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# Building Information Modeling/Building Energy Simulation Integration Based on Quantitative and Interpretative Interoperability Analysis

Carolina Fernandes Vaz [1], Luísa Lopes de Freitas Guilherme [2], Ana Carolina Fernandes Maciel [2], André Luis De Araujo [3], Bruno Barzellay Ferreira Da Costa [4,*] and Assed Naked Haddad [5]

[1] Faculty of Architecture, Urban Planning and Design, Federal University of Uberlândia, Uberlândia 38400-902, Brazil; carolina.vaz@ufu.br
[2] Faculty of Civil Engineering, Federal University of Uberlândia, Uberlândia 38400-902, Brazil; luisa.guilherme@ufu.br (L.L.d.F.G.); anamaciel@ufu.br (A.C.F.M.)
[3] Faculty of Architecture, Urban Planning and Design, Federal University of Uberlândia, Uberlândia 34412-122, Brazil; andre.araujo@ufu.br
[4] Polytechnic Institute, Federal University of Rio de Janeiro, Macaé 27930-560, Brazil
[5] Environmental Engineering Program, Federal University of Rio de Janeiro, Rio de Janeiro 21941-901, Brazil; assed@poli.ufrj.br
* Correspondence: bruno.barzellay@macae.ufrj.br; Tel.: +55-21-99607-7036

**Abstract:** The integration between the building information modeling (BIM) methodology and the building energy simulation (BES) can contribute to a thermo-energetic analysis since the model generated and fed into BIM is exported to simulation software. This integration, also called interoperability, is satisfactory when the information flow is carried out without the loss of essential information. Several studies point out interoperability flaws between the methodologies; however, most of them occur in low-geometry-complexity models during quantitative experiments. The purpose of this research was to analyze the BIM/BES integration based on a quantitative and interpretative interoperability analysis of two buildings with complex geometries located on the UFU Campus (library and Building 5T) in Uberlândia, Brazil. To accomplish this, two geometries of each building were modeled, detailed, and simplified to analyze the data import, workflow, and model correction in the BES software. In the case of the library, the integration of Revit with DesignBuilder and IES-VE was analyzed, and in Block 5T, Revit was used with DesignBuilder and eQUEST. The BES software that presented the best integration with Revit for complex geometries was DesignBuilder, with the best performance being in the interpretative criteria. It was concluded that the simplification of complex geometries is essential for better data transfers. To determine the BES software that has better integration with BIM, a comprehensive evaluation is necessary, considering not only data transfers but also ease of working within BES software, the possibility of corrections in these, as well as the availability of tutorials and developer support.

**Keywords:** building information modeling; building energy simulation; BIM/BES integration; interoperability; thermo-energetic analysis; computer simulation; complex geometries



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## 1. Introduction

Building information modeling (BIM) emerged as a revolutionary technology in the AEC (Architecture, Engineering, and Construction) industry and is characterized by its ability to parameterize models, transfer information, and interconnect projects from various disciplines. With BIM, it is possible to model high-precision geometry and store essential parameters for thermal energy analysis, including lighting, natural ventilation, and HVAC (Heating, Ventilation, and Air Conditioning) systems, facilitating the management of information throughout a building's entire life cycle [1,2].

The building energy simulation (BES) methodology enables a thermo-energetic performance analysis [3]. One way to conduct the process of data transfer within the BES software is to import an existing parameterized model; in other words, import a geometric model with building information associated with the elements [4]. Pereira et al. [5] state that, with the integration of BIM and the BES methodology, thermo-energetic analyzes are maximized, providing more reliable and detailed results. However, interoperability between software in these methodologies still represents a significant challenge for project development and remains one of the main limiting factors in expanding the use of BIM/BES in the AEC industry [6].

Interoperability can be understood as the ability to exchange, communicate, and use data between two or more applications [1]. Good interoperability exists when the flow of information occurs without obstacles and loss of essential information during data transmission between applications. Utkucu et al. [2] add that good interoperability ensures that manual interventions and repetitions are eliminated, resulting in effective energy solutions.

Gao et al. [7] argue that BES tools are still not sufficiently integrated with digital models, which means they do not benefit from the transfer of modeling information. Consequently, the data necessary for the analysis of thermal and energy performance must be manually re-entered into the BES software, making the process time-consuming

Costa and Sicília [8] classify interoperability issues at different levels, namely: syntax, structure, system, and semantic levels of information. Semantic competence refers to the software's ability to transmit data without errors. However, such competence still represents the primary interoperability obstacle, especially in thermo-energetic analyzes. As a potential solution, open standards like Industry Foundation Class (IFC) and Green Building XML (gbxml), along with plugins, were developed to convert information and facilitate communication between software from different developers. Nevertheless, even with the development of protocols, interoperability in the context of thermo-energetic simulations remains a challenge

In a previous study conducted by the authors, the interoperability between the BIM software and three different BES software applications, IES-VE, eQUEST, and DesignBuilder, was analyzed using a simplified model of a single-family house measuring 58 $m^2$. However, when dealing with complex geometries, the choice of BES software for these analyzes cannot be solely based on data transfer capabilities. To address issues that may arise from inefficient data transfers, other factors such as platform corrections, user-friendly interfaces, and technical support should also be considered.

This article aims to assess the interoperability between the BIM software and BES software for thermal energy simulations and identify the most effective integration. Although the process of exporting BIM to BES has been consistently addressed in recent literature, especially applying the OpenStudio/EnergyPlus workflow, it is already well established in academia but is not yet properly disseminated among design professionals. In this context, numerous professionals have pointed out that the use of OpenStudio/EnergyPlus is not trivial, making its application difficult outside the academic environment. In this context, the exploration of other tools is relevant, enabling the evaluation of simpler alternative routes that can be applied by project professionals to aid in decision-making. Therefore, this article aims to help fill this knowledge gap, not only by testing the efficiency of interoperability between tools but also by identifying the most suitable combination for fast and reliable analyzes, which can be performed by professionals who do not have a sophisticated level of training. To achieve this goal, a case study was conducted in two public school buildings characterized by complex geometric elements, including sheds, solar protections, and hollow elements.

*Software's Choice*

The choice for the BIM Revit software was due to it being a software with a free educational license and the BES software due to the previous study mentioned: IES-VE, eQUEST, and DesignBuilder. The results of this study showed that the programs with the best performances were IES-VE and eQUEST. However, both software faced many interoperability adversities caused by highly complex models in the chosen software. Due to the studies and tests performed on the simplified model, the expectation was that transfers would be carried out smoothly, which did not occur. Misconfiguration in the geometric modeling and the absence of constructive elements were some of the impasses found in the eQUEST and IES-VE software. Thus, a new transfer proposal for the DesignBuilder software was carried out since it was the only one in the initial study that had not yet been tested in a complex geometry.

## 2. Literature Review

In order to carry out the state-of-the-art thermal energy simulation with BIM/BES integration, searches were carried out for the most relevant articles in the field in the last five years from three platforms: Scopus, Web of Science, and Science Direct. It was noticed in the results the application of different interoperability tests and methods to solve the data transfer between BIM/BES, in addition to literature reviews on the subject. Among the most used BIM software for BIM/BES interoperability is Revit, followed by Archicad, Allplan, and Edificius [5,6] The most used BES software are Ecotec, Energyplus, GBS, IES-VE, DesignBuilder, IDA-ICE, eQUEST, TRNSYS, Riuska, and Vip-Energy [9–11].

Many researchers conducted BIM/BES interoperability tests to analyze the data transfer between them, in addition to identifying the main limitations of the software. However, a large part addresses the transfer of low-complexity geometries. Therefore, in this literature review, we aim to highlight publications that focus on the transfer of complex geometries, which are a minority in databases.

Zhao et al. [12] performed a BIM/BES interoperability test between Revit and Ecotec based on the modeling of a laboratory in China and concluded that the BIM/BES interoperability is not resolved and that Revit is limited in the insertion of a system input data HVAC. Porsani et al. [13] performed a BIM/BES interoperability test comparing two models, one simple and the other complex, and exported from Revit 2020 to the BES software with the Energyplus engine (DesignBuilder, OpenStudio, and CYPETHERM HE), with the gbxml format for DesignBuilder and OpenStudio and the IFC format for CYPETHERM HE. As a result, the authors presented tables with interoperability errors, as well as solutions for pointed errors. It was found that the BIM/BES interoperability is not solved and that the simple geometry presented fewer export errors than the complex geometry, with the solution being the correction of the model in the BES software. The material properties were not imported correctly. The authors concluded that interoperability with DesignBuilder was the most viable and with OpenStudio, the least viable. Baamer et al. [14] analyzed the BIM/BES integration based on qualitative criteria using experiments in a 449 $m^2$ residence in Saudi Arabia, using Revit and exporting to the BES software using DesignBuilder, IES-VE, GBS, and the Insight 360 plugin. Data transfers (quantitative criteria), usability, and information management (qualitative criteria) were analyzed. The authors concluded that DesignBuilder and IES-VE performed better.

Li et al. [15] performed a BIM/BES interoperability test based on the Revit modeling of a single-family residence in Edmonton, Canada, exported to GBS, and compared the simulated results with monitored ones. The authors concluded that several data were lost in this process, causing a simulation with incorrect results, inferring that interoperability is not resolved. Pan et al. [16] analyzed the efficiency of a high-rise residential building in Hong Kong through the interoperability between BIM and BES, using Revit and DesignBuilder stemming from the exportation with the gbxml format, and concluded that there was a loss of data between them. Rathnasiri et al. [17] analyzed building sustainability based on the GreenBIM method, which approaches three topics, sustainable design, BIM, and building performance, through BIM/BES interoperability (Revit 2017 and GBS) in the case study of an existing building. The authors concluded that BIM/BES interoperability is flawed. Elnabawi and Hamza [18] carried out a BIM/BES interoperability test between

Revit 2017 and DesignBuilder based on the modeling of a building in three locations, Cairo, Alexandria, and Asyu, and concluded that interoperability is not resolved, despite geometry exported correctly, the transfer of non-geometric data failed.

With the purpose of solving BIM/BES interoperability errors, some studies have presented methods, algorithms, and integration with other software. Spiridigliozzi et al. [19] filled this gap by validating the case study of a residence in Italy. The method consisted of modeling the building in BIM with the creation of a single file in IFC that was corrected in SIMPLEBIM and then exported for simulation in IDA-CE (version 4.8). Costa and Sicilia [8] presented a method that facilitates the transformation of data from native BIM formats (such as IFC) for energy analysis with fourteen data mapping patterns and three cases of data transformation, in addition to presenting a metric for this transformation through SPARQL queries. Chong et al. [20] proposed a Bayesian calibration, using Revit and Energyplus, from a digital twin that allows BIM changes to be instantly updated in the BES software. Ying and Lee [21] used the AABB representation which works as a geometric filter to fix the BIM/BES interoperability for complex geometries. The test was carried out from the modeling of a 27-story student housing and a 10-story office building. Lilis et al. [22] presented an algorithm called CBIP validated from the case study of a complex geometry at the Technical University of Crete, which, based on the IFC, correctly identified the spaces and thermal properties of the materials, in addition to displaying the solved geometry.

Some research analyzed BIM/BES workflow. Shalabi and Turkan [23] presented a study with Revit and DesignBuilder to analyze the energy efficiency and environmental comfort of a building by exporting the gbxml file generated in Revit to DesignBuilder. The authors concluded that the workflow is effective, however, adaptations to the model were necessary before the simulation. Rana et al. [24] analyze passive strategies for energy efficiency with BIM/BES workflow through the modeling of office buildings in Khulna, Bangladesh using Revit 2017 and comparisons between two BES software, eQUEST and GBS. It was concluded that the two BES software's presented similar results because they have DOE-2 as a simulation mechanism.

Other research carried out literature reviews on the subject. Sanhudo et al. [11] concluded that the most used BES software is Energyplus, followed by Ecotec, DOE-2, eQUEST, GBS, Radiance, IES-VE, and DesignBuilder, among others. In addition, they concluded that BIM/BES interoperability is complex and unresolved. Through the review by [7], the authors concluded that the BIM/BES interoperability is not resolved due to data loss, assigning five stages, geometry (stage 1), material (stage 2), spaces (step 3), thermal zones (step 4), internal heat gains (step 5) and HVAC systems (step 6), in addition to emphasizing that the importation process with IFC format guarantees step 1, while gbxml explores step 2. Andriamamonjy et al. [25] addressed the main topics on integration with BIM, and identified six main topics, with energy analysis being the least addressed topic, and concluded that interoperability is not resolved and that the workflow BIM/BES is not standardized. Pezeshki et al. [26] concluded that BIM/BES interoperability is not resolved, that the most used BES software is Energyplus, and that the biggest obstacles to the adoption of BIM in offices are cost and staff training. Al Bunni and Shayesteh [27] conducted a systematic review of the use of BIM in school retrofits and concluded that greater training is needed for the effective use of BIM for this purpose. Shehzad et al. [6] mapped the interoperability of BIM with AEC software based on the BIAM model, which analyzes four dimensions of interoperability (technical, organizational, legal, and semantic), and concluded that the four dimensions need to be improved for effective integration between BIM and other software for specific analyzes.

In order to maximize energy simulations, some authors researched plugins for analysis in BIM software. Bonomolo et al. [9] tested the EcoDesign Star plugin in Archicad with the modeling of an 18-story building and concluded that the interface is friendly and the method is effective for energy analysis, despite the plugin not considering the heating systems. El Sayary and Omar [28] presented a new plugin for energy analysis in Revit, based on Egyptian model testing. The plugin proved to be effective and won the Hassan

Fathy Award in 2011. Da Costa et al. [29] developed a model based on BIM/BES software to analyze container houses' performance using different thermal insulators. Computer simulation has proven to be effective for carrying out comparative studies, based on a standard building. Montiel-Santiago et al. [30] used BIM for energy and lighting simulation to obtain certification from the case study of a hospital building in Andalusia, using the Revit software and the Insight 360 plugin. The authors concluded that BIM is a good tool for more sustainable and certified buildings. The same strategy was used by González et al. [31], who integrated BIM/BEM to compare the effects of latitude and orientation on a hypothetical house in different locations. The methodology proved to be effective for quick assessments in the early design stages.

Some research carried out thermo-energetic simulations based on BIM/BES interoperability. Weerasuriya et al. [32] analyzed the energy efficiency of a 40-story residential building in Hong Kong to assess the potential for natural ventilation using BIM and BES interoperability, with eQUEST for energy efficiency and CFD Ansys Fluent for CFD and concluded that natural ventilation influences the energy efficiency of high-rise buildings. Tushar et al. [33] investigated the main passive strategies that influence the energy efficiency of a house in Melbourne, Australia, through the simulation of six scenarios. For this, BIM/BES interoperability with Revit 2018 and FirstRate5 was used. As a result, the authors pointed out that the concrete tile, plywood wall, and waffle floor are the components that most influence the energy efficiency of the analyzed building. Hu [34] simulated a case study of an educational building in the United States based on BIM/BES interoperability using Revit, Tally, and Sefaira, in addition to the following performance tests: reduction of $CO_2$ emissions, reduction of environmental impact, energy consumption, and improvement in indoor comfort. The authors concluded that the interoperability between the software was important for the analysis of the building's performance. Hasan and Defer [35] analyzed the energy efficiency of an office in Fell using Revit and a 3D scan for modeling and Archiwizard software for energy simulation. The authors concluded that the real building consumes more energy than the simulation.

Appendix A presents a compilation of the characteristics of the articles cited in this section that addressed case studies on the exportation of models from BIM to BES.

## 3. Materials and Methods

To achieve the main objective of this study—verification of the interoperability between BIM and BES software for thermo-energy simulations, and identifying the best integration—tests were carried out from parametric models developed in the BIM software, Revit, of two public and school buildings. Both are located at the Federal University of Uberlândia (UFU), Santa Mônica campus, Minas Gerais, Brazil, and are characterized by highly complex geometries, with elements such as solar protections (brise soleil), sheds, atriums, and mezzanines. The case study was the adopted research strategy as it allows the investigation of specific situations, that is, with a limited number of variables, but whose results can be generalized to similar cases. Considering the infinite possibilities of design and choice of materials, which directly influence the thermo-energetic performance of buildings, the use of case studies allows a detailed analysis of the influence of these characteristics in a real, or close to real, context. In this context, the use of case studies provides an understanding of the relationships between several complex variables applied to a controlled system.

Four analysis criteria were established, namely data transfer, user-friendly interface, geometry corrections, and technical support and tutorials, based on the research by [14]. The first criteria studied was the transfer of data between BIM (Revit) and the three BES software, DesignBuilder, IES-VE, and eQUEST, in which eight sub-criteria were analyzed: location, orientation, geometry, vegetation, composition of spaces and zones, building composition and materials thermal properties, internal loads and occupancy schedules, and HVAC systems.

The second analyzed criterion, user-friendly interface, refers to the ability of the software to be intuitive for its learning. The third criterion, corrections in the geometry, corresponds to the facility of BES software in supporting changes in the geometry as a way of solving possible intercurrences in the data transfer process and, finally, the last criteria, technical support and tutorials, refers to assistance offered by software developers and/or communities.

Considering the authors' previous research using BIM/BES integration, with different thematic focuses, tests with a simplified geometry were elaborated together, and through the results of those tests, the initial choice of the software that would be used was IES-VE and eQUEST. However, the researchers went through similar adversities with the programs initially chosen, so, it was decided to carry out the tests with DesignBuilder, in the objects of their research, a library and a university block of laboratories. Therefore, the applications used in this study were Revit 2022, for the parameterized modeling of the buildings, and DesignBuilder (version 7.0.2.006), IES-VE (version 2022), and eQUEST (version 3.65.7175) for thermo-energetic simulation tests.

Considering the different export options in the gbxml file, a first round of tests were performed using "building elements", "rooms/spaces elements", and "conceptual masses and building elements". These three available options allow the user to select the one that best adapts to the level of detail and complexity of the project in question. After conducting preliminary tests, and given the initial focus of the research on evaluating the efficiency in transferring complex geometries, it was found that the "building elements" option was the most appropriate. Therefore, for the present case study, where the model originated in the BIM software is an executive-level design, this option was the one that provided a cleaner export. Therefore, considering the objective of verifying the simplest transfer flow from BIM to BES, this option was adopted as the standard for the remainder of the research.

As one of the advantages pointed out in the BIM/BES interoperability is the modeling in BIM, in order to avoid rework of the BES software, two geometries were created for each building (detailed and simplified) to verify whether the simplified geometry would transfer full data, in addition to pointing out the main flaws in the transfer of detailed geometry.

### 3.1. The Study Objects

The study objects are characterized by presenting highly complex geometries with elements such as sheds, brises soleil, glazed facades, atriums, and mezzanines. The library, located on the Santa Mônica campus, has an approximate area of 5806.00 m$^2$ with three floors, namely the ground floor, first floor, and second floor, and the architectural model is shown in Figure 1.

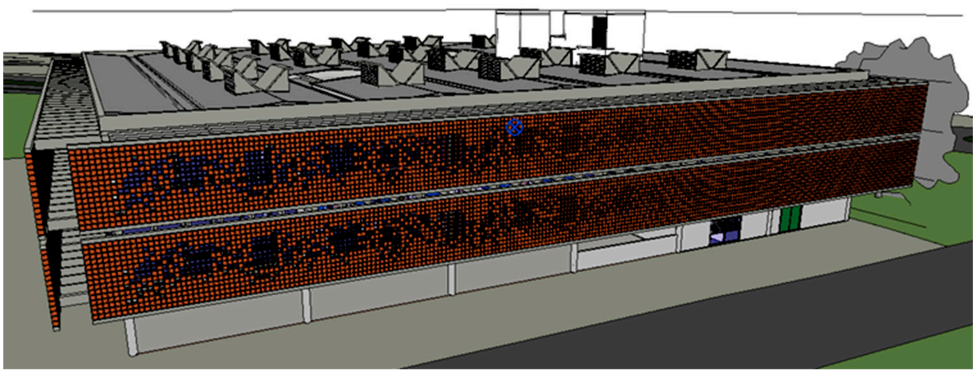


**Figure 1.** Architectural 3D model of the library at the Federal University of Uberlândia.

The university laboratory block, called Block 5T, has an approximate area of 567 m$^2$ with three floors, namely plan basement, ground floor, and first floor, with laboratories, teachers' room, and technicians' room for Physics and Chemistry experiments, and its architectural model is shown in Figure 2.

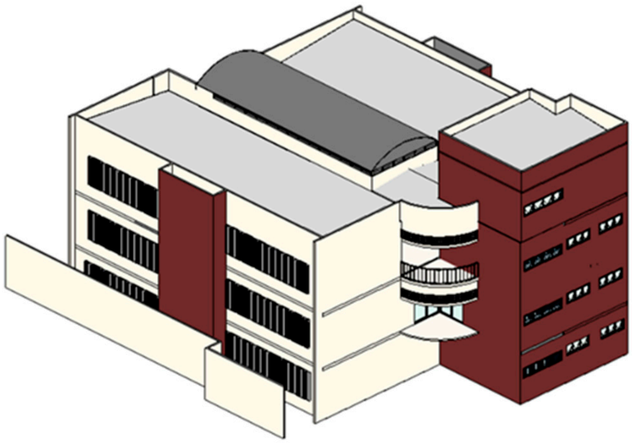


**Figure 2.** Architectural 3D model of Building 5T at the Federal University of Uberlândia.

The tests started from the geometric model of both buildings in Revit and georeferenced in the Santa Mônica campus at the Federal University of Uberlândia, Brazil. The constructive elements of the models were configured with the respective materials, their thermal properties, and thicknesses. It is worth mentioning that this initial configuration was carried out by the authors, however, modeling techniques focused on thermo-energetic analysis were not used. In other words, the projects were developed thinking about construction and not specifically to perform simulations. This information is fundamental, as it corroborates the article's objective of reproducing as much as possible the results generated by professionals who wish to use BES tools to improve the quality of their project, but who do not have formal training to do so. In addition, for the analysis of data transfers, it was necessary to insert other input data such as the configuration of spaces and zones, occupancy schedule, lighting, and equipment, as well as the configuration of the HVAC system, which will be detailed below. This information was entered by the authors to allow the simulation to be conducted.

After all configurations, the analytical energy model was generated and exported according to the accepted format by each BES software. The exported files were opened within the three chosen software, and the transmission of data from the BIM model to BES applications was evaluated.

### 3.2. The Input Data

The input data are all the parameters inserted in the model that allow thermo-energetic simulations in the BES software. Data insertion followed this data transfer sub-criteria, namely location, geometry, thermal property of materials, use and occupancy data, internal heat gains, and HVAC system.

As the objects of study have construction techniques present in Brazil, the materials and their respective thermal properties were configured following the current Brazilian regulations, which are ABNT NBR 15220-2 [36] and catalogs, according to Table 1.

In terms of use and occupancy data for each zone, the maximum determination of students allowed by the university was considered for Block 5T, that is, 40 students + 10% to accommodate repeating students. Thus, for the laboratory rooms, a schedule of 44 people was adopted.

For the library, the use and occupancy schedule was configured following ASHRAE 90.1 [37], which determines the number of people per area allowed for each type of building. In addition, in both buildings, unused environments such as roofs and water tanks were configured as plenum spaces.

For equipment and lighting data, an on-site visit was carried out for Block 5T, where the equipment was quantified, as well as the power of each light fixture in all environments present in the building.

For the library, the power density of lighting and equipment was surveyed from an office building in Brazil, according to studies by André et al. [38], since such parameters are better suited to the Brazilian reality.

**Table 1.** Configured parameters within data transfer criteria.

| Criteria | Configured Parameters |
|---|---|
| Location | Latitude<br>Longitude |
| Geometry | Walls<br>Roof<br>Windows<br>Ceiling<br>Ground |
| Vegetation [1] | Threes |
| Space composition | Spaces<br>Zones |
| Construction composition [2]<br>(Geometry items) | Thickness<br>Thermal conductivity<br>Specific heat<br>Absorbency<br>Thermal resistance [3]<br>Density |
| Occupancy schedule | Internal loads<br>Use and occupation |
| HVAC system [4] | System type<br>Setpoints |

[1] Configured only for the library building. [2] For walls, windows, ceiling, roof, and floor, the following was also configured: visual light transmission solar factor. [3] The thermal resistance was manually calculated, considering the internal resistance added to the external resistance of the elements. [4] Configured only for the Building 5T.

As for the HVAC system data, only Block 5T was configured as the library study aimed at a thermal analysis with natural ventilation and did not require this type of equipment. Through on-site visits, the models of each air conditioner present in the environments were surveyed to obtain the COP, that is, the coefficient of performance. Added to this, the HVAC system in the 5T model was configured as residential 14 SEER/0.9 split/compressed gas afue < 5.5 ton, as this is the configuration that best represents the system used in the region.

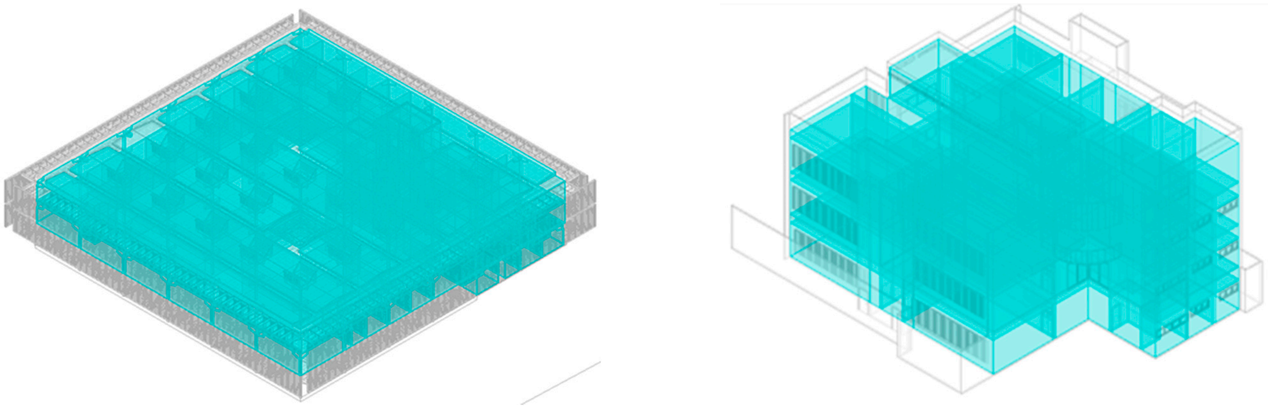
### *3.3. Export to BES Software*

The BIM/BES workflow optimizes environmental analyzes since the geometric model can be created in BIM, fed with the input data necessary for the analysis, and subsequently exported to the BES programs for simulation. According to [39], this workflow is called interoperability and allows import and export between BIM and BES, with the data transfer between them being part of interoperability. Moon et al. [40] indicate six areas of evaluation to verify the data transfer between BIM and BES, those being geometry, spaces and thermal zones, materials, internal loads, occupancy, and air conditioning systems.

To facilitate the interoperability between BIM and BES, class protocols such as IFC, gbxml, IDF, and INP are used [41]. The IFC protocol makes it easy to share information about construction and facilities management. The gbxml protocol, developed by Green Building Studio, is the most commonly used as it was developed for environmental analysis projects [42]. IDF and INP are extensions required by the Energyplus and eQUEST programs, respectively, requiring the gbxml protocol to be exported to GBS and converted to the final format [41]. In this research, version 7.03 of the gbxml protocol was used.

Several authors have pointed out that data transfer between BIM/BES has not been resolved since there is data loss between them, requiring tests to identify the BES programs with better performance in this aspect [12,13,15,18,40]. Other authors analyzed the BES program with better integration with BIM also in an interpretative way, analyzing criteria such as usability and information management [14]. Therefore, tests are needed to identify the BES program with the best integration with the BIM program, which is one of the specific objectives of this research.

After configuring each parameter in the model, the export process began through the creation of analytical energy models (Figure 3a,b).



(**a**) (**b**)

**Figure 3.** Analytical model of energy generated from (**a**) library, (**b**) Building 5T.

The DesignBuilder and IES-VE software adopt the .gbxml format as the interoperability protocol (Figure 4). Thus, after generating the analytical energy models, the library was imported into that software for BIM/BES integration analyzes. The Equest software adopts the .inp format as a protocol, requiring an intermediate platform for the gbxml → inp conversion. In this case, Autodesk Insight was used for such conversion. In the sequence, Block 5T was imported into Equest for analysis.

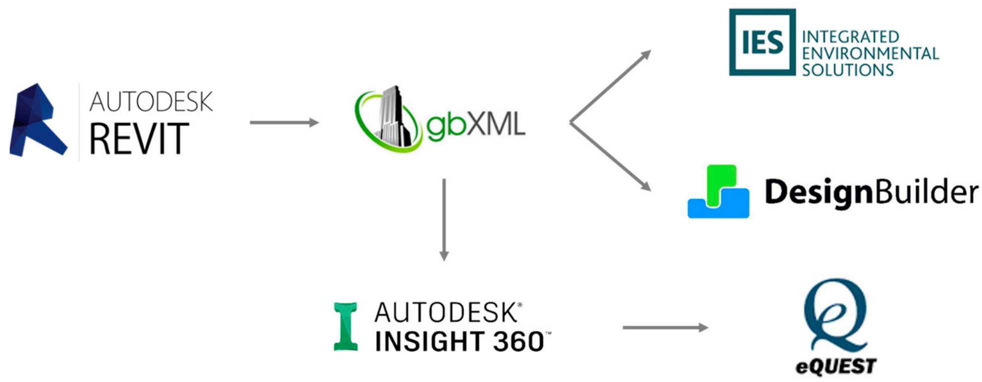


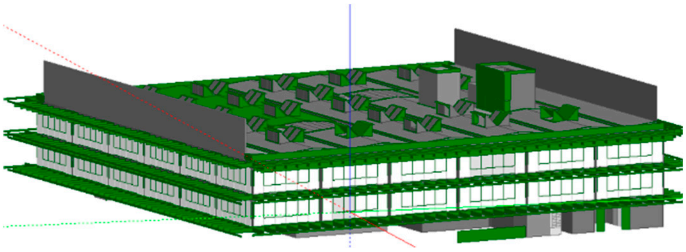

**Figure 4.** Workflow between the BIM and BES software.

## 4. Results and Discussion

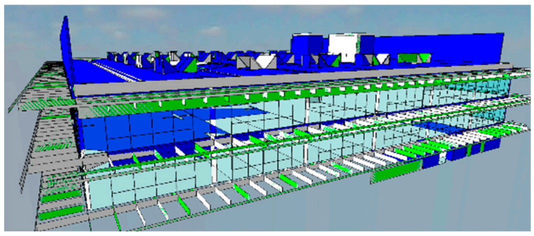
To verify the BES software with the best integration with BIM in models with complex geometries, four criteria were analyzed: data transfer, friendly interface, geometry corrections, and technical support and tutorials.

In the first criteria analysis defined in Methodology (Item 3), data transfer, it is observed that in the case of the library (Figure 5a,b), there were failures in data transfers of detailed geometry in the two analyzed BES software (DesignBuilder and IES-VE), including roof, solar protection, hollow element, trees, atrium and mezzanine voids, sheds, window frames, and curved elements (highlighted in green in Figure 5a, and in green and blue in Figure 5b). It is important to highlight that there is a visible disparity in the graphic quality presented by Figure 5a,b, obtained through the models exported to DesignBuilder and

IES-VE, respectively. The model visualized in DesignBuilder (Figure 5a) presents greater clarity, while the visualization in the IES-VE software is unfavorable. Far beyond aesthetics, comparing and weighing the graphical quality of the models delivered by each of the software is fundamental as it can facilitate or confuse the user when evaluating the import quality of the model.



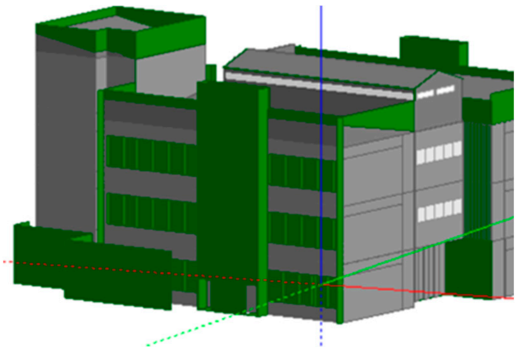
(**a**)



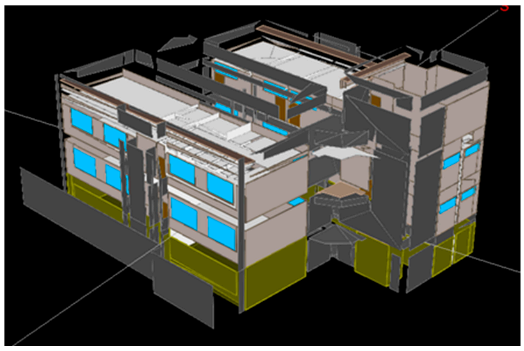
(**b**)

**Figure 5.** Failures on detailed geometry transfer from the library in different BES software: (**a**) DesignBuilder, (**b**) IES-VE.

In Block 5T (Figure 6a,b), it was also observed that there was a failure in the data transfer of geometry in the analyzed software (DesignBuilder and eQUEST), however, in a smaller proportion. The transfer errors in DesignBuilder were the import of hollow elements, atrium coverage, and incorrect insertion of some frames (highlighted in green in Figure 6a), and in eQUEST, errors in the zenith opening, hollow element, metallic tile, solar protection, curved elements, and cracks in the walls (highlighted in yellow and blue in Figure 6b).



(**a**)



(**b**)

**Figure 6.** Failures on detailed geometry transfer from Building 5T in different BES software: (**a**) DesignBuilder, (**b**) eQUEST.

Due to the geometry errors presented, it was decided to remodel the buildings into simplified geometries without interfering with the main characteristics of their envelope. For the library, the hollow elements were modeled as spaced walls to create the same permeability as the detailed geometry, the solar protections were modeled as walls, and the sheds were simplified in the form of a cube with a wall in the center. For the roof, they opted for the simplification in the slab obtained from the manual calculation of the two coverings, and the weighted average between these to arrive at the thermal resistance. Additionally, the trees were modeled as walls. For Block 5T, the simplifications were similar to the library for the elements, solar protection, roof, and hollow elements, differing only in the glazed facade, present in the east orientation of the building, which was modeled as a wall without metallic structure.

In Figures 7 and 8, the simplified geometries exported to the BES software can be seen. However, even so, geometry errors were found in the simplified model of the library, as follows: in DesignBuilder, the shutters of the sheds and the voids of the atriums and mezzanines were not loaded; in IES-VE, in addition to the non-export of shutters and voids in atriums and mezzanines, errors were found in sheds and frames.

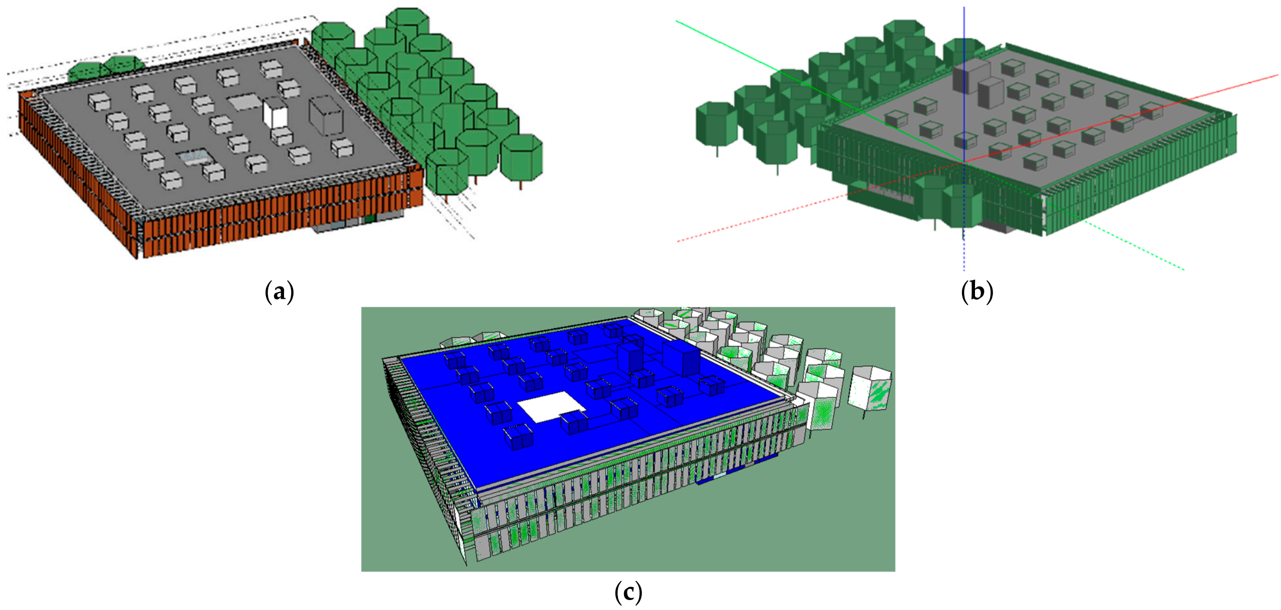


**Figure 7.** Simplified geometry exportation from the library to different BES software: (**a**) Revit, (**b**) DesignBuilder, and (**c**) IES-VE.

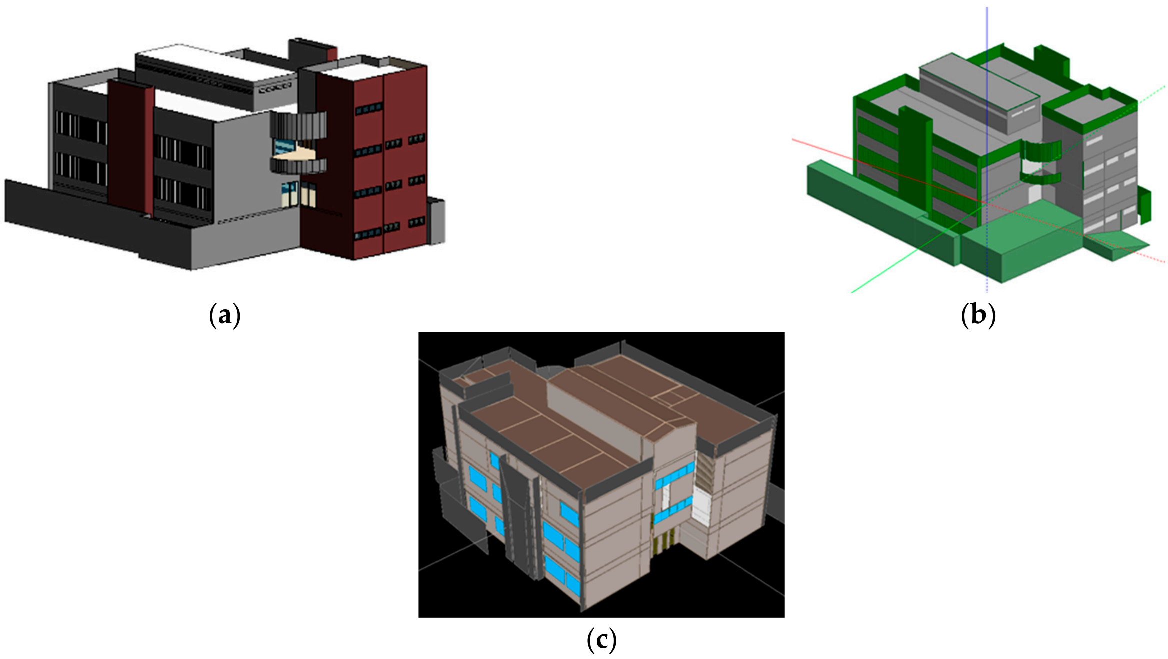


**Figure 8.** Simplified geometry exportation from Building 5T to different BES software: (**a**) Revit, (**b**) DesignBuilder, and (**c**) eQUEST.

For Block 5T, in eQUEST, cracks in the geometry, partial transfer of solar protection and ceilings, and absence of zenith opening were observed. In DesignBuilder, errors were found in the simplification of hollow elements (such as mezzanines, atriums, lanterns, sheds, cobogós, and metal brises without covers), and the inclusion of non-modeled frames in the BIM software.

Finally, Tables 2 and 3 were prepared in order to verify the data transfer between BIM and BES in the two buildings with detailed and simplified geometry, in which it is observed that the simplification of the models interfered not only with better transfer of geometry but also in the more satisfactory importation of thermal properties and location. The percentage calculation was based on the criteria presented in Tables 2 and 3, which were divided into several items. For each item, it was verified whether the data transfer between the BIM and BES software worked or not (Appendix A). The percentages were then calculated based on the simple arithmetic mean between items belonging to the same criterion.

**Table 2.** Data transfer of detailed geometries.

| | Library | | Building 5T | |
|---|---|---|---|---|
| **Criteria** | **DesignBuilder** | **IES-VE** | **DesignBuilder** | **IES-VE** |
| Location | 0.00% | 50.00% | 0.00% | 0.00% |
| Orientation | 100.00% | 100.00% | 100.00% | 100.00% |
| Detail geometry | 25.00% | 8.33% | 83.33% | 58.33% |
| Vegetation | 0.00% | 0.00% | N/A * | N/A * |
| Space composition | 100.00% | 100.00% | 100.00% | 100.00% |
| Construction composition and Thermal properties | 45.65% | 43.47% | 74.46% | 0.00% |
| Internal loads and Schedules | 0.00% | 50.00% | 0.00% | 100.00% |
| HVAC system | N/A * | N/A * | 0.00% | 0.00% |

* Not applicable.

**Table 3.** Data transfer of simplified geometries.

| | Library | | Building 5T | |
|---|---|---|---|---|
| **Criteria** | **DesignBuilder** | **IES-VE** | **DesignBuilder** | **IES-VE** |
| Location | 0.00% | 100.00% | 100.00% | 50.00% |
| Orientation | 100.00% | 100.00% | 100.00% | 100.00% |
| Detail geometry | 72.72% | 63.63% | 91.66% | 58.33% |
| Vegetation | 100.00% | 100.00% | N/A * | N/A * |
| Space composition | 100.00% | 100.00% | 100.00% | 100.00% |
| Construction composition and Thermal properties | 53.65% | 39.02% | 75.51% | 6.12% |
| Internal loads and Schedules | 0.00% | 50.00% | 0.00% | 100.00% |
| HVAC system | N/A * | N/A * | 0.00% | 50.00% |

* Not applicable.

In the final result analysis of the data transfer (Table 4), it is observed that due to the complexity of the library's geometry, the simplification of this model interfered significantly and positively with the data transfer. In Block 5T, which has a less complex geometry, there was an improvement in the data transfer due to the simplification of the model, however, in a less expressive way compared to the library. It is also observed that IES-VE, for the library, presented better data transfer with 78.95% of imported items, and in Block 5T, DesignBuilder presented better data transfer with 66.74% of imported items.

In addition, still in Table 4, the percentage of improvement in data transfer with simplified modeling is verified for each software, and library: 22.25% in DesignBuilder and 28.70% in IES-VE. As for Block 5T, there is an improvement of 15.63% in DesignBuilder and 8.02% in eQUEST. It is observed that the percentage of improvement with simplification increases concerning the complexity of the model since the library presents more complex geometry in relation to Block 5T.

**Table 4.** Final result of data transfer.

| Type | Library | | Building 5T | |
|---|---|---|---|---|
| | DesignBuilder | IES-VE | DesignBuilder | IES-VE |
| Detail geometry | 38.66% | 50.25% | 51.11% | 58.33% |
| Simplified geometry | 60.91% | 78.95% | 66.74% | 66.35% |

Based on the results of the first criterion (data transfer), the analysis of the other criteria was initiated, which are essential for effective thermo-energetic analysis (user-friendly interface, possibility of geometry corrections, technical support, and tutorials). These criteria were analyzed based on tests with the simplified geometry of the two buildings and are presented in Table 5.

**Table 5.** Analyzed criteria to identify the friendliest BES software (BES software performance with simplified geometry).

| Criteria | Library | | Building 5T | |
|---|---|---|---|---|
| | DesignBuilder | IES-VE | DesignBuilder | IES-VE |
| Data transfer | Normal | Good | Good | Normal |
| Friendly interface | Good | Normal | Good | Bad |
| Allowed geometry corrections | Good | Bad | Good | Bad |
| Tutorials and developers' support | Good | Bad | Good | Bad |

Performance Rating (PR)—Bad: PR < 33.33%; Normal: 33.34% < PR < 66.66%; Good: PR > 66.67%.

Considering the three tested BES software and the typologies analyzed in this research, the software with the best integration with Revit was DesignBuilder, as it presented the best performance regarding the user-friendly interface, geometry corrections, technical support, and tutorials. However, it is worth mentioning that there are other software available on the market that can provide better results. Therefore, more research is needed so that the interoperability between software can be more broadly evaluated.

On the aspect corrections in the geometry of the library, such as shutters in the sheds and voids in the atriums and mezzanines, it was possible to execute them quickly based on the tutorials provided by the developer, in addition to allowing the correction of the thermal properties of the materials easiness, enabling the thermo-energetic analysis. Regarding the IES-VE, despite the better data transfer, significant time was spent trying to correct the geometry from tutorials and forums, the interface was not intuitive, the technical support was inefficient, and it was not possible to correct the geometry, which made the thermal simulation unfeasible.

For the eQUEST software, the challenges faced were similar to the IES-VE. Despite the increase in the percentage of data transfer with the model geometric simplification, it was observed that the performance was still not satisfactory for the energy study. The unfriendly interface, out-of-date technical support, and challenges with geometry correction are some of the causes of the many challenges encountered, which made energy analysis impracticable. In DesignBuilder, transferring the detailed model to the simplified one resulted in a significant increase in the total percentage. It was identified that this software adopts its standards for location, internal loads, and occupancy schedule, among others. As a result, DesignBuilder does not detect the parameters of the BIM model, which could be a cause of the non-transfer of this type of data between BIM and BES, resulting in interoperability failures. Therefore, both for detailed and simplified models, such variables required a new configuration within the platform. Despite the limitations on these variables, DesignBuilder achieved excellent performance in transmitting parameters such as geometry and thermal properties, requiring few adjustments, and contributing to more reliable thermo-energetic analyzes. Table 6 shows the main transfer errors found for each BES tool.

**Table 6.** Summary of error types found for each BES tool.

| Type of Error | | Error Description | DesignBuilder | IES-VE | eQUEST |
|---|---|---|---|---|---|
| Detail geometry | Roof | Partially missing geometry | ✓ | ✓ | ✓ |
| | Solar Protection | Partially missing geometry and Incorrect geometry | ✓ | ✓ | ✓ |
| | Hollow Elements | Hollow elements were transferred as flat elements | ✓ | ✓ | ✓ |
| | Curved Elements | Curved elements were transferred as flat elements | ✓ | ✓ | ✓ |
| | Cracks in the Walls | The walls were not suppose to have cracks | | | ✓ |
| | Metallic Tiles | Incorrect geometry | | | ✓ |
| | Atrium | The atrium was transferred as a flat slab | ✓ | ✓ | |
| | Sheds | Partially missing geometry | ✓ | ✓ | |
| | Window frames | Not transferred | ✓ | ✓ | ✓ |
| | Structure | Partially missing geometry | ✓ | ✓ | |
| | Metallic brises | Partially missing geometry | ✓ | ✓ | ✓ |
| | Zenith Opening | Partially missing geometry | | | ✓ |
| Vegetation | Trees | Not transferred | ✓ | ✓ | ✓ |
| Material Thermal Properties | | Partially transferred | ✓ | ✓ | ✓ |
| Internal loads and Schedules | Internal loads | Partially transferred | ✓ | ✓ | ✓ |
| | Usage and scheduling | Partially transferred | ✓ | | ✓ |

## 5. Conclusions

This study aimed to verify the interoperability between BIM and BES software, identifying the best integration in models of complex geometries with quantitative and qualitative analysis. Through a case study in two school and public buildings, called library and Block 5T, four analysis criteria were determined (data transfer, friendly interface, geometry corrections, technical support, and tutorials), and the first criteria were subdivided into location, orientation, geometry, vegetation, composition of spaces and zones, building composition and thermal property of materials, internal loads and schedules, and HVAC systems. Still, two geometry conditions were proposed for the two objects of study: detailed and simplified.

It is possible to conclude, from the comparison of the data transfer of the detailed and simplified geometries of the two buildings, that the simplification of complex geometries is essential to improve the data transfer and effectivity of thermo-energetic simulations. It is worth highlighting that the results obtained in this research refer to the process of analyzing the quality of the geometric transfer and thermal data inserted into the BIM models when exported to the BES software. The results obtained by the energy analysis of the BES software used are not the objective of this manuscript. In other words, the conclusions indicated in this section regarding the effectiveness of the BES software refer to the effectiveness of importing files from a BIM model and not to the accuracy of the energy analyzes provided by the BES software.

Between the Revit and IES-VE software, despite the satisfactory performance in the data transfer criteria for the simplified condition of the library, the same performance was not verified for the criteria of friendly interface, geometry correction, and technical support. Significant time was spent in attempts to correct the flaws in the geometry of the BES software, the interface was not intuitive enough and technical support was contacted several times, however, without success in solving the limitations pointed out by the software.

Between the Revit and eQUEST software, several gaps were observed in data transfers, both for Block 5T in detailed and simplified conditions, with emphasis on the absence of constructive elements such as solar protections, ceiling, and zenith opening. Also, the software has an unintuitive interface, which makes geometry corrections difficult, and has limited and outdated communities and tutorials.

Compared to the results, DesignBuilder proved to be a solution to the interoperability obstacles faced in the previously chosen software. This one had the best performance in terms of the user-friendly interface as it was more intuitive, in terms of geometry corrections, as it allowed quick and easy changes, and in terms of technical support and tutorials since the assistance was efficient, due to the ease of finding tutorial videos and several forums; additionally, the developer's technical support, when necessary, was quick and helpful. However, it still has certain limitations, mainly in data transfer, since some sub-criteria were not transferred, both for the library and Block 5T, in the two conditions studied (detailed and simplified).

Thus, it can be concluded, given the existing challenges demonstrated in the several attempts made in all BES software used, that the BIM–BES flow is still not explored to its potential in the AEC industry. In addition, when choosing a BES software, an evaluation considering a broader perspective is necessary, taking into account not only the data transfer but also the ease of working within the BES software, the possibility of correcting, as well as the assistance capacity of the tutorials and developers. Furthermore, developers need to evaluate interoperability protocols to make the transfer of models from BIM to BES effective and consolidated for thermal energy evaluations.

Another challenge that this research explored was related to the tool used to enter the relevant thermo-energetic data. The possibility of configuring materials directly in the BIM model, and subsequently exporting them to the BES tool just to perform the energy analysis, can bring benefits to the design process. This will enable the designer to make modifications directly to the BIM model, changing the properties of materials as they are created, and immediately analyzing the consequences of these changes on the building's energy performance. This prevents modifications from being made directly in the BES tool, only at the end of the design process, generating rework for the designer who must return to the BIM software to make these alterations. Hopefully, designers will feel encouraged to consider this flow as an integral part of the design process. In other words, energy analysis will be considered part of the design process and no longer a step after project delivery.

Considering the practical and empirical nature of this investigation work, it is certainly subject to several limitations. Among the most relevant is the lack of comparison between the different forms of export available in Revit, in combination with other energy configurations, which would make it possible to verify their effectiveness more broadly. Furthermore, this research focused on exploring the possibility of configuring all model features directly in the BIM tool to facilitate the project flow. However, it is worth highlighting that it is also possible to use BES tools to test different material options to find the combination with the best energy performance for the project. Therefore, it is suggested that future work explore different possibilities for combining energy export/configuration, considering different BIM and BES tools.

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## Appendix A

Compilation of the characteristics of the articles cited in this section that addressed case studies on the exportation of models from BIM to BES.

| Reference | Year | Objective | Software BIM | Plugin or Software BES | Geometry Complexity | Main Results |
|---|---|---|---|---|---|---|
| [18] | 2019 | Explore the energy model accuracy of two different software including Autodesk Revit and DesignBuilder. | Revit | DesignBuilder | Simple | DesignBuilder performed satisfactorily, however, failures occurred when transferring non-geometric data. |
| [19] | 2019 | Implement and test a new workflow that allows to optimize the BIM–BEM interoperability for energy performance assessment of buildings. | Revit | IDA-ICE | Simple | The workflow proved to be valid, with the model presenting all architectural and energy performance information. |
| [20] | 2019 | Propose a framework for the continuous Bayesian calibration of whole building energy simulation (BES) models utilizing data from building information models (BIM) and building energy management systems (BEMS). | Revit | EnergyPlus | Complex | Results showed that discrepancies in the BIM to BEM translation were primarily caused by exporting from the native BIM to gbxml, suggesting a need for the development of well-established guidelines and BIM integration workflow for energy modeling. |
| [15] | 2020 | Explore the interoperability between the commonly used energy simulation and BIM tools and verifies the simulation approach by undertaking a case study. | Revit | EnergyPlus; HOT2000 | Simple | Although a lot of data has been lost in the transfer process, the two software presented very similar results for the conducted case study. |
| [17] | 2020 | Assess the applicability of integrating Green Building Information Modelling for existing green buildings through a practical implementation. | Revit | Green Building Studio | Simple | The data availability appears to be numerically satisfactory, there could be issues due to the lack of accuracy and reliability of data. |
| [23] | 2020 | Proposed a BIM-based framework that combines the output data of building energy simulations, building energy management systems (BEMS), and Computerized Maintenance Management Systems *(CMMS). | Revit | DesignBuilder | Complex | The results showed that the framework enabled the detection of problematic building spaces and identification of potential causes by using the BEMS and CMMS data corresponding to those spaces. |

| Reference | Year | Objective | Software BIM | Plugin or Software BES | Geometry Complexity | Main Results |
|---|---|---|---|---|---|---|
| [30] | 2020 | Assess the relevance of natural and artificial lighting for energy simulation. | Revit | Insight 360 | Complex | Results indicated that the proposed flow is valid and reliable for this type of analysis. |
| [9] | 2021 | Analyze the interaction between BIM and energy simulation through a review of the main existing commercial tools. | ArchiCAD | EcoDesigner STAR | Simple | Workflow was favorable with the exception of HVAC systems. |
| [12] | 2021 | Analyze the continuity and consistency of data exchange between different BIM-related software through the modeling software Revit and the sustainable analysis software Ecotect. | Revit | Ecotect | Simple | The use of this energy simulation software has certain complexity, requires users to be highly professional, and may bring difficulties to designers in building efficiency design. |
| [13] | 2021 | Evaluate whether there is an automated or semi-automated BIM to BEM workflow that could improve the building design process. | Revit | DesignBuilder; OpenStudio; CYPETHERM HE | Simple and Complex | The authors concluded that the interoperability with DesignBuilder was the most viable and with OpenStudio the least viable. |
| [29] | 2023 | Compare the performance of two thermal insulators applied to a temporary shelter container designed to promptly serve vulnerable populations. | Revit | Green Building Studio | Simple | The workflow proved to be valid for low-complexity analysis. |
| [31] | 2023 | Analyze the effects of latitude and orientation on the sunlight illuminance level within a northwest/southeast-oriented hypothetical house with a wide-glassed facade by integrating the BIM and BEM methodologies. | Revit | Green Building Studio | Simple | The methodology proved to be effective for quick assessments in the early design stages. |

## Appendix B

Data transfer results between BIM and BES software.

| | | Detailed Geometries | | Simplified Geometries | |
|---|---|---|---|---|---|
| Criteria | Items | DB * | IES-VE | DB * | IES-VE |
| Location | Latitude | No ** | No | No | Yes |
| | Longitude | No | Yes *** | No | Yes |
| Orientation | North | Yes | Yes | Yes | Yes |
| Detail geometry | External walls | No | No | Yes | Yes |
| | Thermoacoustic tile | Yes | No | Yes | Yes |
| | Waterproof slab | No | No | N/A **** | N/A **** |
| | Sheds | No | No | No | No |
| | Cobogó | No | No | Yes | Yes |
| | External windows | No | No | Yes | No |
| | Partitions | No | No | Yes | Yes |
| | Floor hollows | Yes | No | No | No |
| | Wall hollows | No | No | No | No |
| | Internal slabs | No | No | Yes | Yes |
| | Metallic brises | No | No | Yes | Yes |
| | Domus | Yes | Yes | Yes | Yes |

| | | | Detailed Geometries | | Simplified Geometries | |
|---|---|---|---|---|---|---|
| **Criteria** | **Items** | | **DB *** | **IES-VE** | **DB *** | **IES-VE** |
| Vegetation | Trees | | No | No | Yes | Yes |
| Space composition | Zones | | Yes | Yes | Yes | Yes |
| Construction composition and Thermal properties | External walls | Thickness | Yes | Yes | Yes | Yes |
| | | Thermal conductivity | No | Yes | Yes | Yes |
| | | Specific heat | Yes | Yes | Yes | Yes |
| | | Density | No | Yes | Yes | Yes |
| | | Absorption | No | No | No | No |
| | Thermoacoustic tile | Thickness | Yes | Yes | Yes | Yes |
| | | Thermal conductivity | Yes | Yes | No | Yes |
| | | Specific heat | Yes | Yes | Yes | Yes |
| | | Density | Yes | Yes | No | Yes |
| | | Absorption | No | No | No | No |
| | Waterproof slab | Thickness | Yes | Yes | N/A | N/A |
| | | Thermal conductivity | Yes | Yes | N/A | N/A |
| | | Specific heat | Yes | Yes | N/A | N/A |
| | | Density | Yes | Yes | N/A | N/A |
| | | Absorption | No | No | N/A | N/A |
| Construction composition and Thermal properties | Sheds | Thickness | No | No | No | No |
| | | Thermal conductivity | No | No | No | No |
| | | Specific heat | No | No | No | No |
| | | Density | No | No | No | No |
| | Cobogó | Thickness | No | No | No | No |
| | | Thermal conductivity | No | No | No | No |
| | | Specific heat | No | No | No | No |
| | | Rugosity | No | No | No | No |
| | | Density | No | No | No | No |
| | | Absorption | No | No | No | No |
| | External windows | Total solar transmission | Yes | No | Yes | No |
| | | Light transmission | Yes | No | Yes | No |
| | | Transmittance | Yes | No | Yes | No |
| | Partitions | Thickness | Yes | Yes | Yes | Yes |
| | | Thermal conductivity | Yes | Yes | Yes | Yes |
| | | Specific heat | Yes | Yes | Yes | Yes |
| | | Density | Yes | Yes | Yes | Yes |
| | Internal slabs | Thickness | Yes | Yes | Yes | Yes |
| | | Thermal conductivity | Yes | Yes | Yes | Yes |
| | | Specific heat | Yes | Yes | Yes | Yes |
| | | Density | Yes | Yes | Yes | Yes |
| | Metallic brises | Thickness | No | No | No | No |
| | | Thermal conductivity | No | No | No | No |
| | | Specific heat | No | No | No | No |
| | | Density | No | No | No | No |
| | | Absorption | No | No | No | No |
| | Domus | Thickness | No | No | No | No |
| | | Thermal conductivity | No | No | No | No |
| | | Specific heat | No | No | No | No |
| | | Density | No | No | No | No |
| | | Absorption | No | No | No | No |

| | | Detailed Geometries | | Simplified Geometries | |
|---|---|---|---|---|---|
| Criteria | Items | DB * | IES-VE | DB * | IES-VE |
| Internal loads and Schedules | Internal loads | No | No | No | No |
| | Usage and scheduling | No | Yes | No | Yes |

* DB—DesignBuilder; ** No—Item transfer failed; *** Yes—Item successfully transferred; **** N/A—Not Applicable.

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