and implementation of high-performance requirements [1–4]. To satisfy these high standards, designers must utilize different scenarios, design strategies as well as novel and advanced systems and technologies [5–8]. Building energy modeling is a robust technique that provides a pathway to test, analyze, and optimize various energy efficiency measures and technologies [8–14]. Consequently, building energy modeling can enable better-informed design solutions and compliance with energy codes and standards. Over the past 50 years, a broad spectrum of free (e.g., EnergyPlus, eQuest) and commercial (e.g., IES, TRNSYS) building performance simulation (BPS) tools capable to develop whole-building energy models arrived on the market that vary in many aspects, including their graphical capabilities, accuracy, flexibility, user-friendliness, simulation time, life-cycle applicability, and price [15].

EnergyPlus (E +) is a "new generation" whole-building simulation tool that can simulate multiple building systems using a network of nodes, which offers considerable flexibility in the modeling of building energy system [16]. Integrated Environmental Solutions Virtual Environment (IES VE) is another comprehensive whole-building simulation tool that provides design professionals with a single software environment for a detailed assessment and optimization of building and system designs [17,18]. Today, both IES and EnergyPlus are widely used BPS tools. For instance, [19] conducted a survey that included 108 modelers from engineering and architectural firms involved in the design process of a range of national and international projects and reported that 80% of respondents selected IES as the simulation software they used for energy analysis. Although EnergyPlus can be used as a stand-alone tool, the major barrier to the widespread adoption by

* Corresponding author.
E-mail addresses: miroslava.kavgic@umanitoba.ca (M. Kavgic), afaf.azzouz@stantec.com (A. Azzouz).

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practitioners was the lack of a comprehensive graphical user interface for rapid development of the building's geometry. This situation has changed over the last ten years with the development of several software packages that either uses EnergyPlus as their primary simulation engine (e.g., DesignBuilder, Sefaira, and OpenStudio) or have plug-ins (e.g., SketchUp, Revit) for integration with EnergyPlus. As a result, EnergyPlus became more accessible to building designers and other professionals.

However, since building energy modeling became an integral part of the building design process and compliance with building energy codes and regulations, one of the most discussed issues in the design community is the energy performance gap [20,21]. Many studies have reported that the design phase is a frequent cause of the performance gap due to different reasons [19,22,23]. Some studies identified issues related to the specification of advanced systems and technologies caused by their complex design and operation coupled with software limitations and modelers' poor skills and knowledge [19,22]. For instance, oversimplification of the systems or its inadequate representation may result in inaccurate predictions. Other studies observed that software errors related to inaccuracies in the mathematical modeling of the physical behavior of the building systems and coding might significantly contribute to the energy performance gap [24,25]. For example, some studies had reported large discrepancies, ranging from 17% to 67%, between the predictions of different whole-building energy simulation tools when the same building was modeled, and input parameters were carefully mapped [26–31]. The studies also showed that discrepancy between the software predictions typically increased with the complexity of the case study.

Therefore, to have confidence in the predictions of whole-building energy models, it is necessary to have a thorough understanding of various features, specific capabilities, and limitations of the used BPS tools. For example, since 1985 the PASLINK Network of outdoor test facilities apply dynamic test procedures and parameter identification techniques to enable accurate thermal and solar characterization of the building envelope under real outdoor conditions, which can be used to improve the accuracy of the BPS simulation tools [32,33]. For instance, recently [34] simulated the thermal performance of a PASLINK test cell with a gravel-covered roof test component using a new methodology that improves the characterization of building models and reduces the gap between the simulation and real performance of buildings. Furthermore, to increase reliability in the use of BPS tools, the Building Energy Simulation Test (BESTEST) and ANSI/ASHRAE Standard 140 prescribe standardized and citable test procedures for validating, diagnosing, and improving the current generation of software [35,36]. Although these test procedures model many typical building features such as thermal mass, windows, shading devices, orientation, internal gains, ventilation, and thermostat set point variation, all of them use a single-zone model, except for one that models a sunspace adjacent to a conditioned zone [37]. Consequently, direct transferability of conclusions to multi-zone buildings is challenging and uncertain. Additionally, developed test procedures use ideal air load systems, and therefore they do not evaluate the software's ability to model complex HVAC components and other building systems [35,36].

Previous studies compared the features and capabilities of various software [38–40] or used simple, single-zone/single-room models to investigate differences in the software predictions [27,31,41]. Furthermore, some studies used more complex multi-zone building models to compare the features and capabilities of different building performance simulation tools. For example, Mostafavi et al. [42] used three building simulation tools, eQUEST, IESVE, and Autodesk Green Building Studio, to quantify the predicted energy savings of an envelope retrofit of a seven-story residence hall. Similarly, Abdullah et al. [28] investigated the potential of Vasari/Green Building Studio and Sefaira software to perform a whole-building energy analysis of a 4740 m^2 university building and compared results with the actual building energy performance. Another study [43] compared the energy predictions of an artificial neural network model against the EnergyPlus model of an administration building in São Paulo. Andolsun et al. [30] compared EnergyPlus and DOE-2.1E using several case studies that ranged from a sealed box to a detailed residential building. Schwartz and Raslan [26] compared Tas, EnergyPlus, and IES-VE on the example of simplified 32-story student residential hall and compared modeling results against two sustainability rating systems BREEAM and LEED. Choi [44] used six simulation tools, HEED, EnergyPro, BeOPT, eQUEST, DesignBuilder, IES-VE Pro, to investigate the correlation of energy use intensities between 15 residential projects. While these studies provided valuable information regarding the capabilities of different BPS tools to perform whole-building energy analysis, many of them demonstrate considerable discrepancies between the aggregated energy predictions, and especially for complex buildings, which can undermine the confidence in the use of BPS software for building design optimization and certification. Furthermore, there is a limited body of literature that compares different BPS tools on the HVAC system level and especially for complex institutional buildings. One such study created a five-zone ideal building model to investigate the constant air volume and variable air volume systems of EnergyPlus, DeST, and DOE-2.1E and compared them in detail to assess their similarities and differences [45]. While the findings from this study are significant, they are based on an unrealistic building model, which makes their direct transfer to realistic building models developed according to the final construction drawings difficult and uncertain.

This study seeks to extend the existing knowledge and understanding required for successful integration of BPS tools in different stages of the building design process and code compliance. Additionally, it also attempts to address the energy performance gap due to the differences in simulation predictions that may be caused by algorithmic differences, modeling limitations, or input dissimilarities. Two comprehensive and widely used BPS tools, EnergyPlus and IES, have been compared and discussed using a four-story LEED silver university building equipped with multiple and complex HVAC systems. Furthermore, this is the first study to provide a comparison between EnergyPlus and IES using three scenarios that are often used in the building design process: free-floating, ideal air load system, and detailed scenario. Consequently, this study provides new information regarding capabilities of two extensively used BPS tools to model advanced and innovative buildings, and in particular HVAC systems that are becoming used increasingly in high-performance commercial and institutional buildings worldwide. Therefore, the findings are likely to be of interest to an audience in either academia or industry and can deliver valuable guidance for other studies focused on whole-building energy modeling. This paper first provides a detailed description of the case study. Next, it presents modeling assumptions and a description of the two models. After that, three model scenarios are described and compared. The final section provides conclusions, limitations and future work.

2. Building description

Currently, under construction, the Stanley Pauley Engineering Building (SPEB) is located at the Fort Garry campus of the University of Manitoba, Winnipeg, Canada. The SPEB will accommodate various space types, including student areas, laboratories, fabrication spaces, and offices. Fig. 1-a shows that the orientation of the building is 26° to the west of true north. As illustrated in Fig. 1-b, the SPEB consists of one-floor below-grade and three floors above-grade, with a total floor area of 4200 m^2. A bridge link will connect the building to the Engineering and Information Technology Complex (see Fig. 1-a). On the East side, the building will be adjacent to the existing Stanley Pauley Centre. Window to wall ration is around 60%, with the most glazing on the South and West sides of the building (see Fig. 1-b).

The building design incorporates multiple envelope systems, which consists of double glazed, argon filled, insulating, low-E curtain wall

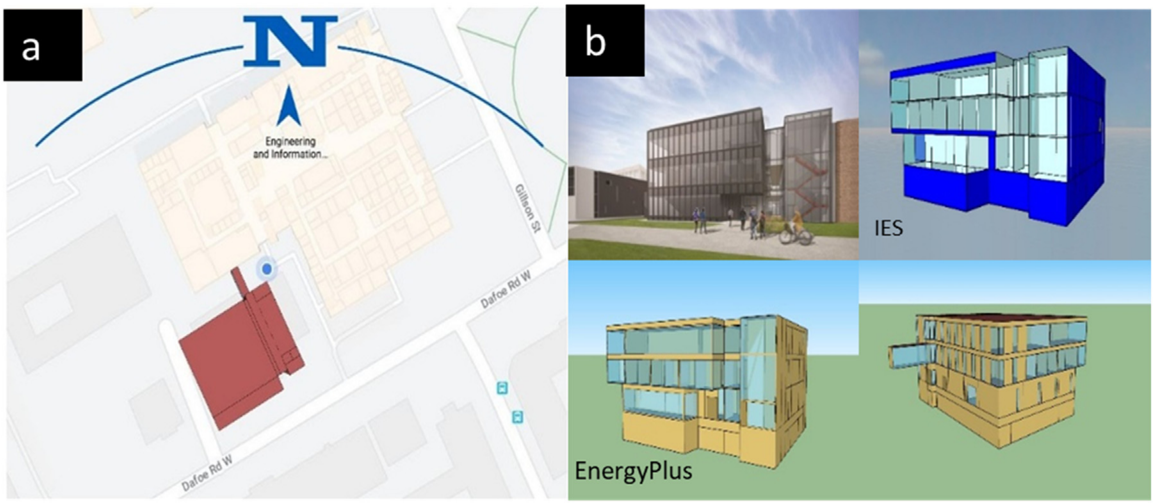
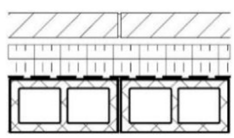


Fig. 1. (a) Top view of the SPEB [46], (b) Front and back sides of the SPEB [47].

Table 1
Stanley Pauley Engineering Building constructions and materials.

Construction type	Constructions and materials	
Exterior wall		– 90 mm x 90 mm x 590 mm concrete masonry (outer layer) – 25 mm air gap – 125 mm 2 layers (50 mm + 75 mm) board insulation – Air/vapor barrier membrane – 200 mm concrete masonry unit (inner layer)
Roof		– Roofing membrane (outer layer) – Styrene-butadiene-styrene modified bitumen cap sheet – Styrene-butadiene-styrene modified bitumen base sheet – 250 mm 2 layers (150 mm + 100 mm) board insulation – tapered board insulation for back slopes – Vapor retarder – Concrete slab (inner layer)
Floor		– 150 mm concrete slab
Interior partition		– 12.5 mm Plasterboard – steel studs / furring @ 400 mm O.C. – − 12.5 mm Plasterboard
Window		– 6 mm low-E outer glazing layer – Spacer: stainless steel finish: black – 13 mm argon filled gap – 6 mm inner glazing layer

glass, and well insulated external walls. Table 1 summarizes and describes the details of the main building's materials and constructions.

A high-energy performance combination of hydronic and air systems will serve the SPEB to meet the building's heating and cooling load requirements. Furthermore, a frost resistant, dual-core energy recovery ventilation system will provide 100% of the fresh air to the building. The outside air will be primarily distributed throughout the variable-air-volume units, whereas two-pipe fan-coil units will circulate a mixture of direct outside air and local recirculated air within the space as needed. Heating or cooling water will be flowing through cross-linked polyethylene piping embedded in the concrete floor of specific areas (e.g., mainly perimeter zones) to assist in heating or cooling. In heating mode, the radiant system will provide the baseline heating while the air system will provide the trim. Because of the thermal lag of the concrete slab, in heating mode, the fan coil units will satisfy any temporary changes in the room temperature. The active floors serve areas where direct sunlight strikes the floor. The floors will flow cooled water derived from the central campus chilled water system. Central high-pressure steam and pumped condensate return will be provided to SPEB through a new connection routed through the lower level of the Engineering and Information Technology Complex. The presence of multiple systems in one zone will vary upon the location, occupancy type, and the internal loads of that particular zone. Both the radiant floor system and the fan coil units will be supplied with hot and chilled water by the central physical plant at the University of Manitoba.

3. Modeling methodology

Three different building models of the SPEB that vary in their complexities, namely, free-floating model, ideal air system model, and detailed model are developed to investigate the application of the BPS tools in different stages of the building design process. The IES models of the SPEB were developed by the consulting company Stantec, whereas the research team at the University of Manitoba developed EnergyPlus models. It is important to note that Stantec developed their detailed IES model to demonstrate minimum energy performance for new LEED construction.

Building simulation programs often differ regarding their architecture and algorithms used to model buildings and their energy systems [30,31,36]. For example, IES combines several modules to perform dynamic whole-building energy analysis [17]. ModelIT is the single central 3D data model at the core of the IES that provides geometry data shared by all modules. ApacheSim is a central simulation processor which enables assessment of building's thermal performance as well as shares results and inputs across other IES modules, such as ApacheHVAC for modeling of HVAC systems, MacroFlo for airflow analysis, and SunCast for advanced 3D solar analysis. Moreover, VistaPro enables quick and easy analyzes of the results from one or more simulations. Development of a detailed and realistic whole-building energy model of a complex building with diverse and complicated HVAC systems such as the SPEB requires the use of all these modules. Therefore, Model-It, SunCast, Apache, MacroFlo, and VistaPro were used for all three models (i.e., free-float, ideal air system, and detailed), whereas ApacheHVAC was used to model HVAC system in the detailed model. Although user-friendly programs such as DesignBuilder, Sefaira, and OpenStudio use EnergyPlus as their simulation engine, in this study, SketchUp/Euclid plug-in is used to develop 3D geometry and perform thermal zoning of the Stanley Pauley building, whereas EnergyPlus was used to model all other components for the following reasons. First, some of the programs such as DesignBuilder don't use the latest updated version of EnergyPlus. Second, EnergyPlus allows increased capability and flexibility in the modeling of HVAC systems, which was particularly important due to the complex HVAC systems that were modeled in detailed. Last, considering that the above mentioned user-friendly simulation packages use EnergyPlus as an engine, the results would be the same regardless whether they are produced using these tools (e.g., DesignBuilder) or by only using EnergyPlus.

Consequently, different user inputs may be required to model the same building envelope elements or HVAC system components. The adopted research methodology closely mapped the input parameters, kept the simulation settings the same or as close as possible, and followed the final construction drawings. The following sections provide insight into implemented modeling assumptions and describe the critical input parameters such as weather file, thermal zoning, materials and constructions, internal loads, schedules, and HVAC systems.

3.1. Weather data

To ensure the consistency of environmental conditions and since the SPEB is still under construction, both models used CWEC.epw weather file for Winnipeg. The CWEC file contains 12 typical meteorological months composed of hourly weather data records that are selected from a 30-year database of Canadian Weather Energy and Engineering Datasets with the purpose of predicting the average heating and cooling loads in buildings [48]. Fig. 2 shows CWEC's monthly maximum, minimum, and average outdoor air dry-bulb temperatures along with relative humidity (RH) and solar radiation. It is evident that Winnipeg experiences extreme temperature fluctuations that range from + 35 °C in summer to − 35 °C in winter. Consequently, the construction of low-energy buildings, and in particular, commercial and institutional buildings, which typically have higher energy requirements, is challenging.

3.2. Zoning approach

According to the ASHRAE standard 90.1 [49], thermal zones may be combined into thermal blocks when three main conditions are met. First, all the zones in the block should have the same load and scheduling characteristics. Second, to accurately model solar heat gains, the glazing for all zones included in the thermal block must have the same orientation, or at least their orientations must be within 45 degrees of each other. Third, to accurately model the performance of the system(s) serving the block, the same type of HVAC system must serve all the zones within the block. Therefore, to simplify the EnergyPlus and IES models without compromising their accuracy and robustness, zones with the same orientation, served by the same HVAC system(s) and with the same occupancy schedules were grouped. This approach reduced the number of zones by approximately 30% and resulted in 98 thermal zones in total. Free 3D modeling program SketchUp Make/Euclid 0.9.3 is used to develop the EnergyPlus model, and the IES model is created using ModellIt application within IES. In both programs, the surrounding buildings are modeled as simple cuboids to consider the effect of shading. Fig. 3 illustrates the implemented zoning approach.

3.3. Materials and constructions

In EnergyPlus and IES envelope construction is the assembly of multiple layers defined from outside to the inside where each layer represents a specific material defined based on its physical properties (e.g., thickness, thermal conductivity, density, and specific heat). The thickness of each layer was taken from the final construction drawings provided by the developer, whereas the thermophysical properties were taken from the Manitoba Energy Code for Buildings (MECB) [50]. Similarly, windows are created by defining two layers of glazing separated by a gap filled with argon. There are two main limitations related to the modeling of complex envelopes and façades in EnergyPlus and IES. First, EnergyPlus and IES perform only one-dimensional heat transfer through multilayered construction calculations [51], and thus all materials are defined as flat layers regardless of their actual shape. Second, because EnergyPlus and IES assume that highly conductive and thin materials do not contribute to the overall thermal resistance or heat capacity of the construction, they have to be omitted from the

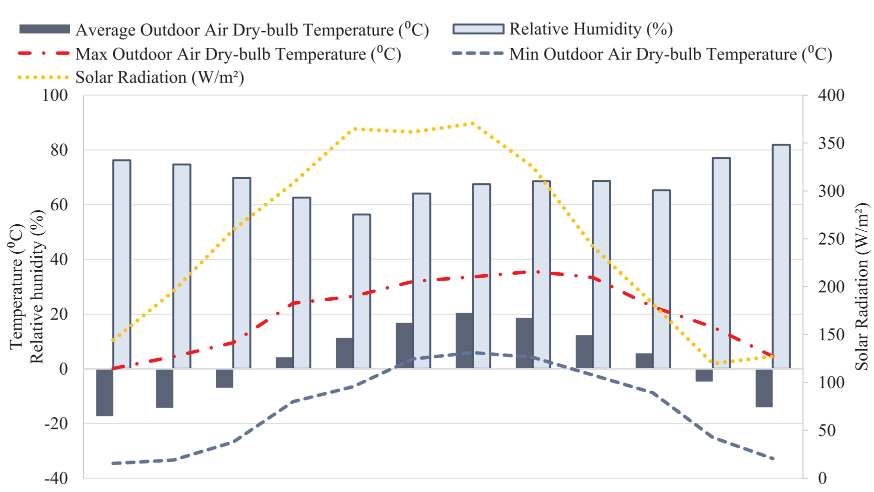


Fig. 2. Monthly outdoor air dry-bulb temperatures, RH, and solar radiation.

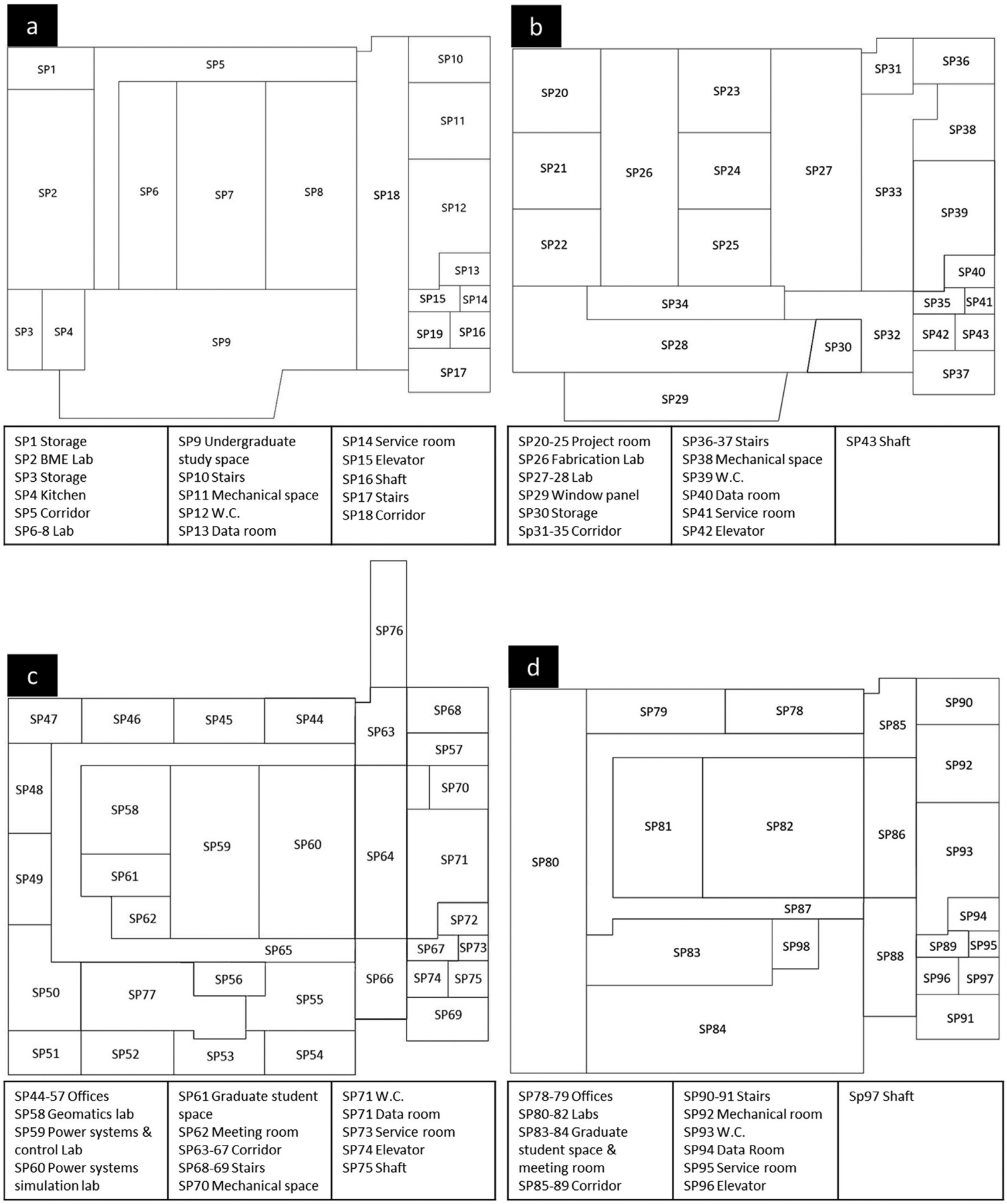


Fig. 3. Thermal zones of the SPEB: (a) Basement, (b) First Floor, (c) Second Floor, and (d) Third Floor.

Table 2
Comparison of the calculated U-values of the envelope elements in IES and EnergyPlus.

Construction type	U-value (W/m^2 K)	
	IES	EnergyPlus
Exterior wall	0.262	0.263
Roof	0.135	0.135
Floor	3.441	3.445
Interior partition	1.788	1.789
Window	1.375	1.379

simulation [52]. Therefore, developed models exclude all thin metal sheets. While U-values are very similar between the two software (see Table 2), the Solar Heat Gain Coefficient (SHGC) of glazing in both models is 0.24.

3.4. Internal loads and schedules

Internal gains have a considerable impact on energy consumption [53]. Therefore, people, internal lights, equipment, and plug-loads were defined as internal gains following realistic schedules. People are modeled by defining the occupancy density based on the occupancy category such as labs, offices, and study areas, whereas the design team established the density values for each category. Since people's

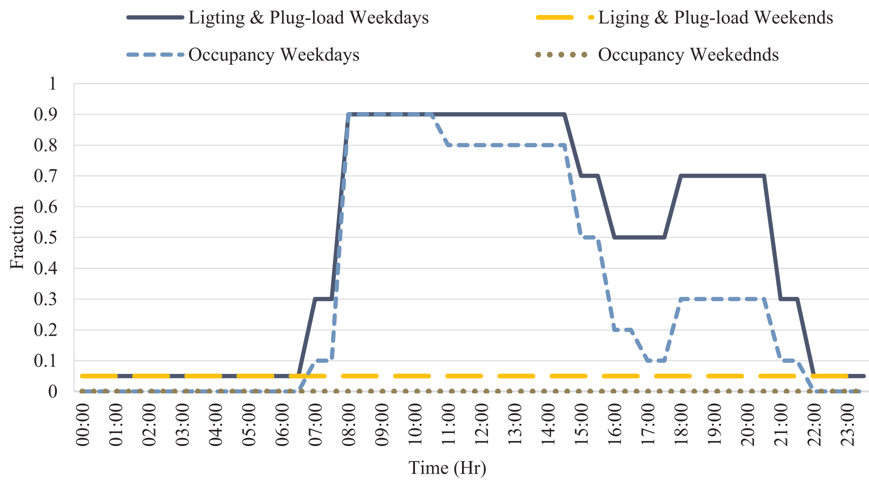


Fig. 4. Internal lights, plug-loads, and occupancy schedules.

activities differ depending on the occupancy type, the people's activity level was defined to reflect each zone [52,54]. For instance, a higher activity level is assigned to labs and student spaces than offices. Each type of internal gain is controlled by detailed schedules for weekdays and weekends, which are created by modifying the operating schedule D for school and university proposed by the National Energy Code of Canada for Buildings (NECB) to match the observed occupancy in the existing engineering buildings on campus [55]. Fig. 4 illustrates the schedules of internal lights, plug-loads, and occupancy.

Furthermore, the building's lighting power density was defined based on the requirements provided by the design team, and it varies upon the space type from 0.323 to 24.43 W/m^2 and day (e.g., weekday or weekend). Equipment power consumption and sensible heat gains were defined based on the equipment available in different zone types (e.g., data centers in data rooms, welding equipment in the welding shop). Table 3 lists the zone types with high sensible gains, their power consumption and period of operation. Additionally, plug-loads such as computers, printers, and monitors energy use intensity (W/m^2) were specified according to the MECB [50].

3.5. Simulation of HVAC systems in EnergyPlus and IES models

In both EnergyPlus and IES models, the hydronic and air systems were modeled to follow the same set-point and set-back temperatures (see Table 4). While both models followed final construction drawings and specifications of the HVAC systems, due to the dissimilarities in the software architectures and modeling assumptions, there are some differences in the modeling of the HVAC systems. The following sections describe the HVAC modeling approach and assumptions applied in IES and EnergyPlus.

3.5.1. IES model

The HVAC system was built using the Apache HVAC module in IES [17]. Outdoor air is supplied using a dedicated outdoor air system template (DOAS) supplying 100% outdoor air. IES has pre-defined HVAC templates that include a DOAS system with air-to-air heat recovery on the system-level and fan coil units on the terminal level. The use of the HVAC templates significantly accelerated the modeling process of the SPEB and completion of the project. On the system-level, the AHU has heating and cooling coils designed to maintain the supplied outdoor air at a constant temperature of 12.8 °C at all times. The outdoor air flow rate varies in the supplied zones based on the demand, using demand controlled ventilation. On the zone-level, radiant floor and fan-coil unit systems are defined to meet the cooling and heating loads of the zones. The perimeter zones have a combination of floor radiant and fan-coil units, whereas core zones are served with fan-coil units only. The radiant system is modeled within the zone as a radiant panel that is massive and behaves as a floor surface and therefore approximates the performance of a hydronic radiant slab. Fan-coil units are defined to have heating and cooling coils, and the specifications were defined as proposed by the final construction drawings.

Table 4
Heating and cooling set point and set back temperatures for weekdays and weekends.

Time	Weekdays		Weekends	
	Heating (°C)	Cooling (°C)	Heating (°C)	Cooling (°C)
Set point 06:30 a.m.–10:30 p.m.	21.1	23.8	18.3	26.6
Set back 10:30 p.m.–06:30 a.m.	18.3	26.6	18.3	26.6

3.5.2. EnergyPlus model

Modeling of a complex HVAC system is more challenging in EnergyPlus than in IES and in particular when thermal zones are served by more than one system (e.g., fan-coil units and radiant system). In this case, HVAC templates in EnergyPlus cannot be used and to present a system each component must be created individually using the IDF Editor and connected to other components using the node system. This

Table 3
Zones' types, their sensible gains, power consumption and period of operation.

Zone type	Sensible heat gain (kW)	Power consumption (kW)	Operation period (h)
Data rooms	20	54	24 (every day)
BME Lab	9.7	51.9	1 (weekdays only)
Spray Paint Booth	0.35	4.8	1 (weekdays only)
Mech/Elect Room	9	9	24 (every day)
Welding Shop	0.23	64	0.5 (weekdays only)
Electric Vehicles Lab	1.2	229.1	1 (weekdays only)

approach increases the flexibility of the BPS tool and allows modeling of more complex and diverse HVAC systems. However, it also increases modeling efforts as well as the need for knowledge of each HVAC system component and its connection with other equipment. Therefore, several hot and chilled water loops were defined to supply the radiant floor systems and coils with hot and chilled water. The DOAS was modeled to deliver 100% outdoor air through VAV units, which were modeled using the AirTerminal: SingleDuct:VAV: NoReheat object [52]. To model the energy-recovery ventilator (ERV), the air-to-air heat exchanger object HeatExchanger: AirToAir:SensibleAndLatent was added to the air loop of DOAS [52]. Heating and cooling coils were defined as a part of DOAS to maintain a temperature of 12.8 °C. The hydronic radiant system in EnergyPlus was modeled by defining internal source construction and by creating the low-temperature variable flow radiant using ZoneHVAC: LowTemperatureRadiant:VariableFlow object [52]. The radiant floor system is connected to a separate water loop because the supplied chilled and hot water temperatures differ between the coils that serve radiant floor heating and those that serve the fan-coil units, AHU and ERV. The ZoneHVAC: FourPipeFanCoil object was used to model fan-coil units with recirculation fans at a constant speed [52].

4. Results and discussion

To compare EnergyPlus and IES capabilities to simulate different model complexities that are often used in the building's design process, three models of the university building are developed in each BPS tool according to three scenarios: free-floating, ideal load air system, and detailed.

4.1. Free-floating scenario

Free-floating building model does not have defined heating and cooling systems or internal heat gains. As a result, internal environmental conditions depend only on the envelope performance and outside weather changes. ASHRAE 90.1 performs free-floating analysis as a basic test to compare the performance of energy modeling tools regarding temperature calculation [56]. Furthermore, the free-floating analysis is a useful method to investigate passive solar solutions and technologies (e.g., shading, window types, and façade systems) as well as to test different heating and cooling systems in the early stage of the building design. The created EnergyPlus and IES free-floating models of the SPEB have an infiltration rate of $0.25\,\mathrm{l/s\,m^2}$ to comply with the National Energy Code of Canada for Buildings NECB 2011 [57] and ASHRAE 90.1 performance paths [56].

Pearson correlation coefficient, which ranges from + 1 (perfect positive correlation) over 0 (no correlation) to − 1 (perfect negative correlation), indicates a high positive linear correlation between the models' hourly predictions, ranging from 0.995 for the basement to 0.998 for the other three floors. Furthermore, Fig. 5 presents a comparison of the daily average floor air temperatures between the EnergyPlus model and IES model, whereas Fig. 6 compares the probability distributions of the hourly floor indoor air temperatures. Overall, there is a high agreement in the air temperature trends and fluctuations across the floors throughout the year, and especially for the middle floors (i.e., first and second floor). Fig. 5 indicates that the variability of the air temperatures increases with the floor level, and particularly in the EnergyPlus model. Additionally, during the winter season, the indoor air temperatures of the EnergyPlus model were higher in the basement and lower on the above-grade floors compared to the IES model. Also, the above-grade floors of the EnergyPlus model experienced higher air temperatures than those of the IES model during January and February as well as over the spring and summer (i.e., April to August). Furthermore, the probability distributions, illustrated in Fig. 6, show that the above-grade floors of the EnergyPlus model exhibited greater dispersion of the average floor air temperatures than the above-grade floors of the IES model, and especially the top floor.

Table 5 summarizes descriptive statistics for the floor average indoor air, outdoor air and ground temperatures. The standard deviation confirms the previous findings and demonstrates that variability of the basement temperatures of the EnergyPlus model is comparable to the ground temperature variability and lower than the variability of the basement temperatures of the IES model. Moreover, the standard deviation of the EnergyPlus model increases with floor level, whereas it is almost the same for the second and top floor in the IES model. The minimum and maximum temperatures also suggest that the changes in the boundary conditions govern more the calculation of the indoor air temperatures in the EnergyPlus model than the IES model. Table 5 also indicates that the mean air temperature differences were within 1.0 °C for all floors, except for the basement (~1.5 °C). Furthermore, the differences between the minimum air temperatures of the middle floors were within 1.0 °C, while for the basement and third floor they were 4.95 °C and 2.31 °C, respectively. Similarly, the differences between the maximum air temperatures of the middle floors were within 1.5 °C, whereas for the top floor and the basement they were 3.2 °C and 2.33 °C, respectively. Because of the high heating and cooling loads of the top floor, it is very likely that the related differences between the EnergyPlus and IES models will have a higher impact on the energy predictions than the temperature discrepancies of the basement.

Fig. 7 and Table 6 provide further insights into discrepancies between the indoor air temperatures predicted by the two models. Thus, Fig. 7 illustrates the floor monthly average air temperature differences between the EnergyPlus model and the IES model throughout the year. Additionally, Table 6 presents the percentage of time the EnergyPlus model over- or under-predicted the hourly floor indoor air temperatures throughout the seasons compared to the IES model. Approximately 70% of the time, the EnergyPlus model predicted higher indoor air temperatures than the IES model and the temperature differences between the two models vary across the floors (see Table 6). For example, the differences between the monthly average air temperatures of the EnergyPlus and IES models were the smallest on the second and third floors, as 77% and 50% of the time, respectively, they were within 1.0 °C. On the other hand, the differences between the monthly average air temperatures of the EnergyPlus and IES models were the largest on the top floor and the basement, since 77% and 65% of the time, respectively, they were between 1.0 °C and 3.0 °C. Furthermore, Fig. 7 and Table 6 show that the basement in the EnergyPlus model had higher temperatures in the winter than in the basement of the IES model, whereas other floors had higher temperatures in the summer. Additionally, 70–100% of the time during the winter the differences were within 1.0 °C for all floors, except for the basement (9%), whereas in the summer it was vice versa. Approximately 30% of the time, the EnergyPlus model predicted lower indoor air temperatures than the IES model, and 100% of the time, for all floors, except for the basement (4%), this was during the winter months. Furthermore, around two-thirds of the time when the EnergyPlus model under-predicted indoor air temperatures, the temperature differences between the two models were within 1.0 °C, for all floors, except for the top floor (34%).

The likely reason for differences between the models' predictions is the use of different algorithms in the EnergyPlus and IES software to calculate the heat transfer through the building envelope. Even though both programs apply the Heat Balance Model [58,59], which assumes a well-stirred air in the thermal zone [60], they implement different algorithms for applying the same method. As a result, it was not possible to have completely equivalent inputs for the EnergyPlus and IES model. For example, since IES uses a finite difference approach to calculate conduction through the walls, a conduction finite difference solution algorithm [59] has been selected in the EnergyPlus model. However, it was not possible to specify the same algorithm for the calculation of convective heat exchange between the exterior building surface and the external environment, which can have a significant impact on the models' predictions and can be 3–4 times higher than the long-wave radiative heat exchange [61]. In IES, only McAdams algorithm [59] is

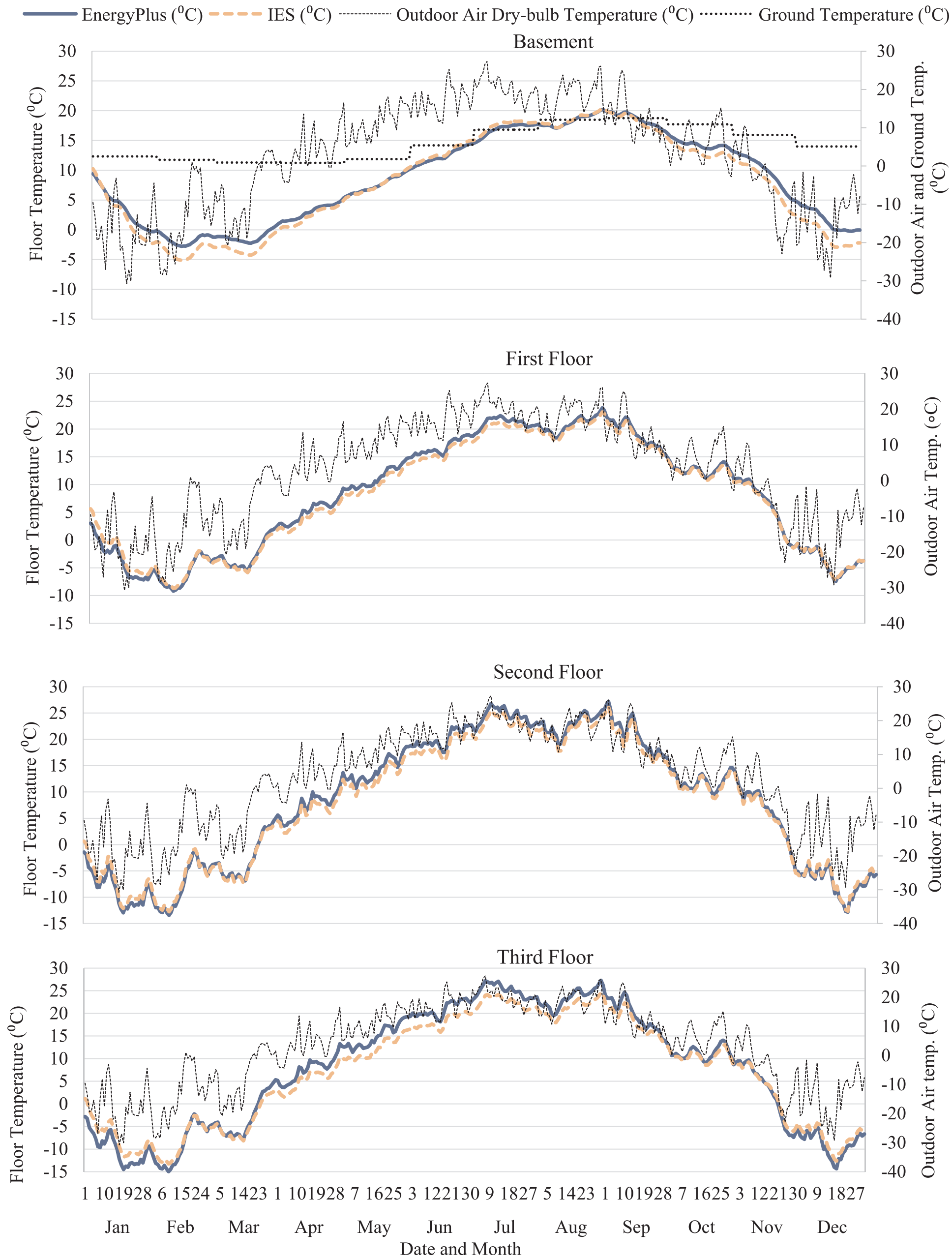


Fig. 5. EnergyPlus and IES daily average indoor air temperatures over a year by floor.

used to calculate the external convective heat transfer coefficient. EnergyPlus offers more flexibility in this respect as several different algorithms can be used, but none of them is identical to the McAdams model [58]. Considering the roughness of the building surfaces (see Table 1), the assigned model in the EnergyPlus model is DOE-2 [62], which is a combination of the MoWiTT model that is appropriate for smooth surfaces [63] and BLAST model that corrects for less smooth surfaces [64].

Furthermore, EnergyPlus offers multiple choices to calculate beam solar radiation entering a zone through exterior windows. However, due to the zoning approach, which included zones that have a non-convex shape (e.g., L-shape), a “FullExterior” method was used in this study [58]. IES uses SunCast module to calculate the solar gain onto specific geometric surfaces, which also accounts for the direct radiant exchange between the surfaces of the room [59]. Implementation of different algorithms to calculate solar gains might be another reason for the discrepancies in the models’ predictions. For example, EnergyPlus and IES perform different calculations to estimate incident irradiance, the solar position in the sky and the related irradiance data.

4.2. Ideal load air system scenario

The ideal load air system is an object defined to supply heating and cooling to a zone to meet any heating or cooling demand of the zone at all times with 100% efficiency. Consequently, zone air temperatures are identical to the specified set-point temperatures over occupied hours and set-back temperatures over unoccupied hours. Alongside with the free-floating, the ideal load air system is widely used to investigate geometry in the early stages of the building design, to study and test complex building materials as well as to optimize building envelope performance [52]. The ideal load air system was added to the EnergyPlus and IES free-floating models with the same set-point and set-back temperatures as defined in the detailed model (see Table 4). Table 7 shows that IES predicted 6 MWh (1.7%) higher heating loads

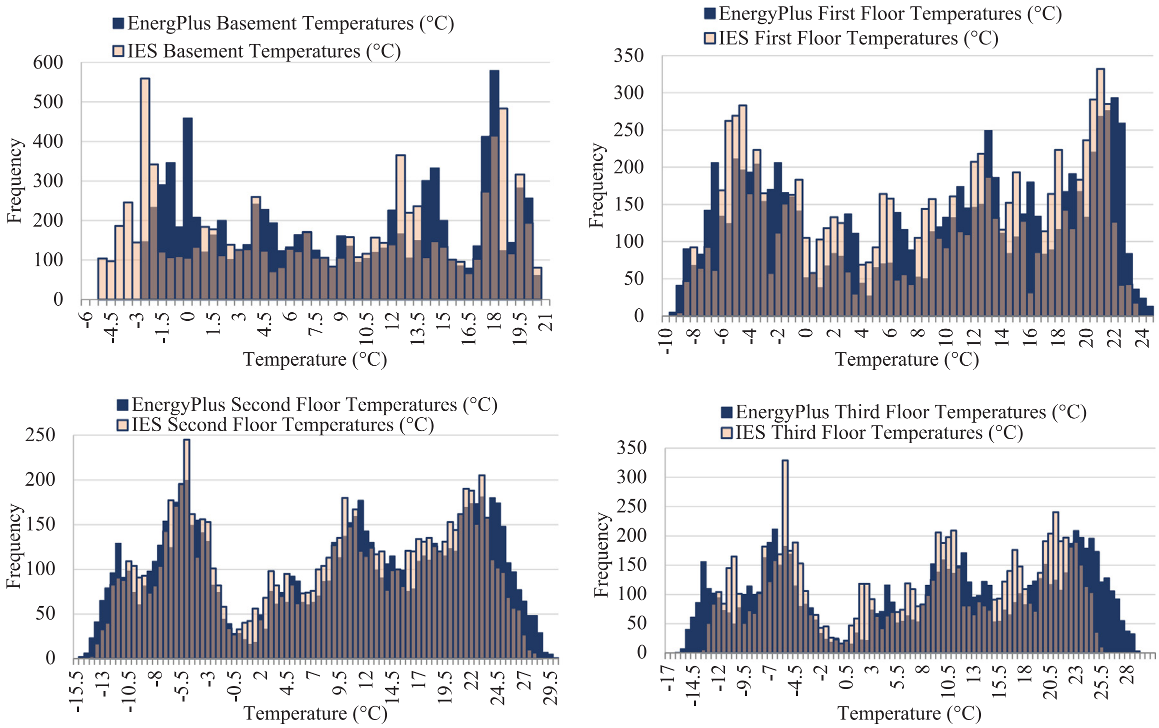


Fig. 6. EnergyPlus and IES probability distributions of the hourly indoor air temperatures by floor.

than the EnergyPlus model (335 MWh), whereas EnergyPlus calculated 0.86 MWh (7.8%) higher cooling loads than the IES model (10.2 MWh). Also, there is good agreement between the EnergyPlus and IES predictions of the average and peak loads. These differences are within the range of the Evaluation of Building Energy Analysis Computer Programs [65] test results for the EnergyPlus and IES [66] as well as published studies [27,45]. It is important to note that the very low cooling energy consumptions predicted by the two models are due to the absence of internal loads in this scenario.

Figs. 8 and 9 provide further insights into the behavior of the EnergyPlus and IES models by comparing their peak heating and cooling loads. Fig. 8 illustrates that both models calculated the peak heating load at 8 a.m. on Monday, January 18th, which with an average daily dry-bulb air temperature of − 27.1 ^{0}C is not the coldest day in the weather file. The coldest days are January 17th and 19th, with the daily average air temperatures of − 30.7 °C and − 30.0 °C, respectively. The likely explanation is the weekend set-back temperature (18.3 °C) combined with the low outdoor air temperatures in the night between Sunday and Monday (see Fig. 8), which lead to an increase in the usage of the ideal air load system. Furthermore, due to the significantly higher (~50–60%), solar irradiance levels the EnergyPlus and IES models had lower total heating demand on the January 17th and 19th than on the January 18th (see Fig. 8). Fig. 8 also indicates that over the weekend (January 16th and 17th) there is excellent accordance between the heating loads of the EnergyPlus and IES models, whereas the slight over-prediction of the EnergyPlus model might be related to the under-prediction of the indoor air temperatures presented in the free-floating scenario. The difference between the heating loads occurred at 6:30 a.m. on January 18th when the weekend set-back temperature (18.3 °C) changed to weekday set-point temperature (21.1 °C), and the IES model consumed 8.8% more energy than the EnergyPlus model to increase the indoor air temperature for 2.8 °C.

Fig. 9 illustrates that EnergyPlus model calculated the peak cooling load (38.2 KWh) at 3 p.m. on August 30th and the IES model calculated the peak cooling load (42.1 KWh) at 7 p.m. on July 5th. These results are not surprising considering that the calculations of peak cooling are more complicated than peak heating load calculations because peak cooling load occurs during the daytime when solar radiation is present, whereas the peak heating load typically occurs before sunrise. Consequently, the implementation of different algorithms to calculate solar gains might be the reason for the differences in the calculation of the peak cooling loads. Moreover, the EnergyPlus model predicted approximately 10% higher total cooling energy demand on August 30th (400 KWh) than on July 5th (360 KWh) and around 2% higher peak cooling load, whereas the IES model had almost the same total cooling loads on July 5th (378 KWh) and August 30th (377 KWh) and around 10% higher than the peak cooling load on July 5th. The analysis of the weather conditions showed that August 30th has significantly lower daily average solar radiation (314 W/m^2) than July 5th (520 W/m^2) but around 2.0 °C higher daily average air temperature. Similar to the results of the free-floating scenario, these findings suggest that the EnergyPlus model is more sensitive to the changes in outdoor air

Table 5
Descriptive statistics for floor temperatures, outdoor air temperatures and ground temperatures.

Temperature (°C)	Outdoor air temperature	Ground temperature	Basement		First Floor		Second Floor		Third Floor	
			E +	IES	E +	IES	E +	IES	E +	IES
Mean	2.78	5.90	9.36	7.87	8.17	7.79	8.25	7.68	7.90	7.03
SD	15.1	4.5	5.9	8.1	10.1	9.7	12.4	11.7	13.1	11.6
Minimum	− 34.59	0.80	− 0.27	− 5.22	− 9.69	− 9.16	− 15.17	− 14.23	− 16.08	− 13.77
Maximum	35.60	12.50	18.10	20.43	24.36	23.47	29.56	28.14	28.59	25.39

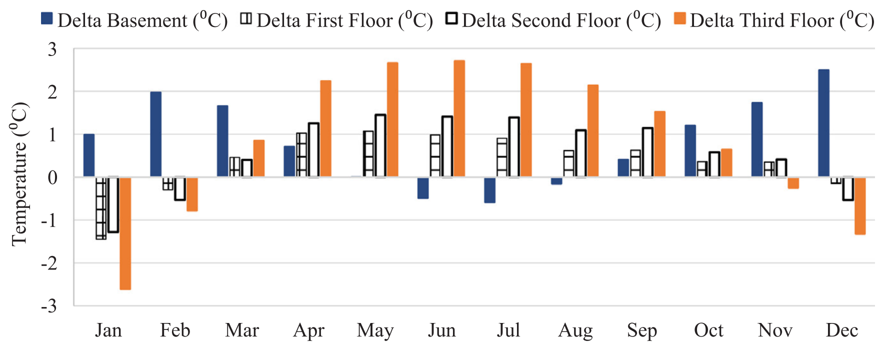


Fig. 7. Monthly average air temperature differences between the EnergyPlus and IES by floor.

Table 6
Percentage of time EnergyPlus over- and under-predicted indoor air temperatures compared to IES.

EnergyPlus	Basement %	First Floor %	Second Floor %	Third Floor %
Over-predicts total	**70**	**78**	**74**	**70**
≤ 1 °C	35	77	50	23
1 °C – 2 °C	43	23	40	50
≥ 2 °C	22	0	10	27
Winter months	*69*	*36*	*32*	*28*
≤ 1 °C	9	100	85	70
1 °C – 2 °C	59	0	15	26
≥ 2 °C	32	0	17	4
Summer months	*31*	*64*	*68*	*72*
≤ 1 °C	93	65	35	4
1 °C – 2 °C	7	35	54	30
≥ 2 °C	0	0	11	66
Under-predicts total	**30**	**22**	**26**	**30**
≤ 1 °C	100	67	68	34
1 °C – 2 °C	0	27	30	40
≥ 2 °C	0	6	2	26
Winter months	*4*	*100*	*100*	*100*
≤ 1 °C	100	67	68	34
1 °C – 2 °C	0	27	30	40
≥ 2 °C	0	6	2	26
Summer months	*96*	*0*	*0*	*0*
≤ 1 °C	100	0	0	0
1 °C – 2 °C	0	0	0	0
≥ 2 °C	0	0	0	0

Table 7
Percent of time EnergyPlus model over- and under-predicted indoor air temperatures.

Energy demand (kWh)	EnergyPlus	IES
Heating total	**335×10^3**	**341×10^3**
Average	38	39
Minimum	0	0
Maximum	200	205
Cooling total	**11.06×10^3**	**10.2×10^3**
Average	1.2	1.2
Minimum	0	0
Maximum	38.2	42.1

temperatures compared to the IES model. On the other hand, the changes in solar radiation seem to have a significant impact on the calculations of the peak cooling load in the IES model.

Fig. 10 compares the total floor heating and cooling loads of the EnergyPlus and IES models and shows very good accordance between the models' predictions. Moreover, while it is expected that the top floor has higher cooling and heating loads compared to other levels, it is not the case in this study due to the conditioning of the heavily glazed link bridge on the north side of the second floor (see Fig. 1).

Figs. 11 and 12 compare models' monthly floor heating and cooling load predictions, respectively. There is a consistency between these findings and the results of the free-floating scenario. For example, Fig. 11 illustrates that in the winter months (December, January, and February), the second and third floors of the EnergyPlus model had higher heating loads than second and third floors of the IES model. Considering that during these months the free-floating EnergyPlus model predicted lower air temperatures than the IES model (see Fig. 5), it required more energy than the IES model to meet the set-point temperatures. Furthermore, Fig. 11 demonstrates that the heating energy demand is present during most of the year. Having in mind that the free-floating EnergyPlus model calculated higher indoor air temperatures for all floors, but the basement, during all months except December, January, and February (see Fig. 7), this resulted in the 6 MWh over-prediction of the total heating energy demand of the IES model compared to the EnergyPlus model. Over the summer, the EnergyPlus model calculated higher cooling energy loads than the IES model. A possible explanation for this finding is higher air temperatures for all floors, except the basement, of the free-floating EnergyPlus model (see Figs. 5 and 7).

4.3. Detailed scenario

This section compares and discusses the EnergyPlus and IES model developed according to the final construction drawings. Fig. 13 shows that the discrepancy between the total energy consumption is less than 2.1%, whereas the percentage differences between the annual heating, cooling, lighting and plug-load predictions are around 0.7%, 7.6%, 0.6%, and 0.13%, respectively. Furthermore, the Energy Use Intensity (EUI), which expresses energy use as a function of the building size (kWh/m^2/year), shows that EnergyPlus model's EUI of 386 kWh/m^2/year is approximately 1.8% lower than IES model's EUI of 393 kWh/m^2/year. Additionally, Table 8 compares the mean, maximum, minimum and standard deviation of the heating and cooling energy consumption between the two models. There is a very good agreement between the EnergyPlus and IES models' aggregated energy predictions, and in particular in comparison to several similar studies. For example, Abdullah et al. [28] reported a difference of 36% between the EUIs' of 4740 m^2 university building modeled in Vasari/GBS (505 kWh/m^2) and Sefaira (324 kWh/m^2) software. Another study modeled an institutional building under three different climates using eQuest, DesignBuilder, and Vasari and reported discrepancies in the electricity consumption between 3% and 24% [29]. Andolsun et al. [30] compared EnergyPlus and DOE-2.1E using several case studies that ranged from a sealed box to a detailed residential building and demonstrated that EnergyPlus under-estimated total building loads by around 17% compared to DOE-2.1E. Waddell et al. [31] developed a single-zone model in eQuest, IES, TRACE700, and EnergyPlus to compare cooling load calculations and reported discrepancies between 22% and 67%, whereas the difference between EnergyPlus and IES was around 40%.

Fig. 14 shows that similar to the results of the ideal air load

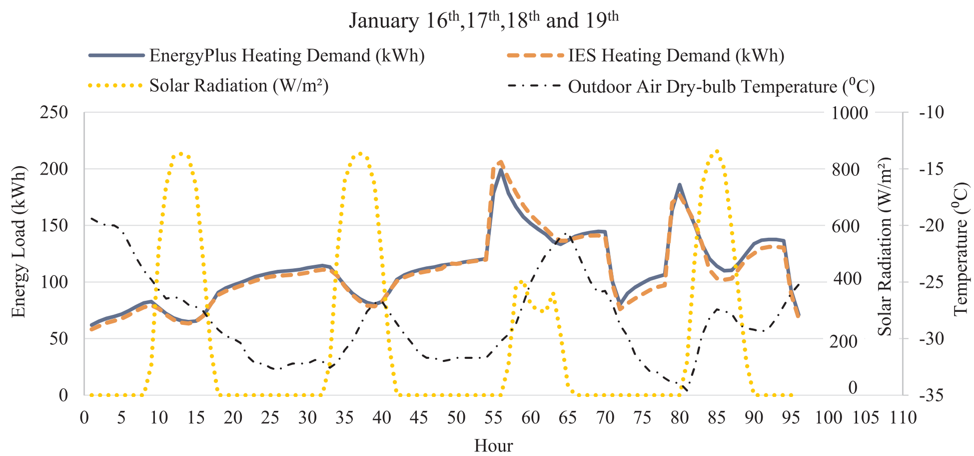


Fig. 8. EnergyPlus and IES hourly heating energy loads on January 16th, 17th, 18th, and 19th.

scenario, better accordance exists between the models' heating than cooling energy consumption profiles. For cooling energy consumption, the difference between the EnergyPlus and IES model predictions is particularly pronounced during the summer months. Considering that the cooling load calculations are inherently more complicated as they involve solving unsteady equations with unsteady boundary conditions and internal heat sources, a more significant discrepancy between the models' predictions are anticipative. Furthermore, these findings are in agreement with the results of some previous studies, which also reported higher discrepancies for cooling than heating energy consumption. For instance, Schwartz, and Raslan [26] modeled a 32-story student residential hall, located in London, UK in EnergyPlus and IES and showed that EnergyPlus predicted around 21% lower heating energy consumption and more than four times higher cooling energy consumption. Zhu et al. [27] compared building thermal load modeling capabilities and simulation results of EnergyPlus, DeST, and DOE-2.1E and concluded that the difference between annual cooling loads was around 35%, whereas the annual heating loads from DOE-2.1E were about 20% lower than those from EnergyPlus or DeST.

Fig. 15 illustrates the total monthly heating and cooling energy consumption of the EnergyPlus and IES models along with their average indoor air temperatures during an occupied (06:30 a.m.-10:30 p.m.) and unoccupied (10:30 p.m.-06:30 a.m.) hours over the year. During the occupied winter hours, the EnergyPlus model calculated higher heating and lower cooling energy consumptions than the IES model, whereas during the unoccupied winter hours the IES model predicted higher heating energy consumptions that the EnergyPlus model, whereas the cooling energy consumptions were almost equal between the two models. Furthermore, during the occupied summer hours the IES model calculated higher cooling energy consumptions compared to the EnergyPlus model. Fig. 15 also shows that the EnergyPlus model predicted 0.65 °C (November) to 1.2 °C (March) lower monthly average indoor air temperatures that the IES model during the unoccupied winter hours, whereas it maintained higher indoor air temperatures than the IES model during the summer months. Consequently, the tighter air temperature range of the IES model might be the reason for higher energy consumptions of the IES model compared to the EnergyPlus model. The EnergyPlus model, on the other hand, predicted higher cooling energy consumption during the shoulder seasons (i.e., March, April, September, and October). A possible reason for this might be the shoulder seasons' weather conditions, which differ from the rest of the year as they are characterized by the quick temperature changes from day to day as well as warmer and longer days with cold nights. For example, Fig. 16 shows that the EnergyPlus model consumed more cooling energy during the days with daily average outdoor air temperatures below 20 °C, whereas the IES model used more cooling energy during the days with daily average outdoor air temperatures above 20 °C.

To better illustrate the differences in the indoor air temperature variations between the models, Figs. 17 and 18 compare the indoor air temperature distributions during occupied and unoccupied hours, respectively. Additionally, Table 9 summarizes the temperatures' mean, standard deviation, minimum and maximum values, whereas Table 10 shows the percentage of time the EnergyPlus model over- and under-predicted indoor air temperatures compared to the IES model. It is evident that the indoor air temperatures of the EnergyPlus model have

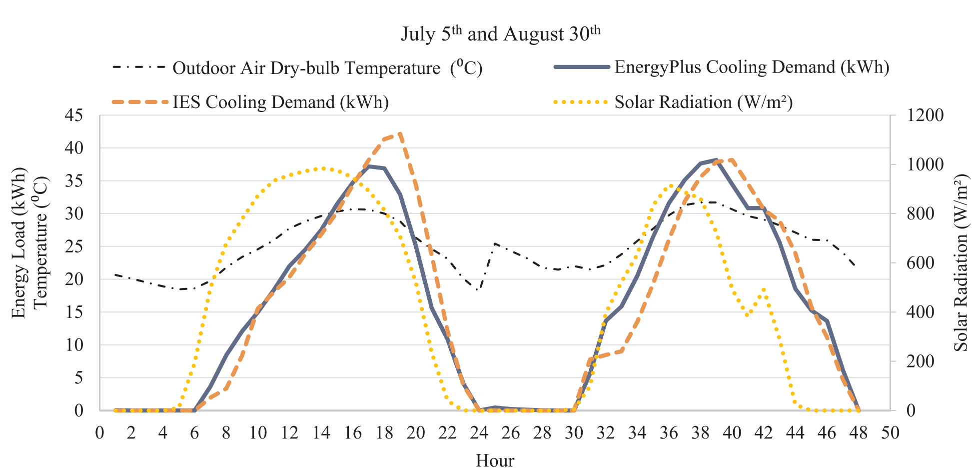


Fig. 9. EnergyPlus and IES hourly cooling energy loads on July 5th and 6th, and August 30th.

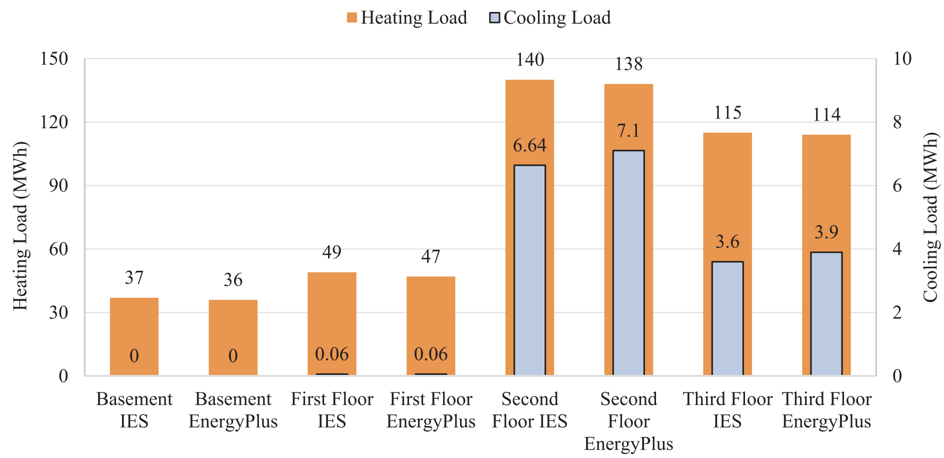


Fig. 10. EnergyPlus and IES annual heating and cooling energy consumptions by floor.

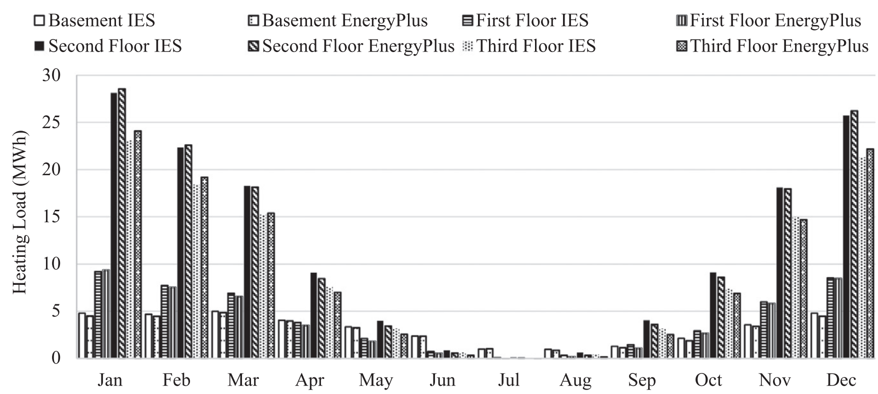


Fig. 11. EnergyPlus and IES monthly heating loads by floor.

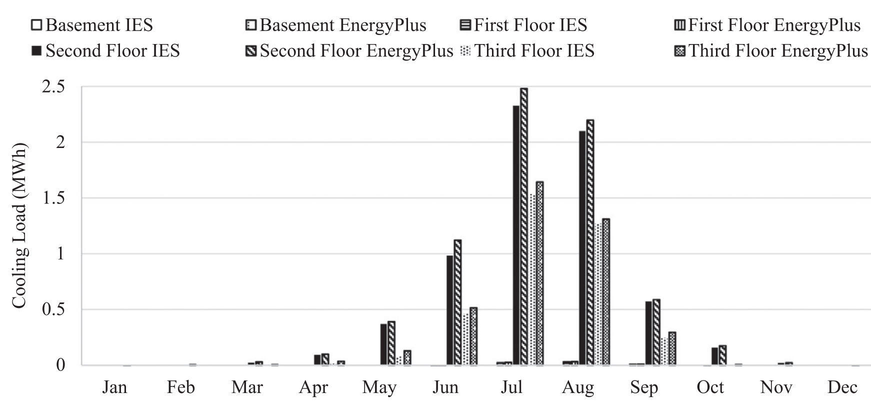


Fig. 12. EnergyPlus and IES monthly cooling loads by floor.

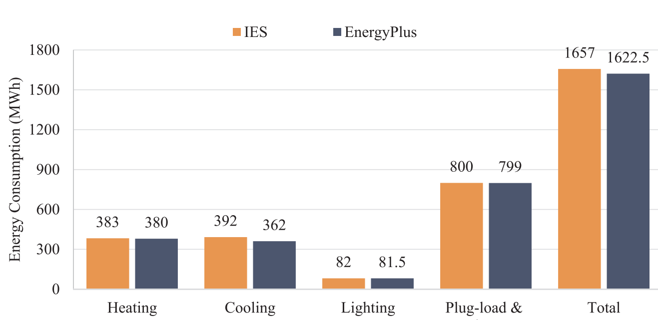


Fig. 13. EnergyPlus and IES annual energy consumptions by end-uses.

higher variability than the indoor air temperatures of the IES model across all floors. Considering the operation of the HVAC systems in reality where indoor air temperatures vary within the specified temperature range (i.e., dead-band) to improve the efficiency of the system and reduce energy consumption, the variations of the indoor air temperatures within the EnergyPlus model are expected. Similar to the results of the free-floating scenario, the largest discrepancies between the models' calculations of the indoor air temperatures exist for the below-grade and top floor. Also, in the EnergyPlus model, the standard deviation increases with floor level, whereas in the IES model it is the lowest for the top floor and basement and the highest for the first floor (see Table 9). The mean air temperature values are similar across the floors with differences ranging from 0.03 °C to 0.78 °C. The more considerable differences exist between the temperatures' minimums and

Table 8
Descriptive statistics for EnergyPlus and IES heating and cooling energy consumptions.

Energy use	Heating			Cooling		
(kW)	EnergyPlus	IES	Percentage difference (%)	EnergyPlus	IES	Percentage difference (%)
Mean	43.4	43.7	0.7	41.3	44.8	8.1
SD	47.4	40.4	15.9	36.8	36.8	0
Minimum	0	0	0	17.4	18.0	3.4
Maximum	239.7	202.8	16.7	208.9	266.3	24.2

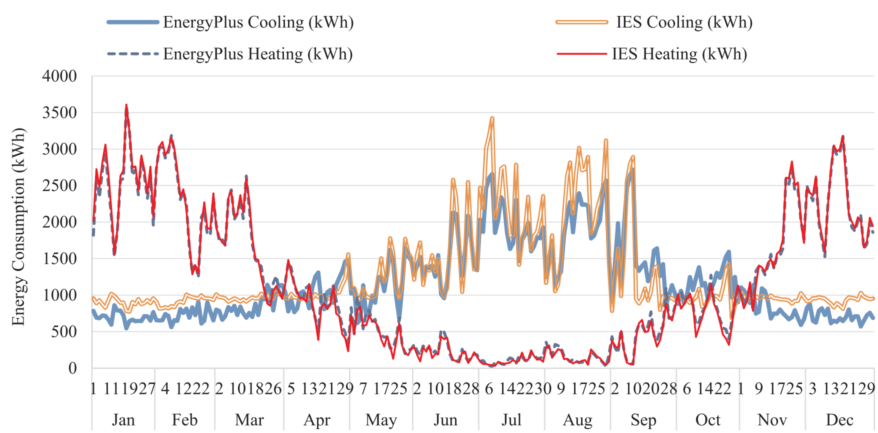


Fig. 14. EnergyPlus and IES total daily heating and cooling energy consumptions.

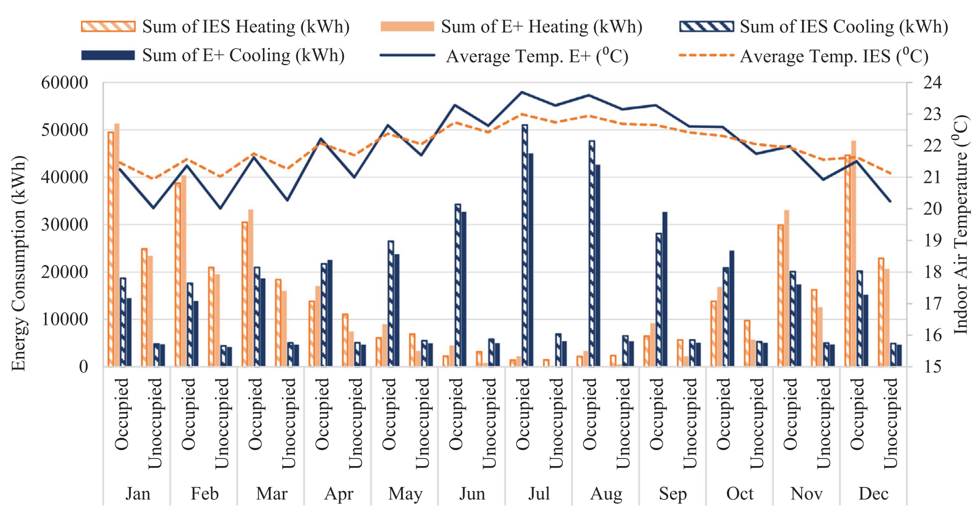


Fig. 15. EnergyPlus and IES heating and cooling energy consumptions and average monthly indoor air temperatures during the occupied and unoccupied hours throughout the year.

maximums, which range from 0.24 °C to 2.03 °C and from 1.0 °C to 2.42 °C, respectively. These results along with the previous findings further explain differences in the predictions of the energy consumptions between the two models. Furthermore, Table 10 shows that the EnergyPlus model compared to the IES model over-predicted the indoor air temperatures during the summer time and under-predicted them during the winter time. Nevertheless, in both cases, the air temperature differences were typically less or equal to 1.0 °C. It can also be seen that most of the time the basement and the first floor over-predicted the air temperatures compared to the IES model. The second and third floors show different patterns. On the one hand, the second floor over-predicted the air temperatures during the occupied hours and under-predicted them during the unoccupied hours compared to the IES model. On the other hand, the third floor under-predicted the air temperatures during both occupied and unoccupied hours compared to the IES model. Moreover, similar to the results shown in Figs. 17 and 18, the temperature differences between the EnergyPlus and IES models increases with the floor level and are higher for the second and third floors than for the basement and first floor. These results can be explained with the large glazing surface areas found on the second and third floors than the basement and first floor.

Fig. 19 illustrates the breakdown of the heating and cooling energy consumptions between the radiant system and air system for the IES and EnergyPlus models. It is evident that there are significant differences regarding the utilization of the air and radiant systems between the two models. Thus, the radiant system meets approximately 23% of the total cooling energy demand in the EnergyPlus model and only around 9% in the IES model. In heating mode, the difference in the utilization of the radiant system is less, as the radiant system covers approximately 75% of the total heating energy demand in the EnergyPlus model and around 60% in the IES model.

Fig. 20 provides further insight into the models' utilization of the

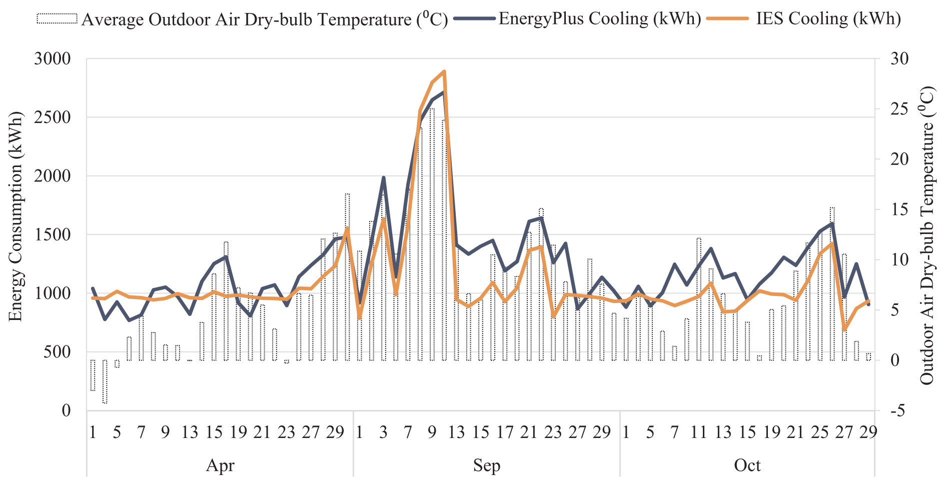


Fig. 16. EnergyPlus and IES cooling energy consumptions and outdoor air temperatures during April, September, and October.

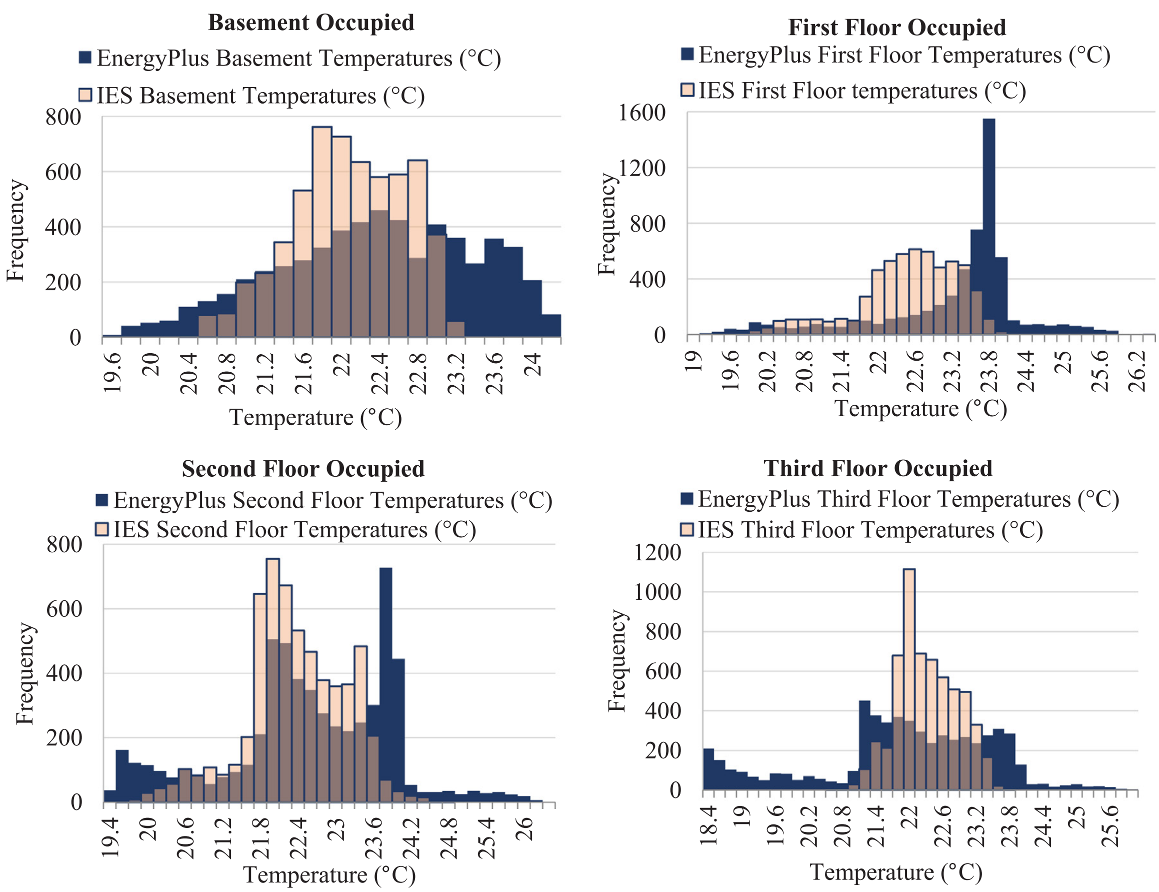


Fig. 17. EnergyPlus and IES indoor air temperature distributions during the occupied hours (06:30 a.m.-10:30 p.m.) by floor.

radiant and air systems throughout the year. It shows that the discrepancy between the utilization of the air system occurred during the summer months when the air cooling system within the IES model consumed around 26% more energy than the air cooling system within the EnergyPlus model. Furthermore, the air cooling system within the IES model consumed nearly 27% more energy during the winter season compared to the air cooling system within the EnergyPlus model. Similarly, the air heating system within the IES model consumed nearly 30% more energy during the winter season than the air heating system within the EnergyPlus model. Higher utilization of the air system in the IES model is the likely reason for the differences in the predictions of the indoor air temperatures between the models as well as smaller indoor air temperature variations in the IES model compared to the EnergyPlus model. Furthermore, Fig. 20 also shows that the EnergyPlus model on average maintained lower indoor air temperatures during the winter season and higher indoor air temperatures during the summer season than the IES model, which is the likely reason for the higher heating and cooling energy consumptions of the IES model compared to the EnergyPlus model.

Figs. 21 and 22 compare the models' peak heating and cooling loads, respectively. As in the ideal air load scenario, both models calculated the peak heating loads at 8 a.m. on January 18th (see Fig. 21). On the other hand, the IES model calculated the peak cooling load at 12 p.m. on August 17th, while the EnergyPlus model calculated the

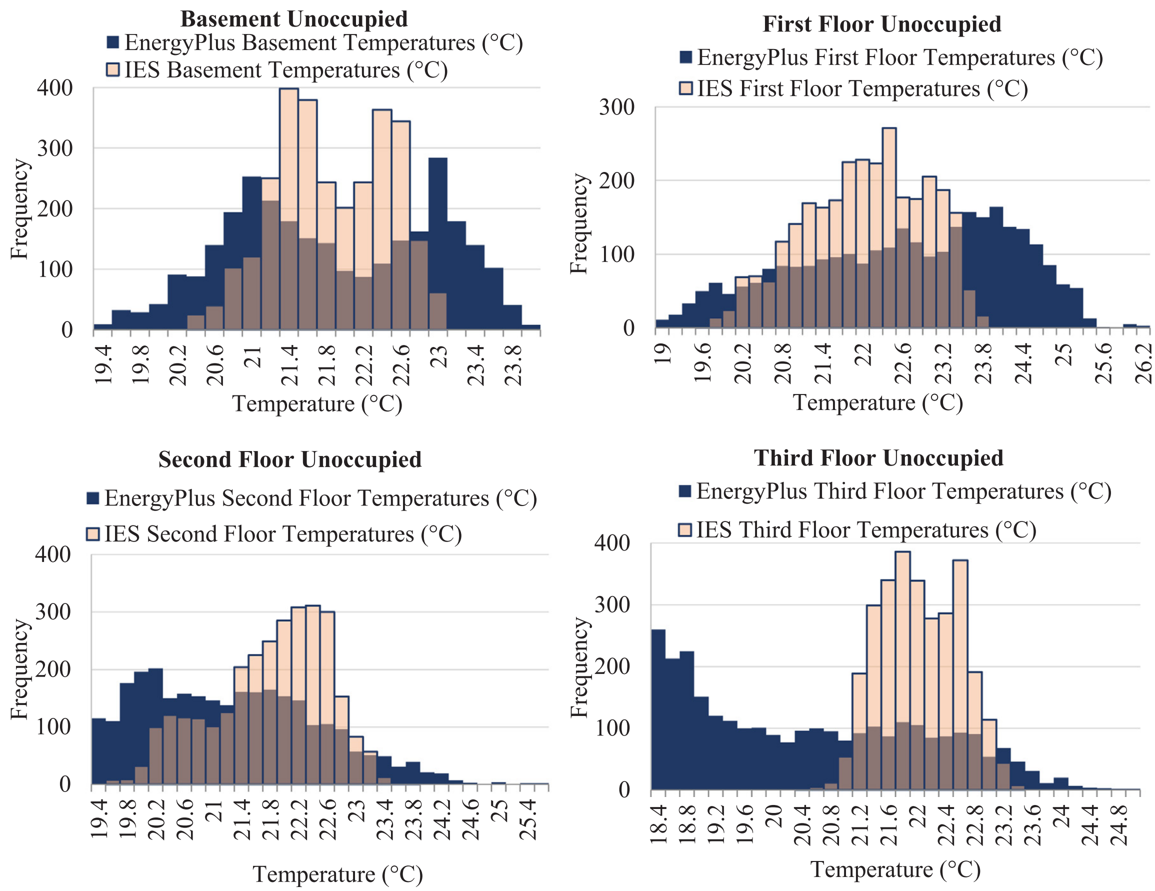


Fig. 18. EnergyPlus and IES indoor air temperature distributions during the unoccupied hours (10:30 p.m.-07:30 a.m.) by floor.

Table 9
Descriptive statistics for EnergyPlus and IES indoor air temperatures by floor.

Temperature	Basement		First floor		Second floor		Third floor	
(°C)	EnergyPlus	IES	EnergyPlus	IES	EnergyPlus	IES	EnergyPlus	IES
Mean	22.10	21.91	22.95	22.23	22.04	22.07	21.33	22.12
SD	1.08	0.60	1.37	0.88	1.44	0.84	1.73	0.56
Minimum	19.34	20.25	18.89	19.58	19.21	19.45	18.29	20.33
Maximum	24.19	23.19	26.37	23.95	26.15	24.67	25.88	23.61

peak cooling load at 17 p.m. on September 10th (see Fig. 22). As in the previous results, Fig. 21 demonstrates that the EnergyPlus model relied more on the radiant system, which has a slow thermal response time, whereas the IES model mostly used the fast response air system to meet the building's heating demand. Fig. 22 shows a similar behavior of the two models in cooling mode. Consequently, the energy profiles of the two models have different peaks and valleys as the IES model maintained the indoor air temperatures within the tighter range compared to the EnergyPlus model.

The disparity between the energy consumption and operation of the models' HVAC systems are most likely related to some differences in the modeling approach. For instance, in the IES model, the air system is simulated using templates, whereas in the EnergyPlus model the air and radiant systems are built from the individual components (e.g., each coil of the fan-coil units is defined individually). Consequently, it was not possible to model the same controls. For example, in the EnergyPlus model the sequencing of the HVAC equipment is applied on the zone level (e.g., radiant system or the fan-coil), while in the IES model it is implemented on the system level (e.g., hot water loops). Therefore, as per the final construction drawings, in EnergyPlus the radiant system is the first system intended to serve the load and the air system second, which might be the reason for the larger utilization of the radiant system in the EnergyPlus model compared to the IES model. There is a limited body of literature that compares predictions of building performance simulation tools on the HVAC system level and especially for complex buildings such as the SPEB. One study created an ideal building model to investigate the constant air volume and variable air volume systems of EnergyPlus, DeST, and DOE-2.1E and compared them in detail to assess their similarities and differences [45]. The study concluded that the main influencing factors for HVAC discrepancies are the algorithms used for the HVAC component models and their control strategies. Furthermore, it was also revealed that differences between the HVAC systems' energy consumption could be within a 10% range only if all component models are chosen to be similar, and the same or equivalent inputs for the HVAC systems are used and sometimes there is no way to map between the user inputs directly.

5. Conclusion

Work presented herein is the first to compare the EnergyPlus and

Table 10
Percentage of time EnergyPlus model over- and under-predicted indoor air temperatures compared to IES mode.

EnergyPlus	Basement %		First Floor %		Second Floor %		Third Floor %	
	Occupied	Unoccupied	Occupied	Unoccupied	Occupied	Unoccupied	Occupied	Unoccupied
Over-predicts total	**74**	**50**	**94**	**76**	**84**	**27**	**45**	**17**
≤ 1 °C	89	97	73	48	96	68	100	72
1 °C– 2 °C	11	3	27	46	4	30	0	24
≥ 2 °C	0	0	0	6	0	2	0	4
Winter months	*48*	*35*	*47*	*35*	*47*	*10*	*25*	*1*
≤ 1 °C	90	100	63	81	99	100	100	100
1 °C – 2 °C	10	0	37	19	1	0	0	0
≥ 2 °C	0	0	0	0	0	0	0	0
Summer months	*52*	*65*	*53*	*65*	*53*	*90*	*75*	*99*
≤ 1 °C	88	97	82	29	94	66	100	71
1 °C – 2 °C	12	3	18	61	6	32	0	25
≥ 2 °C	0	0	0	10	0	2	0	4
Under-predicts total	**26**	**50**	**6**	**24**	**16**	**73**	**54**	**83**
≤ 1 °C	100	100	100	100	85	70	84	26
1 °C – 2 °C	0	0	0	0	15	30	10	21
≥ 2 °C	0	0	0	0	0	0	6	53
Winter months	*54*	*65*	*98*	*99*	*40*	*36*	*71*	*60*
≤ 1 °C	99	99	100	100	84	64	85	8
1 °C – 2 °C	1	1	0	0	16	36	8	15
≥ 2 °C	0	0	0	0	0	0	7	77
Summer months	*46*	*35*	*2*	*1*	*60*	*64*	*29*	*40*
≤ 1°C	100	100	100	100	87	80	83	54
1 °C – 2 °C	0	0	0	0	13	20	13	31
≥ 2 °C	0	0	0	0	0	0	4	15

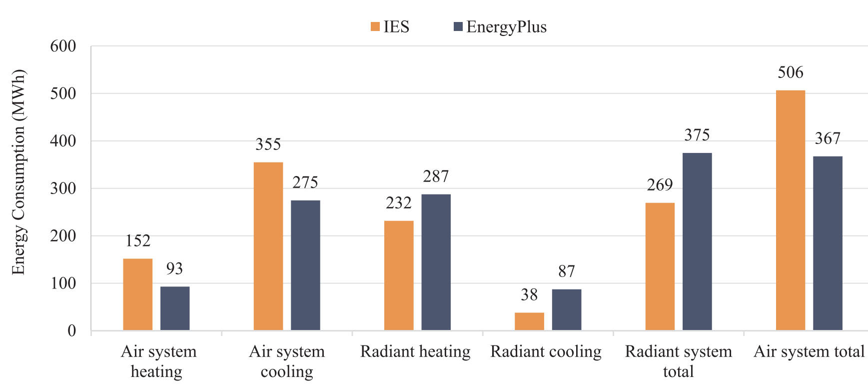


Fig. 19. EnergyPlus and IES model comparison of heating and cooling energy consumptions on the system level.

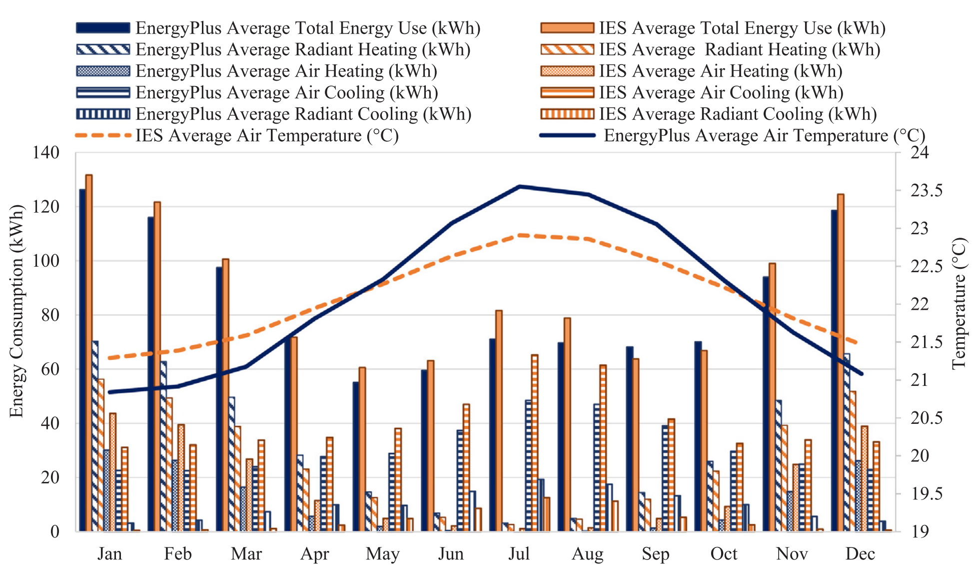


Fig. 20. EnergyPlus and IES monthly average total energy consumptions, cooling and heating energy consumptions by the system and indoor air temperatures over the year.

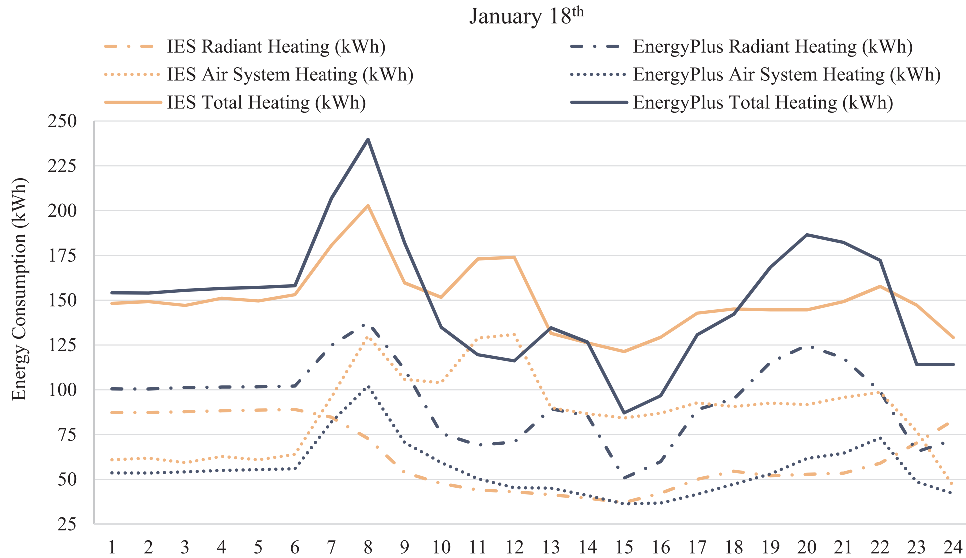


Fig. 21. EnergyPlus and IES total hourly heating energy consumptions, heating energy consumption by the system, indoor air temperatures and solar radiation on January 18th.

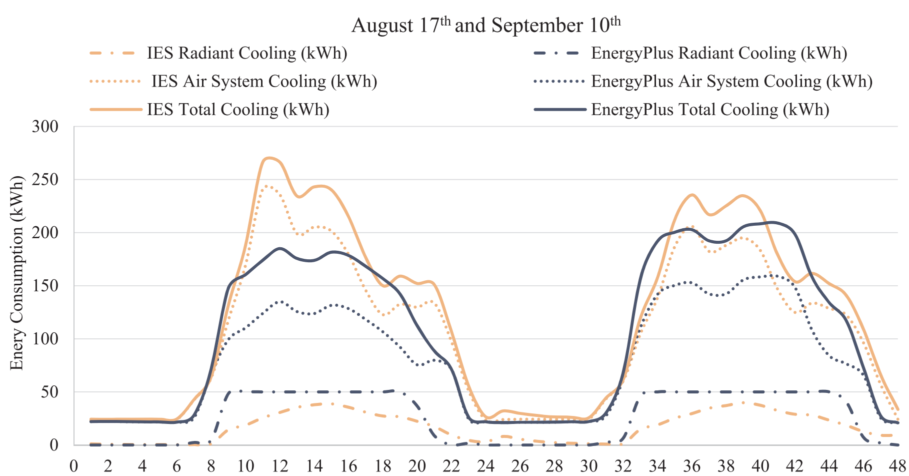


Fig. 22. EnergyPlus and IES total hourly cooling energy consumptions, cooling energy consumption by the system, indoor air temperatures, outdoor air temperatures, and solar radiation on August 17th and September 10th.

IES models of a multi-purpose university building using three scenarios: free-floating, ideal air load system, and detailed. This approach allowed a comparison of the different model complexities that are often used in the building design process. The main conclusions of this study are as follows:

I. Aggregated predictions of the EnergyPlus and IES models – The energy performance gap is one of the most discussed issues in the design community since energy modeling became an integral part of the building design process. The reliability of results from BPS tools depends on various factors such as the quality of input data [67], modeler's knowledge and competence [19], applied methods in simulation engine [44,68], and oversimplification of complex technologies [19]. Some studies reported rather large differences (i.e., ranging from 17% to 67%) between the aggregated (e.g., total energy consumption) predictions of widely used BPS tools when modeling the same building and carefully mapping the input parameters [26–31]. These findings can lead to reduced confidence in the performance and reliability of extensively used BPS tools and their suitability for application in different phases of the building design process. In particular, as it is not realistic in daily practice to produce equivalent building models using two different BPS tools to compare their results.
In contrast to the existing findings [35], which reported that EnergyPlus model predicted considerably lower (~21%) heating energy consumption and more than 4 times higher cooling energy consumption than IES model of the same building, the results from this study show that closely mapping the input parameters can lead to a very good agreement between the aggregated energy predictions of the two BPS tools. For example, the difference between the predictions of heating energy consumption between the EnergyPlus model and the IES model of the SPEB was less than 1%, whereas the difference between the predictions of cooling energy consumption was less than 10%. One possible explanation for better agreement between the EnergyPlus and IES compared to the existing findings is differences in the complexity of the case studies. For example, modeling of a mid-rise building allowed us to implement detailed thermal zoning, whereas Schwartz and Raslan [35] modeled a high-rise building that required simplification and use of the 'average floor.' Some studies have shown that zoning strategy and simplification of the model can have a significant impact on the models' energy predictions [69,70]. Another possible explanation is the use of the newer versions of EnergyPlus and IES that are becoming closer in their predictions as a result of the comparative testing

methods such as ANSI/ASHRAE Standard 140 [23] as well as other procedures designed to improve the accuracy of the BPS tools such as PASLINK Network [33]. The high consistency between the models' aggregated predictions are particularly pertinent and encouraging for certification programs such as LEED, which take into account aggregated energy consumption data in their assessments.

II. Temperature predictions of the EnergyPlus and IES models – The findings from the free-floating and detailed scenarios demonstrate the higher variability of the indoor air temperatures across the floors of the EnergyPlus model compared to the IES model. Furthermore, they indicate that the EnergyPlus model is more sensitive to the changes in the outdoor air temperatures compared to the IES model. Moreover, the results of the detailed scenario also show that unlike the EnergyPlus model, the IES model maintained indoor air temperatures within a tighter temperature range than the defined dead-band range (21.3 °C to 23.8 °C).

III. Disaggregated predictions of the EnergyPlus and IES models – It is known that issues related to the specification of advanced systems and technologies due to the level of their complexity and controls can affect model's predictions [19]. Analysis and comparison of the disaggregated results provide additional support to these findings as they show that even small dissimilarities in the modeling of the HVAC system and their controls can lead to significant differences in the energy predictions at the system level. For example, the EnergyPlus model used the radiant system approximately 28% more than the IES model, whereas the IES model relied around 27% more on the air system than the EnergyPlus model. The likely reason for the discrepancies between the models' energy predictions at the system level is the use of templates to model the air system within the IES model. Furthermore, higher utilization of the air system in the IES model is the likely reason for smaller indoor air temperature variations and higher total heating and cooling energy consumptions of the IES model compared to the EnergyPlus model. These findings emphasize the importance of the modeler's assumptions regarding the modeling of HVAC systems and their impact on the model's predictions. This is also recognized by the ASHRAE Standard 205 entitled *"Representation of Performance Simulation Data for HVAC&R and Other Facility Equipment,"* which recently concluded its first advisory public review. The developing standard will facilitate the sharing of equipment characteristics for performance simulation by defining specific data elements that represent the complete performance of equipment for use in BPS tools [71].

6. Limitations and future research

One limitation of this study is the lack of comparison of the models' predictions against the measured data since the SPEB is still under construction. Therefore, the future work will include comprehensive on-site measurements and collection of various building-related information required for the validation of the developed models. Furthermore, the findings are based only on one mid-rise LEED silver building, and it may be that modeling buildings with different complexities and characteristics would yield different results between the predictions of the EnergyPlus and IES models. For example, modeling of a small (e.g., only a few thermal zones) single-family house with a simple HVAC system is likely to result in a closer agreement between EnergyPlus and IES, whereas modeling of a high-rise LEED Platinum building might result in a larger discrepancy due to the additional complexities such as larger number of thermal zones and more complex building systems.

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References

[1] H. Chen, W.L. Lee, Energy assessment of office buildings in China using LEED 2.2 and BEAM Plus 1.1, Energy Build. 63 (2013) 129–137, https://doi.org/10.1016/j.enbuild.2013.03.031.
[2] M. Michael, L. Zhang, X. Xia, An optimal model for a building retrofit with LEED standard as reference protocol, Energy Build. 139 (2017) 22–30, https://doi.org/10.1016/j.enbuild.2017.01.006.
[3] W.L. Lee, Benchmarking energy use of building environmental assessment schemes, Energy Build. 45 (2012) 326–334, https://doi.org/10.1016/j.enbuild.2011.11.024.
[4] O. Awadh, Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis, J. Build. Eng. 11 (2017) 25–29, https://doi.org/10.1016/j.jobe.2017.03.010.
[5] R. Komurlu, D. Arditi, A.P. Gurgun, Applicability of LEED's energy and atmosphere category in three developing countries, Energy Build. 84 (2014) 690–697, https://doi.org/10.1016/j.enbuild.2014.07.095.
[6] Guy R. Newsham, Sandra Mancini, BJB, Do LEED-certified buildings save energy? Yes, but…, Energy Build. 41 (2009) 1386–1390, https://doi.org/10.1016/j.enbuild.2009.08.006.
[7] Z. Duan, X. Zhao, J. Liu, Q. Zhang, Dynamic simulation of a hybrid dew point evaporative cooler and vapour compression refrigerated system for a building using EnergyPlus, J. Build. Eng. 21 (2019) 287–301, https://doi.org/10.1016/j.jobe.2018.10.028.
[8] D.B. Jani, M. Mishra, P.K. Sahoo, Performance analysis of a solid desiccant assisted hybrid space cooling system using TRNSYS, J. Build. Eng. 19 (2018) 26–35, https://doi.org/10.1016/j.jobe.2018.04.016.
[9] W. Lv, C. Shen, X. Li, Energy efficiency of an air conditioning system coupled with a pipe- embedded wall and mechanical ventilation, J. Build. Eng. (2017), https://doi.org/10.1016/j.jobe.2017.11.010.
[10] B. Li, P. Wild, A. Rowe, Performance of a heat recovery ventilator coupled with an air-to-air heat pump for residential suites in Canadian cities, J. Build. Eng. 21 (2019) 343–354, https://doi.org/10.1016/j.jobe.2018.10.025.
[11] I. Korolija, L. Marjanovic-Halburd, Y. Zhang, V.I. Hanby, UK office buildings archetypal model as methodological approach in development of regression models for predicting building energy consumption from heating and cooling demands, Energy Build. 60 (2013) 152–162, https://doi.org/10.1016/j.enbuild.2012.12.032.
[12] A. Dutta, A. Samanta, Reducing cooling load of buildings in the tropical climate through window glazing: a model to model comparison, J. Build. Eng. (2017), https://doi.org/10.1016/j.jobe.2017.12.005.
[13] Mousa WAY, W. Lang, A. Waleed, Simulations and quantitative data analytic interpretations of indoor-outdoor temperatures in a high thermal mass structure, J. Build. Eng. (2017), https://doi.org/10.1016/j.jobe.2017.05.007.
[14] H. Sghiouri, A. Mezrhab, H. Naji, Shading devices optimization to enhance thermal comfort and energy performance of a residential building in Morocco, J. Build. Eng. (2018), https://doi.org/10.1016/j.jobe.2018.03.018.
[15] Building Energy Software Tools (BEST) Directory, a directory of information on more than 150 energy tools from around the world. U.S. Energy Department n.d. 〈https://buildingenergysoftwaretools.com/〉.
[16] E. Documentation, US Department of Energy. 〈http://dx.doi.org/10.1007/978-1-4302-3889-8_1〉, 2018.
[17] V.E. IES, Integrated environmental solutions virtual environment, 2015. 〈https://www.iesve.com/〉.
[18] D.B. Crawley, J.W. Hand, M. Kummert, B.T. Griffith, Contrasting the capabilities of building energy performance simulation programs Drury, Build. Environ. 10 (2006) 264–273, https://doi.org/10.1016/j.buildenv.2006.10.027.
[19] S. Imam, D.A. Coley, I. Walker, The building performance gap: are modellers literate? Build. Serv. Eng. Res. Technol. 38 (2017) 351–375, https://doi.org/10.1177/0143624416684641.
[20] A. Figueiredo, J. Kämpf, R. Vicente, R. Oliveira, T. Silva, Comparison between monitored and simulated data using evolutionary algorithms: reducing the performance gap in dynamic building simulation, J. Build. Eng. 17 (2018) 96–106.
[21] M.M. Salehi, B.T. Cavka, A. Frisque, D. Whitehead, W.K. Bushe, A case study: the energy performance gap of the Center for Interactive Research on Sustainability at the University of British Columbia, J. Build. Eng. 4 (2015) 127–139.
[22] P. De Wilde, The gap between predicted and measured energy performance of buildings: a framework for investigation, Autom. Constr. 41 (2014) 40–49, https://doi.org/10.1016/j.autcon.2014.02.009.
[23] C. Trust, Closing the gap–lessons learned on realising the potential of low carbon building design, 2011.
[24] B. Polly, N. Kruis, D. Roberts, Assessing and Improving the Accuracy of Energy Analysis for Residential Buildings, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2011.
[25] R. Judkoff, J. Neymark, Model validation and testing: the methodological foundation of ASHRAE standard 140, Trans. Soc. Heat. Refrig. Air Cond. Eng. 112 (2006) 367.
[26] Y. Schwartz, R. Raslan, Variations in results of building energy simulation tools, and their impact on BREEAM and LEED ratings: a case study, Energy Build. 62 (2013)

350–359, https://doi.org/10.1016/j.enbuild.2013.03.022.
[27] D. Zhu, T. Hong, D. Yan, C. Wang, A detailed loads comparison of three building energy modeling programs: EnergyPlus, DeST and DOE-2.1E, Build. Simul. 6 (2013) 323–335, https://doi.org/10.1007/s12273-013-0126-7.
[28] A. Abdullah, B. Cross, A. Aksamija, Whole building energy analysis: a comparative study of different simulation tools and applications in architectural design, ACEEE Summer Study Energy Effic. Build. (2014) 11.
[29] K. Kensek, A. Martinez, T. Tucker, Comparing Building Performance Trends in Three Energy Simulation Programs, 2010, pp. 1–8.
[30] S. Andolsun, C. Culp, A comparison of EnergyPlus to DOE-2.1 E: Multiple cases ranging from a sealed box to a residential building, 2008.
[31] C. Waddell, S. Kaserekar, Solar gain and cooling load comparison using energy modeling software, SimBuild 150AD (2010) 150–159.
[32] P.H. Baker, H.A.L. Van Dijk, PASLINK and dynamic outdoor testing of building components, Build. Environ. 43 (2008) 143–151.
[33] P.H. Baker, Evaluation of round-robin testing using the PASLINK test facilities, Build. Environ. 43 (2008) 181–188.
[34] S. Martínez, A. Erkoreka, P. Eguía, E. Granada, L. Febrero, Energy characterization of a PASLINK test cell with a gravel covered roof using a novel methodology: sensitivity analysis and Bayesian calibration, J. Build.Eng (2018).
[35] ASHRAE, 2001. ANSI/ASHRAE Standard 140-2001, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs, 2001.
[36] R. Judkoff, J. Neymark, International Energy Agency building energy simulation test (BESTEST) and diagnostic method, Natl. Renew. Energy Lab (1995) 296, https://doi.org/10.2172/90674.
[37] J. Neymark, R. Judkoff, D. Alexander, P. Strachan, A. Wijsman, IEA BESTEST multi-zone non-airflow in-depth diagnostic cases. in: Proceedings of 12th IBPSA, Sydney, 2011, pp. 14–6.
[38] E. Bellos, C. Tzivanidis, A. Kouvari, K.A. Antonopoulos, Energy Transp. Glob. Warm. (2016) 327–338, https://doi.org/10.1007/978-3-319-30127-3.
[39] S.G. Attia, A. De Herde, Early design simulation tools for net zero energy buildings: a comparison of ten tools. in: Proc Build Simul 2011 12th Conf Int Build Perform Simul Assoc, 2011, pp. 94–101.
[40] B.D.B. Crawley, C.O. Pedersen, L.K. Lawrie, F.C. Winkelmann, EnergyPlus: energy simulation program, ASHRAE J. (2000) 49–56 ⟨http://dx.doi.org/10.1.1.122.6852 ⟩.
[41] J. Yang, H. Fu, M. Qin, Evaluation of different thermal models in energyplus for calculating moisture effects on building energy consumption in different climate conditions, Procedia Eng. 121 (2015) 1635–1641, https://doi.org/10.1016/j.proeng.2015.09.194.
[42] N. Mostafavi, M. Farzinmoghadam, S. Hoque, Envelope retrofit analysis using eQUEST, IESVE Revit Plug-in and Green Building Studio: a university dormitory case study, Int. J. Sustain Energy 34 (2015) 594–613, https://doi.org/10.1080/14786451.2013.848207.
[43] A.H. Neto, F.A.S. Fiorelli, Comparison between detailed model simulation and artificial neural network for forecasting building energy consumption, Energy Build. 40 (2008) 2169–2176, https://doi.org/10.1016/j.enbuild.2008.06.013.
[44] J.H. Choi, Investigation of the correlation of building energy use intensity estimated by six building performance simulation tools, Energy Build. 147 (2017) 14–26, https://doi.org/10.1016/j.enbuild.2017.04.078.
[45] X. Zhou, T. Hong, D. Yan, Comparison of HVAC system modeling in EnergyPlus, DeST and DOE-2.1E, Build. Simul. 7 (2014) 21–33, https://doi.org/10.1007/s12273-013-0150-7.
[46] Google map. n.d. doi:⟨http://www.google.ca/maps⟩.
[47] UM Today n.d. doi:⟨http://news.umanitoba.ca/federal-and-provincial-governments-pledge-36m-to-renew-infrastructure-at-university-of-manitoba/⟩.
[48] Natural resources Canada, doi:⟨https://www.nrcan.gc.ca/home⟩, 2014.
[49] ASHRAE (American Society of Heating R and A-CE). Energy standard for buildings except low-rise residential buildings. ASHRAE Stand 901-2010.
[50] Manitoba Energy Code for Buildings (MECB). home page: ⟨http://www.firecomm.gov.mb.ca/codes_energy.html⟩.
[51] N. Simões, J. Prata, A. Tadeu, Contribution of linear thermal bridges to the overall thermal performance of the building envelope: dynamic analysis, Eco-Archit. V. Harmon Archit. Nat. 142 (2014) 321.
[52] EnergyPlus, Input output reference. The encyclopedic reference to EnergyPlus input and output, US Dep. Energy (2018) (n.d.), ⟨https://energyplus.net/sites/default/files/pdfs/pdfs_v8.3.0/InputOutputReference.pdf⟩.
[53] R. Ward, R. Choudhary, Y. Heo, A. Rysanek, Exploring the impact of different parameterisations of occupant-related internal loads in building energy simulation, Energy Build. 123 (2016) 92–105, https://doi.org/10.1016/j.enbuild.2016.04.050.
[54] A.F. Handbook, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc Atlanta, GA, USA, 2005.
[55] NRC Canada, National Energy Code of Canada for Building, 2015 ⟨https://www.nrc-cnrc.gc.ca/eng/publications/codes_centre/2015_national_energy_code_buildings.html⟩.
[56] ASHRAE. ANSI/ASHRAE/IES Standard 90.1-2016 – Energy Standard for Buildings Except Low-Rise Residential Buildings, n.d.
[57] Canada NRC, National Energy Code of Canada for Buildings, 2011.
[58] EnergyPlus, Engieering References. The Reference to EnergyPlus Calculations. US Department of Energy n.d. ⟨https://energyplus.net/sites/default/files/pdfs_v8.3.0/EngineeringReference.pdf⟩, 2018.
[59] IES VE . ApacheSim Calculation Methods. Integrated Environmental Solutions. ⟨http://www.iesve.com/downloads/help/Thermal/Reference/ApacheSimCalculationMethods.pdf⟩.
[60] C.O. Pedersen, D.E. Fisher, R.J. Liesen, Development of a Heat Balance Procedure for Calculating Cooling Loads, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA (United States), 1997.
[61] M. Mirsadeghi, D. Cóstola, B. Blocken, J.L.M. Hensen, Review of external convective heat transfer coefficient models in building energy simulation programs: implementation and uncertainty, Appl. Therm. Eng. 56 (2013) 134–151, https://doi.org/10.1016/j.applthermaleng.2013.03.003.
[62] LBL, Building Technologies Program, Lawrence Berkeley Laboratory, Berkeley, CA n.d, 1994.
[63] M. Yazdanian, J.H. Klems, Measurement of the exterior convective film coefficient for windows in low-rise buildings, J. Hydrol. 139 (1993) 79–96, https://doi.org/10.1149/1.2221597.
[64] G.N. Walton, Passive solar extension of the building loads analysis and system thermodynamics (BLAST) program, U. S. Army Constr. Eng. Res Lab Champaign 40 (1981) 41.
[65] ANSI/ASHRAE, Standard 140-2007—Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs, ASHRAE Inc., Tullie Circle NEAtlanta, GA, 1791, p. 30329 ⟨www.ashrae.org⟩ (n.d.).
[66] M. Gough, C. Rees, Tests performed on ApacheSim in accordance with ANSI/ASHRAE standard 140-2001, Illum. Eng. Soc. North Am. Glas (2004).
[67] A. Dodoo, U.Y.A. Tettey, L. Gustavsson, Influence of simulation assumptions and input parameters on energy balance calculations of residential buildings, Energy 120 (2017) 718–730.
[68] P. Nageler, G. Schweiger, M. Pichler, D. Brandl, T. Mach, R. Heimrath, et al., Validation of dynamic building energy simulation tools based on a real Test-Box with thermally activated building systems (TABS), Energy Build. 168 (2018) 42–55.
[69] M. Martin, N.H. Wong, D.J.C. Hii, M. Ignatius, Comparison between simplified and detailed EnergyPlus models coupled with an urban canopy model, Energy Build. 157 (2017) 116–125.
[70] Y. Chen, T. Hong, Impacts of building geometry modeling methods on the simulation results of urban building energy models, Appl. Energy 215 (2018) 717–735.
[71] N. Kruis, D. Ph, C.S. Barnaby, L. Member, B.L. Software, Reading and writing standardized HVAC performance data : an early implementation of ASHRAE standard 205P abstract, 2018, pp. 352–358.