

## Article

# BIM-Based Energy Analysis and Sustainability Assessment—Application to Portuguese Buildings

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**Abstract:** Buildings are responsible for several negative impacts on the environment, most of them related to nonrenewable energy consumption, increasing the concern regarding buildings energy efficiency. In this context, computer software has been used to estimate the energy needs of the built environment, and the Building Information Modelling (BIM) methodology can be used to simplify this process. This study aims to validate a BIM-based framework to streamline the energy analysis of Portuguese buildings, based on the method of the national regulation for the thermal performance of residential buildings. Currently, designers need to spend considerable time assessing all the building characteristics and performing the mandatory calculations for energy performance analysis. It is also intended to link the results of the energy simulation with a Building Sustainability Assessment method—SBTool<sup>PT</sup>-H. The purpose is to demonstrate how it is possible to benefit from this approach to simultaneously improve building sustainability during the design stage. To do so, different case studies were modelled in Autodesk Revit and exported to a BIM energy tool to perform energy simulation analysis. The results were validated against the official assessment method of the Portuguese thermal regulation and were successfully used to assess the SBTool<sup>PT</sup>-H energy efficiency category. The research outcomes provide design teams with a reliable BIM-based framework to improve building energy performance and to develop thermal projects while enhancing building sustainability. It also increases the knowledge about the integration of sustainability assessment in the BIM environment, providing new insights for complete integration.

**Keywords:** Building Information Modelling (BIM); Building Energy Modelling (BEM); energy efficiency; Building Sustainability Assessment (BSA); sustainability



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## 1. Introduction

As society is growing, there is an increasing concern about building occupants' comfort demand and energy consumption. The main reasons are directly related to weak buildings energy performance and irrational energy use [1]. Energy efficiency is an essential factor to achieve sustainable development. It is necessary to optimise energy use without compromising the indoor environmental quality, using efficient technologies and passive and active construction solutions [1,2]. Energy efficiency is related to the building's performance in the three sustainability dimensions:

- Environment—due to resources use and carbon emissions;
- Society—due to indoor environmental comfort;
- Economy—due to energy cost and its impact on household income.

Hence, Building Sustainability Assessment (BSA) schemes usually evaluate a set of building energy-related characteristics and performance. Such schemes can provide a decision support framework for designers to improve the sustainability of buildings, as well as to evaluate them according to local standards and regulations. Effectively acting

on energy use and building sustainability is an essential path to achieve better, ecological, comfortable and cost-effective buildings.

Facing the increasing capabilities of Building Information Modelling (BIM) for the construction industry, designers and researchers are extensively applying it to manage building data and improve efficiency and global quality [3]. During the last five years, the use of BIM for sustainable construction purposes has also witnessed exponential growth [4]. BIM allows storing multi-disciplinarily information into a single model, promoting a real-time collaboration environment among stakeholders through the building life cycle [5]. Between BIM most known applications, its connection with Building Energy Modelling (BEM) has been used to improve buildings energy performance. BEM is a powerful tool to analyse and enhance building energy performance and thermal comfort, providing project teams with concise data to evaluate the performance and environmental impacts of different design solutions [6,7]. Despite the recognised advantages during the design phase, there is still a great scalability potential, as several designers still do not use BIM for energy analysis due to the required knowledge and time to prepare the energy model and interpret the results [8].

Regardless of the benefits and different BIM approaches to perform energy analysis, BIM is not being used in the Portuguese context to develop mandatory thermal projects. Major BIM energy tools are usually region-oriented, and calculation engines are not, according to the Portuguese energy regulations. Furthermore, Portuguese building technologies and indoor environmental quality standards are quite different from most European countries [9]. Portuguese designers can only benefit from those tools in the optimisation of the building design. Additionally, Portuguese legislation requires a thermal project for every building to issue construction permits. Nowadays, designers are required to manually fill a set of calculation spreadsheets with the building's characteristics, requiring in-depth knowledge about the building and the energy calculation method, as well as substantial time to carry out the analysis.

Facing the knowledge gap, this study primarily aims to define and apply a BIM process that can support and optimise the thermal project of Portuguese buildings. Thus, the first Research Question (RQ) of this research arises—"Can BIM support and optimise Portuguese buildings thermal project?". To provide an answer, a suitable BIM-based method will be identified and applied to Portuguese residential buildings case studies. The BIM software results will face a conventional approach to prove the reliability of the method and answer the second RQ—"Is the BIM-based method reliable and according to the Portuguese standards?". Since energy efficiency is a standard sustainability indicator in BSA methods [10,11], the development of a new BIM-based approach creates the opportunity to link energy simulation results with a local BSA method, leading to the last RQ—"Can the results be used for a sustainability assessment scheme?". Therefore, it will be possible to effectively demonstrate how it is feasible to benefit from this approach in the process of improving the sustainability of a building during the design stage. Additionally, it will also enhance the integration of BSA in the BIM collaborative process and promote the use of BSA methods by the Portuguese designers.

## 2. Literature Review

### 2.1. Buildings Energy Performance

The European Union (EU) authorities and the society have raised awareness about the negative impacts of buildings on the environment. The relation between the construction industry and environmental problems has already been proven by the scientific community [12–14]. The European building stock is still responsible for 40% of the total energy use and 36% of CO<sub>2</sub> emissions [15]. To improve buildings efficiency and reduce the energy demand, the EU has approved a set of standards. In this context, the most important is the Energy Performance of Buildings Directive (EPBD), updated in 2010 [16]. The principal goal was to create a main legal instrument to improve EU buildings energy performance.

In Portugal, the EPBD and other Directives were transposed to the Portuguese legal framework by the Decree Law 118/2013 in 2013, composed by the Buildings Energy Certification System (SCE), by the Residential Buildings Energy Performance Regulation (REH) and by the Services and Commercial Buildings Energy Performance Regulation (RECS) [17]. In 2018, Portugal was the seventh European country with more dependence on energy imports, with 75.9% of the consumed energy being imported [18]. The Portuguese building sector (residential and service buildings) was responsible for 31.9% of the country energy demand, exceeded by the industry and transportation sectors. According to the SCE, in 2019, almost 61% of the 1.78 million Portuguese energy classified buildings were rated less than B- (minimum requirement for new buildings). This was justified, since the majority of the Portuguese buildings were built before the first national thermal regulation in 1990. A 2020 energy report [18] highlighted the potential savings of 60% on the building energy demand by adopting energy efficiency measures. More than half of them are related to interventions on the building envelope, i.e., in external walls (24.7%), roofs (13.3%), ground floors (4.4%) and windows (10.4%).

## 2.2. BIM and BEM

Construction projects are becoming more difficult and complicated. New approaches, like BIM, have been introduced in construction companies to support designers in managing all the project information [4,19,20]. BIM can be defined as a working methodology that makes it possible to manage the 3D drawing and the project data in a digital format during the entire building life cycle [21]. BIM can improve design and management processes productivity, with stakeholders working in real-time collaboration [4,22]. BIM implies a building information model, which is an object-oriented parametric model, with all the project data. The model Level of Development (LOD), which ranges from 100 to 500, specifies and articulates the content and reliability of the BIM model [23].

BIM creates an excellent opportunity to incorporate sustainable measures throughout the design process [24]. Some authors have already identified the preconstruction and project phases as the critical ones, where the main decisions regarding building sustainability must be taken [20,25,26]. Since that is also the phase when projects can most benefit from BIM, the influence that it can have in enhancing buildings sustainability becomes clear [27]. BIM can provide information about the estimated building performance even in the very early design stages [8].

In 2008, Krygiel and Nies [28] recognised seven aspects where BIM can be used to support sustainable design. Five of those—Building Orientation, Building massing, Daylight Analysis, Renewable Energy and Energy Modelling—were directly energy-related criteria. Therefore, an energy analysis can significantly benefit from BIM [10], leading to several BIM-based energy-related research—BEM [6,7]. BIM and BEM allow designers to evaluate different design options during the project early stages, creating the opportunity to develop optimised buildings with higher energy efficiency and comfort. However, such application is frequently performed in an isolated manner, empowered by the use of energy simulations in the early phases of the project. Furthermore, BEM integration in BIM collaborative workflow is also not sufficiently developed and synchronised, and energy-efficient design strategies are often not well-implemented [7].

Within the context of BIM, model interoperability between software is usually made with Industry Foundation Classes (IFC), Green Building XML (gbXML) or direct plug-ins. These are the most common open standard data schemas, which are commonly used for information exchange between BIM and BEM tools [6,29,30]. Kamel and Memari [31] highlighted the differences between both when used for energy simulation purposes. Despite the use of the Green Building XML schema (gbXML) mainly for the energy simulation domain, only rectangular geometry is readable, and it does not allow the targeting of specific areas of a project. The IFC is commonly used for different domains of application (a more comprehensive type of data), and it is capable of reading any geometry. Nevertheless, some data is still not transferred appropriately, leading to the development of corrective add-ins.

Depending on the energy analysis type and intended accuracy, the model must have a certain LOD [32]. Farzaneh et al. [33] suggested that the LOD should be defined according to the information requirements. However, the design process must also be “user-friendly”, with a LOD that allows quick modelling and provides reliable results [5]. An accurate energy assessment requires, at least, a LOD of 300, while a simpler analysis, such as, i.e., solar exposure, only requires a LOD 200, without materials and spaces characteristics [34].

On the application field, several reviews have been made comparing the analysis capabilities and end-users of energy analysis tools, highlighting the capabilities of Autodesk Green Building Studio (GBS) and Integrated Environmental Solutions Virtual Environment (IESVE) [35,36]. Regarding the modulation software, Autodesk Revit is one of the most used, capable, and embracing BIM platforms [37–39]. Existing reviews pointed out Autodesk Revit as the most used BIM platform by researchers when concerning producing sustainable and efficient buildings.

Using Autodesk Revit and GBS, Abanda and Byres [40] concluded that a building’s orientation can have a considerable impact on the building energy consumption. Gourlis and Kovacic [39] applied BIM to analyse the energy efficiency of industrial buildings using EnergyPlus. They highlighted that the BIM and BEM approach is still not mature enough, requiring a significant amount of time, assumptions and remodelling. Ryu et al. [11] presented a simulation process based on Autodesk Revit to assess energy-related BSA credits. They concluded that BIM could produce significant time savings, but considerable time was wasted in double-checking and geometry correction. Montiel-Santiago et al. [19] submitted a hospital BIM model to a set of analyses on Insight 360, suggesting an energy renovation package able to save 47% of the actual building energy demand. Carvalho et al. [41] conducted an energy renovation of a Portuguese dwelling using GBS and DesignBuilder. The main benefit of BIM in the Portuguese context was the decision support provided to designers in the early project stages, as none of the BIM tools considered the Portuguese thermal regulation (REH).

Despite the advantages, most researchers have reached a common conclusion about BIM for energy purposes—there is still an interoperability gap between BIM modulation platforms and BIM energy tools [26,42,43]. BEM is not integrated correctly into the BIM environment, and often, a continuous information flow in the digital modelling is not possible. The lack of interoperability between BIM and BEM makes it challenging to create projects that are seeking sustainable and efficient energy performances [30]. Gao et al. [7] argued that BIM models usually contain high-level data that is too complicated for the BIM energy tools to understand. Designers are also required to assume a set of parameters for the simulations, and human behaviour is usually treated as robots [44]. Furthermore, the existence of several BIM energy tools, parameters and approaches [45] makes it difficult to establish a common procedure, usually making unfeasible comparisons between buildings. There is a need to establish common procedures and standards to perform an energy analysis and to characterise the information exchanges between BIM platforms and energy tools [10,31,45].

### 2.3. Building Sustainability Assessment

#### 2.3.1. Overview

In the last two decades, several worldwide entities have developed BSA methods. These methods aim at implementing and spreading sustainable principles and evaluating and monitoring buildings performance and gathering information to support decision-making [46–48]. Some of their benefits include environmental conservation; improved building performance and occupants’ comfort, health and safety [49].

BSA methods are usually characterised by assessing some partial building features and aggregating the results into a sustainability score. They provide an opportunity for projects to demonstrate their ecological, economic and social benefits to the local community [50]. The most known BSA methods, which provide a basis to all the other approaches, are the Building Research Establishment Environmental Assessment Methodology (BREEAM)

from the Building Research Establishment (BRE), Leadership in Energy and Environmental Design (LEED) from the United States Green Building Council (USGBC) and Sustainable Building Tool (SBTool) from the international initiative for a Sustainable Built Environment (iiSBE) [51,52].

Nowadays, BSA methods are usually applied after the design is completed (or even after the building construction), turning possible modifications to improve the building sustainability unbearable or too expensive [53]. This can be justified due to the amount and complexity of data and documentation required for the evaluation. The application of BSA methods is also a voluntary approach worldwide, with the absence of mandatory legislation. Additionally, the assessment procedure is a time-consuming process—particularly in performance-based methods—which is usually incompatible with project companies' short deadlines [54,55], making it necessary to search for more efficient and expeditious approaches. For instance, Zhang et al. [53] suggested a real-time green building rating method that can identify potential ways to optimise the final rating during the design process. Some other constraints were also identified by researchers, such as errors from manual and traditional measuring tools or through calculations or even during data collection [56,57]. These types of errors can have great impact on the environment, since these methods are the main source of shaping sustainable decisions in projects [8]. User-friendly restrictions, the complex credit structure and the required user knowledge are also common issues that hinder the use of BSA methods [49].

The Portuguese scenario for BSA methods still has a long run. Portuguese designers often neglect sustainability assessment schemes, since there is not any mandatory sustainable evaluation for buildings. Additionally, performing a BSA is a time-consuming and complex process. To date, Portugal has not had an official BSA method, and only a couple of building sustainability rating schemes have been explicitly developed for the country conditions, such as the SBTool<sup>PT</sup>-H, LiderA and Domus Natura [58,59]. According to Pires and Fidélis [60], the development of sustainable indicators in Portugal lacks political commitment and vision, as well as poor stakeholder involvement. Nevertheless, existing methods have already been adapted to embrace different Portuguese building types, such as residential houses, hospitals, schools, offices, or even urban areas [48,61,62].

### 2.3.2. BIM Integration

Despite the recent trend on the use of BIM for sustainability purposes, there is still a lack of research considering all the sustainability dimensions [4]. Regardless of the potential benefits, so far, BIM has not been used comprehensively to obtain the required information for a sustainability assessment [27]. The existing BIM software stills lacks sustainability issues, and exchange format files are still in need of further developments [52,63]. Thus, the opportunity for the BSA methods to benefit from BIM capabilities has emerged, as well as the possibility of integrating the different BSA methods in the BIM collaborative process. Beyond the direct benefits for project teams and buildings occupants, significant advantages are expected to the construction industry, such as more sustainable and ecological buildings and a reduction in the potential environmental impacts. With the increasing maturity of BIM, a higher integration of building sustainability is also expected [4].

Currently, BIM is most commonly used to support the assessment of LEED, mainly in the categories of energy and atmosphere and materials and resources [29,37]. Nevertheless, several authors [63–67] focused their research on assessing different credits from all LEED categories. BREEAM has also attracted researchers' attentions. BIM has been used to support the assessment of BREEAM credits on the Materials, Energy, Water, Land use and Ecology, Health and Wellbeing and Waste and Pollution categories [8,66,68,69]. Edwards et al. [8] identified which criteria from BREEAM and LEED can be assessed with some recognised BIM tools. Most of them can often provide data to assess energy-related and indoor comfort-related categories of both schemes.

Other attempts for different BSA schemes have also been made, with Wong and Kuan [24] assessing 26 out of 56 criteria of BEAM Plus method with BIM in a faster

and more accurate way. On the Australian Green Star Building Certification, Gandhi and Jupp [70] used BIM to evaluate 66% of the office building scheme credits. Hoseini et al. [71] suggested that BIM can also support the assessment of 75% of New Zealand Green Star Certification with the development of proper guidelines. Concerning SBTool, Carvalho et al. [27,72] developed a conceptual framework for the integration of BIM with the Portuguese BSA method for residential buildings—SBTool<sup>PT</sup>-H. The assessment procedure of almost all the SBTool<sup>PT</sup>-H criteria can significantly benefit from the use of BIM. They also compared the feasibility of using BIM in SBTool<sup>PT</sup>-H with its use in other BSA methods, such as LEED and BREEAM [37].

Despite the benefits, a common conclusion is that BIM is not properly oriented and has not achieved its full potential to sustainable building design [8,27,73]. There are also frequent interoperability issues between BIM platforms and tools, with some information lost, requiring additional time for model checking and corrections. The common standards for data exchange must also be further developed to include more sustainability issues [4,74,75]. Chong et al. [74] argued that future BIM standards should consider a requirement for sustainability assessment, while Gandhi and Jupp [70] asked for specific BIM coordination and execution plans.

### 2.3.3. SBTool<sup>PT</sup>-H

The BSA method SBTool is considered the most comprehensive of all the methods due to its flexibility to be adjusted to the region local context [48,52]. SBTool has already influenced Austria's, Spain's, Japan's and Korea's national rating systems, and custom versions are in use in Italy, the Czech Republic and Portugal [76,77]. The transposition of the SBTool to the Portuguese residential scenario (SBTool<sup>PT</sup>-H) was done to create a generic method to assess the sustainability of existing, new and renovated Portuguese buildings. This method aims at supporting design teams since the early design stages and raising awareness to adopt more sustainable construction solutions. In SBTool<sup>PT</sup>-H, there are a total of 25 parameters, sorted by nine categories, which are divided into three sustainability dimensions: Environment, Society and Economy. The scheme structure is presented in Appendix A. Each parameter has a different weight according to the national standards and practices, and it is classified with a quantitative "score" that results from the comparison between the performance of the analysed building and two benchmarks: best and conventional sustainable practice. Each "score" is normalised to establish a dimensionless value that expresses the building performance in comparison to the benchmarks [78]. In this dimensionless scale, 0 corresponds to the conventional practice and 1 to the best practice. The normalised value is then converted into a qualitative scale that ranges from E to A+, where D corresponds to the conventional practice and A to the best practice.

Since the aim of this research is to use BIM-based energy simulation results to support the assessment of BSA methods, it is required to further investigate SBTool<sup>PT</sup>-H energy efficiency-related criteria.

The energy efficiency category (C3) from SBTool<sup>PT</sup>-H gathers two sustainability parameters related to building energy efficiency: P7—Primary Energy and P8—On-site energy production from renewables. To obtain high scores in these parameters, it is essential to optimise the building energy efficiency and on-site energy production from renewable sources by improving the building envelope and energy systems. Both parameters are based on calculation methods defined in the Portuguese regulation REH, forcing designers to perform different and time-consuming calculations to achieve the required data for the assessment.

The assessment of the energy efficiency category follows the general pattern of the remaining categories, where the building performance is compared with the national benchmarks. Thus, for the assessment of P7, the primary energy needs of the case study ( $P_{ENR} = N_{tc}$ ) are compared with two benchmarks: the Portuguese conventional practice ( $P_{ENR*} = N_t$ ) and best practice ( $P_{ENR*} = 0.25 \times N_t$ ); according to the current thermal regulation, the national best practice corresponds to a building that consumes 25% or less

energy than a conventional building. The comparison is carried out using a quantitative normalised value, which results from the application of Equation (1). Then, the final result ( $\overline{P_{ENR}}$ ) is reached by converting the normalised value into a qualitative scale, according to Table 1.

$$\overline{P_{ENR}} = \frac{P_{ENR} - P_{ENR*}}{P_{ENR*} - P_{ENR*}} \quad (1)$$

where:

$\overline{P_{ENR}}$ —case study normalised result for P7;

$P_{ENR}$ —case study result for P7;

$P_{ENR*}$ —national best practice for P7;

$P_{ENR*}$ —national conventional practice for P7.

**Table 1.** Conversion from the quantitative to the qualitative performance scales in SBTool<sup>PT</sup>-H.

Qualitative Level	Quantitative Value
A+	$p > 1.00$
A	$0.70 < p \leq 1.00$
B	$0.40 < p \leq 0.70$
C	$0.10 < p \leq 0.40$
D	$0.00 \leq p \leq 0.10$
E	$p < 0.00$

For the assessment of P8, the renewable energy production ( $P_{ER}$ ) of the case study is compared again with two benchmarks: the Portuguese conventional practice ( $P_{ER*}$  = production from renewables of 50% of the energy needs for Domestic Hot Water—DHW) and best practice ( $P_{ER*}$  = production from renewables of 90% of the total primary energy needs). Once again, the comparison is made using the normalised value (Equation (2)), and the final result ( $\overline{P_{ER}}$ ) is according to the qualitative scale of Table 1.

$$\overline{P_{ER}} = \frac{P_{ER} - P_{ER*}}{P_{ER*} - P_{ER*}} \quad (2)$$

where:

$\overline{P_{ER}}$ —case study normalised result for P8;

$P_{ER}$ —case study result for P8;

$P_{ER*}$ —national best practice for P8;

$P_{ER*}$ —national conventional practice for P8.

### 3. Materials and Methods

The primary purpose of this study is to define and apply a BIM process that can support and optimise the mandatory energy performance analysis of Portuguese buildings. To date, despite the several studies about using BIM to assess the energy performance of buildings, none of those has defined and identified a suitable method for Portuguese dwellings that is according to the Portuguese legislation. Furthermore, the process should also provide data for a sustainability assessment since energy performance simulation results are usually valuable insights for the energy performance category of BSA methods. Nowadays, the application of BSA methods is not a standard procedure between Portuguese construction companies, due to the required time, knowledge and resources for the assessment. It is then necessary to take essential steps for the integration of BIM and BSA methods to effectively improve building sustainability. To guide the research, the following RQ were defined:

- RQ1: Can BIM enhance and optimise Portuguese buildings energy efficiency and buildings thermal project?
- RQ2: Is the BIM-based method reliable and according to the Portuguese standards?
- RQ3: Can the results be used for sustainability assessments?

As a first step, it is necessary to identify a suitable process and software to perform an energy analysis according to the Portuguese regulations. Additionally, the process should consider Autodesk Revit as a BIM platform, since it was identified as the most commonly used software.

A study from Carvalho et al. [27] developed a conceptual framework for the integration of BIM in SBTool and suggested BIM approaches for each criteria assessment. For the energy-related criteria (P7—Primary Energy and P8—On-site energy production from renewables), they identified Cypetherm REH as the most suitable tool to estimate the energy performance of Portuguese residential buildings. In this tool, the calculation method is based on the Portuguese thermal regulation (REH), and it automatically produces the necessary information for the mandatory analysis of the building energy performance and national energy label. Cypetherm REH is one of the several software from CYPE Ingenieros, a Spanish company that develops computer software to support the AEC industry stakeholders. This software is adequately adapted to the national standards, and it is the most used among the Portuguese building design offices. Furthermore, Cype software has an add-in for BIM platform Autodesk Revit that allows exporting BIM models using IFC format. This process uses the BIMServer.center (<https://bimserver.center>) cloud, which acts as an intermediary platform between the selected software.

Following the previous goals, Cypetherm REH (version 2020d, Cype, Portugal) was selected to carry out the energy analysis for this research. However, the method of the Portuguese energy regulation requires as the input the amount of on-site renewable energy production, and the Cypetherm REH does not allow to perform this simulation. Therefore, the user must perform the simulation in an external software tool and input it into the software. To avoid the use of different climate databases, an official spreadsheet from the Portuguese Directorate-General for Energy and Geology (DGEG) was used to assess the case study's minimum requirements for renewable energy production. The simulation results from Cypetherm REH will be validated against the official Portuguese assessment method, i.e., using the official REH Excel spreadsheet (version V3.15 of 23 July 2020) for the evaluation of the building's thermal performance, which was developed by IteCons and University of Coimbra [79]. Currently, the method commonly used by designers requires considerable time to assess the building envelope characteristics, to select the calculation parameters and to perform a set of calculations. From the results of this stage, it will be possible to answer both RQ1 and RQ2.

After the simulation procedure, the results will be used to evaluate the two parameters of the SBTool<sup>PT</sup>-H energy efficiency category: P7 and P8. Cypetherm REH provides enough data for a comprehensive evaluation of both energy-related parameters. The assessment is made by linking the results from Cypetherm REH with SBTool<sup>PT</sup>-H evaluation spreadsheet, without performing any other calculations. Here, it will be possible to provide an answer for RQ3. The research procedure is summarised in Figure 1.

To apply the suggested procedure a case study is required. It must be framed under the scope of both REH and SBTool<sup>PT</sup>-H, i.e., must be a residential building. Thus, two different case studies were selected for the analysis: an existing building and a new building project (Figure 2).

The existing building is a 3-bedroom single-family house located in Porto, Portugal. It is representative of most of the common characteristics from Portuguese residential buildings built during the 1970s [80,81] in terms of: thermal resistance of the envelope elements (no insulation); construction materials (brick wall, sloped roof with ceramic tile, prestressed slab and wooden frame windows); typology (3-bedroom) and floor area (less than 100 m<sup>2</sup>). Since the first Portuguese thermal regulation was only introduced in 1990 [82], the dwelling has no insulation materials, creating a need for improving the thermal behaviour of the building envelope. The dwelling total net floor area is 74.92 m<sup>2</sup>, the interior floor to ceiling height is 3.05 m and the glazed area is 6.3 m<sup>2</sup>. The building is at an altitude of 155 m and located 5 km from the coastline. This case study will be submitted to an energy analysis as it is—the reference Model—and then, the building envelope will

be optimised—the optimised Model. After, another simulation is going to be carried out to demonstrate how the simulation tool can support the designer’s decision-making in comparing the performance of different design scenarios. The optimisation is made by only improving the building envelope thermal resistance, and the aim is to reduce at least 70% of the building energy demand and meet the current national standards. The optimised model concerns an energy renovation scenario, and it was defined according to the actual thermal requirements.

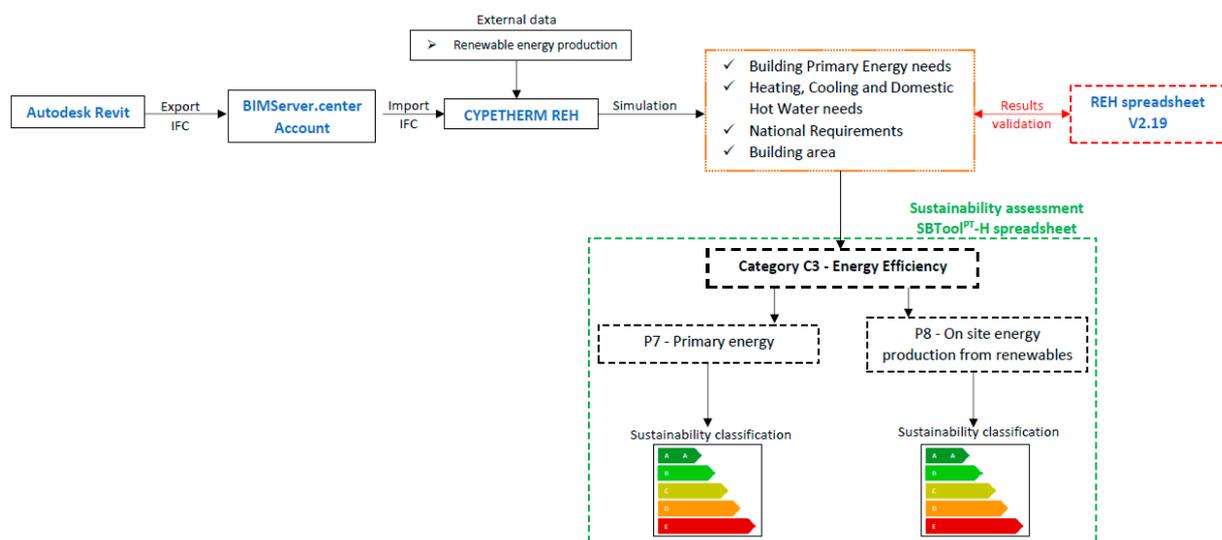


Figure 1. Simulation procedure.

The new building project case study is also a 3-bedroom single-family house located in Porto, Portugal (altitude of 155 m and located 5 km from the coastline). The building has not yet been built and is representative of almost all characteristics of the Portuguese dwellings nowadays [81]: construction materials (double-brick wall, flat roof, lightweight block and beam slab and aluminium window frame with thermal break); typology (3-bedroom); windows area (window-to-floor ratio of 15–20%) and floor area (average of 150 m<sup>2</sup>). The building total net area is 143.53 m<sup>2</sup>, the interior floor-to-ceiling height is 2.60 m and the glazed area is 39.66 m<sup>2</sup>. Since, in this case study, it is necessary to fulfil the REH minimum energy requirements, only one virtual model was made and analysed. This design scenario was already defined to match the regulation best practices.

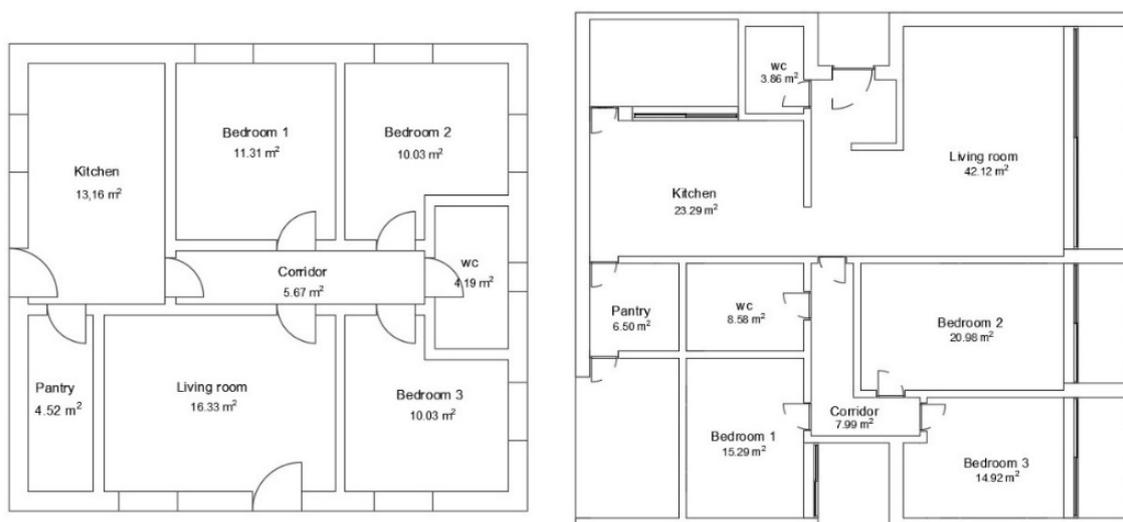


Figure 2. Floor plan of the case studies: existing model and new building model.

The thermal characteristics of both case studies scenarios are presented in Table 2. The surface albedo for walls, doors and roofs was defined as a bright colour ( $D = 0.4$ ), which influenced the building summer gains (more gains with darker colours and fewer with brighter colours). The efficiencies of all the systems (heating, cooling, DHW and solar) were kept constant for all the simulations. The simulations also considered gains and losses by natural ventilation, and the adopted ventilation renovation rates (air changes per hour—ach) were according to the recommendations of the Portuguese regulation REH (winter = 0.4 ach, summer = 0.6 ach).

**Table 2.** Construction solutions and systems.

Element	Existing Building		New Building
	Reference Model	Optimised Model	
Exterior walls	Simple brick wall (15 cm) $U = 1.69 \text{ W}/(\text{m}^2\text{K})$	Double brick wall (15 + 11) with XPS insulation (6 cm) in the middle $U = 0.40 \text{ W}/(\text{m}^2\text{K})$	Double brick wall (15 + 11) with XPS insulation (5 cm) in the air cavity (2 cm) $U = 0.38 \text{ W}/(\text{m}^2\text{K})$
Interior walls		Simple brick wall (11 cm) $U = 1.78 \text{ W}/(\text{m}^2\text{K})$	
Floor slab	Lightweight block and beam slab (20 cm) and wooden floor finishing (3 cm) $U = 1.60 \text{ W}/(\text{m}^2\text{K})$	Lightweight block and beam slab (20 cm), with interior XPS insulation (7 cm) and wooden floor finishing (3 cm) $U = 0.34 \text{ W}/(\text{m}^2\text{K})$	Lightweight block and beam slab (25 cm), with interior XPS insulation (4 cm) and wooden floor finishing (3 cm) $U = 0.30 \text{ W}/(\text{m}^2\text{K})$
Roof slab	Lightweight block and beam slab (25 cm) $U = 2.02 \text{ W}/(\text{m}^2\text{K})$	Lightweight block and beam slab (25 cm), with exterior XPS insulation (8.5 cm) and waterproof membrane $U = 0.35 \text{ W}/(\text{m}^2\text{K})$	Lightweight block and beam slab (25 cm), with exterior XPS insulation (8.5 cm), waterproof membrane and gravel (5 cm) $U = 0.35 \text{ W}/(\text{m}^2\text{K})$
Sloped roof	Lightweight block and beam slab (25 cm) with ceramic tile $U = 2.02 \text{ W}/(\text{m}^2\text{K})$	Lightweight block and beam slab (25 cm) with ceramic tile $U = 2.02 \text{ W}/(\text{m}^2\text{K})$	-
Windows—glass	Single glass 6 mm (Solar factor 0.85) $U = 2.50 \text{ W}/(\text{m}^2\text{K})$	Double-glass 6 mm + 4 mm (Solar factor 0.78) $U = 1.50 \text{ W}/(\text{m}^2\text{K})$	
Windows—frame	Wooden frame (w/ exterior shutter) $U = 2.50 \text{ W}/(\text{m}^2\text{K})$	Aluminium frame with thermal break (w/ exterior shutter) $U = 1.50 \text{ W}/(\text{m}^2\text{K})$	
Exterior doors		French wooden door $U = 1.50 \text{ W}/(\text{m}^2\text{K})$	
Interior doors		Wooden light door $U = 2.50 \text{ W}/(\text{m}^2\text{K})$	

## 4. BIM Model for Energy Simulation

### 4.1. Building Modelling

The first research step consisted of creating the BIM models in the BIM platform Autodesk Revit (version 2019, Autodesk, United States of America). By allowing a parametric modulation, building elements automatically recognise each other, and the related parameters are established between them. After setting the building location and orientation, it was necessary to define the thermal characteristics of the building. For this purpose, the materials Heat Transfer Coefficients ( $U$ ) and density were set, according to ITE 50 from the Portuguese national civil engineering laboratory (LNEC) [83], so they could be representative of the Portuguese context. Then, the simulation tool recognises every building compartment; the function of each element was set (interior or exterior) for walls, floors, doors and roofs and the “room” function applied to every compartment. At this

step, the compartment-specific properties such as name, dimensions and boundaries were organised. Finally, the model energy settings, interferences and errors were also rapidly checked by using the integrated functions of Autodesk Revit. Overall, the models can be classified as a LOD 300—they contain data about the building form, openings/windows, interior spaces and partitions, floors, walls, dimensions and material properties [34]. Note that the model creation may be performed in another BIM platform, such as ArchiCAD or Bentley, since the only requirement is the capacity to export the model in the IFC format.

#### 4.2. IFC Upload Using Open BIM Collaboration Add-In

Then, BIM models were uploaded into the BIMServer.center account (through IFC). For this specific case, this step was made using the Open BIM collaboration add-in for Autodesk Revit, avoiding the need to save the model in IFC and uploading it to the web page of BIMServer.center. Note that the add-in requires the use of Autodesk Revit. However, it is still possible to directly upload IFC models to the platform. After that, a new project was created in Cypetherm REH and the IFC file imported from the BIMServer.center account. The software allows to import materials libraries from the user's directory, and therefore, it was linked to the materials library from Autodesk Revit.

#### 4.3. Building Envelope, Systems and Thermal Bridges

When the BIM models were uploaded into Cypetherm REH, a couple of setbacks were faced. First, it was noticed that the materials library was not successfully linked. According to Cype technical support, it only allows linking materials libraries from other Cype software. The materials were defined again according to ITE 50, which are available on the Cype database. The building's location was also not accurately transmitted, and it was necessary to define it again. Since the software considers REH parameters, the climatic zones are automatically defined (which are used for the determination of the building envelope thermal quality requirements). Despite the general interoperability quality of the building's geometries and compartment identities, in these specific case studies, it was possible to notice slight differences in the compartment's floor-to-ceiling heights. This may be caused in Autodesk Revit upon the creation of the energy analytical model. The compartment volumes were adjusted according to the case studies models. A synthesis of the interoperability is presented in Table 3. To avoid some of these issues, it is recommended to double-check the BIM models first in IFC Builder software, which is used to create and adapt BIM models for Cype software use. Thus, geometry and identity errors can be easily corrected before importing the model into the energy analysis tool.

**Table 3.** Interoperability synthesis.

Successfully Transmitted	Not Transmitted
Building geometry	Building location
Building orientation	Material characteristics
Walls and floors thickness	Compartment's height
Opening's identity, size and location	Building energy system
Compartment's area	
Compartment's identity	

Next, it was necessary to complete the information regarding the building envelope. For every building element, i.e., external and internal walls, ground floor and roof, it was essential to confirm if all the imported data was in accordance with the BIM model and specify the absorption coefficient and the case study's typology (number of rooms). Cypetherm REH will then automatically calculate the thermal capacity and the U-values of the building elements, according to the selected materials. Regarding the interior and

exterior doors, only the U-value (if not correctly transmitted) and the absorption coefficient must be defined.

Concerning the windows, some more adjustments were necessary. Since Autodesk Revit does not allow designers to define all the parameters that influence the simulation, some actions are required in Cypetherm REH. The glazing type must be correctly defined according to ITE 50 from LNEC, such as the thickness of the air cavity, the glass solar factor and the glazed fraction (0.7 for all the simulations). The window frame characteristics must also be completed in terms of typology and U-value. Finally, the accessories, such as shading devices, must be defined in terms of colour, position and solar reduction factor (0.07 for all the simulations).

At last, it was necessary to define the systems for the dwellings—namely, the heating, cooling, DHW and the on-site systems—to produce energy from the renewables (e.g., solar thermal collectors). Since Autodesk Revit does not allow designers to set all this information, it must be directly defined in Cypetherm REH. For the heating, cooling and DHW systems, it is necessary to select the energy source (e.g., electricity or fuel) and the equipment type (e.g., split, multi-split, chiller or boiler). The natural ventilation renovation rates are also defined here. Additionally, the system wattage and efficiency must be stated, as well as the heated floor area. Concerning the renewable energy source, which is mandatory for new buildings and major renovations, Cypetherm REH allows choosing between solar and photovoltaic (PV) panels. For these case studies, solar panels were selected and the panel area, production, efficiency and losses defined.

Regarding the thermal bridges, since Autodesk Revit performs parametric modelling, Cypetherm REH recognises the connections between different elements and automatically defines the existing linear thermal bridges. The user must only define how to calculate the correspondent transmittances according to the selected standard. For these case studies, REH-simplified values were used, according to Table 7, from Despacho n<sup>o</sup> 15793-K/2013 [84].

## 5. Results and Discussion

### 5.1. BIM-Based Energy Simulation

Before performing any simulation in Cypetherm REH, it was necessary to estimate the amount of energy produced on-site from renewables. The use of on-site renewable energy is mandatory according to the Portuguese thermal regulation, and, therefore, Cypetherm REH does not allow performing any simulation without defining a renewable energy system. According to the Portuguese thermal regulation, the minimum amount of renewable energy to be produced on-site must be equivalent to half of the building DHW needs. In this study, it was assumed the introduction of a solar thermal collector with an area of 2 m<sup>2</sup> in each of the building's roofs, with a 35° slope and oriented to the south quadrant. The amount of renewable energy that can be produced was defined according to the national minimum requirements. By selecting the building location, altitude and main obstructions in the official spreadsheet from the DGEG, the minimum requirements calculated for the location were 1366 kWh per year. This value will be used for all the case studies simulations, both in Cypetherm REH and in the official REH Excel spreadsheet (version V3.15). Within the BIM environment, it would be easy to export the model to other energy simulation tool to assess renewable energy production. However, energy simulation software usually has different climatic databases, and using both would result in inaccurate outcomes.

With all the required data, it is possible to conduct energy performance simulations. First, the existing reference model was simulated in Cypetherm REH. Then, the existing optimised model was created in Autodesk Revit by introducing insulation layers into the building envelope and by replacing the windows with more efficient ones. The model was quickly updated into BIMServer.center using the Autodesk Revit Open BIM add-in, which automatically updates it in Cypetherm REH. The new building project model was also created in Autodesk Revit and simulated once in Cypetherm REH. Only one scenario was considered, as the goal was to demonstrate the method applicability for new buildings.

The simulation results—heating needs ( $N_{ic}$ ), cooling needs ( $N_{vc}$ ), primary energy needs ( $N_{tc}$ ) and DHW needs ( $Q_a$  and  $N_{ac}$ ), as well as the regulation (REH) limit values—are presented in Table 4. The existing reference model (without insulation) achieved heating, cooling and total needs far above the national limits. The results were as expected, due to the inexistence of any insulation material in the building. The scenario of the energy renovation—optimised model—accomplished the REH requirements and reached a reduction of 78.5% on the building total primary energy needs. This was mainly achieved by reducing the heating needs in over 80%. For the new building project, the current construction techniques and materials were used, reaching primary energy needs below the existing model (despite its larger area). This difference was mainly due to the building heating needs, which were almost 30% lower than the existing optimised model. The primary energy consumption ( $N_{tc}$ ) results from the application of Equation (3) are

$$N_{tc} = \frac{1 * N_{ic}}{\eta_i} * fp_{ui} + \frac{1 * N_{vc}}{\eta_v} * fp_{uv} + \frac{1 * N_{ac}}{\eta_a} * fp_{ua} - \frac{E_{ren} + E_{solar}}{A_p} \quad (3)$$

where:

$N_{tc}$ —building primary energy (PE) needs (kWh<sub>PE</sub>/(m<sup>2</sup>.year));

$N_{ic}$ —building heating needs (kWh/(m<sup>2</sup>.year));

$N_{vc}$ —building cooling needs (kWh/(m<sup>2</sup>.year));

$N_{ac}$ —building DHW needs (kWh/(m<sup>2</sup>.year));

$fp_{ui}$ —conversion factor to convert the final heating energy into PE;

$fp_{uv}$ —conversion factor to convert the final cooling energy into PE;

$fp_{ua}$ —conversion factor to convert the final DHW energy into PE;

$\eta_i$ —heating system efficiency;

$\eta_v$ —cooling system efficiency;

$\eta_a$ —DHW system efficiency;

$E_{ren}$ —renewable energy produced for electric use (kWh/year);

$E_{solar}$ —renewable energy produced for DHW use (kWh/year);

$A_p$ —total net floor area (m<sup>2</sup>).

**Table 4.** Cypetherm REH results.

Energy Needs	Existing Building		New Building
	Reference Model	Optimised Model	
$N_{ic}$ kWh/(m <sup>2</sup> .year)	201.21	38.61	27.12
Limit value $N_i$ kWh/(m <sup>2</sup> .year)		49.00	68.07
$N_{vc}$ kWh/(m <sup>2</sup> .year)	4.98	4.35	7.91
Limit value $N_v$ kWh/(m <sup>2</sup> .year)		9.15	9.15
$N_{tc}$ kWh <sub>PE</sub> /(m <sup>2</sup> .year)	518.29	111.26	80.17
Limit value $N_t$ kWh <sub>PE</sub> /(m <sup>2</sup> .year)		165.79	195.61
$Q_a$ (kWh/year)		2139.85	
$N_{ac}$ kWh/(m <sup>2</sup> .year)		28.56	

The conversion factors  $fp_{ui}$ ,  $fp_{uv}$  and  $fp_{ua}$  take the value of 2.5 if the energy source is electricity and the value of 1 for the fuel sources. The efficiency of the systems is represented by  $\eta_i$  for the heating system (with a value of 1),  $\eta_v$  for the cooling system (with a value of 3) and  $\eta_a$  for the DHW system (with a value of 0.93).  $E_{ren}$  and  $E_{solar}$  concern the amount of

renewable energy proceeded by the building (1366 kWh/year). All these values were used for all the simulations with both models.

According to the REH calculation procedure, the existing reference model achieved an F mark on the energy label resulting from the relation between  $N_{tc}$  and  $N_t$ , while the existing optimised model achieved a B mark. The new building project model reached an A level for the national energy label.

With this BIM-based method, the process to perform and compare energy performance simulations is enhanced. The requested amount of time is considerably reduced, and designers can quickly understand the impact of the rehabilitation scenario or other construction solutions on the building energy demand. Furthermore, Cypetherm REH automatically creates all the documentation and drawings for the building thermal project. Users can select documents such as “Energy performance label”, “Compliance with REH requirements”, “Thermal inertia”, “Thermal bridges description”, “Obstruction factors” and “Elements and material description”, as well as personalise their own drawings. This is mandatory data to deliver within the building thermal project to obtain a construction permit. Regarding the comparison of scenarios, Cypetherm REH also allows introducing improvement measures directly. However, the BIM model in Autodesk Revit must be manually updated later.

## 5.2. BIM-Based Energy Simulation Validation

At this stage, with the performance of such analysis, it was feasible to assume that RQ1 can be positively answered. Nevertheless, it is essential to validate this tool and process against a conventional and official method—RQ2. Thus, the Cypetherm REH simulation results were compared with the ones obtained from an official REH spreadsheet (conventional calculation process).

The simulation parameters for the REH spreadsheet were set equal to the ones of Cypetherm REH, namely: Building location, building typology, interior height, altitude, orientation, compartments and elements area, elements characteristics, systems efficiency and type, as well as thermal bridges (which were obtained from Cype’s “thermal bridges description” and later defined in the REH spreadsheet). Overall, all the input data in both methods were kept constant. During the validation simulation with the REH spreadsheet, the conventional procedure was adopted, but the BIM model was used to quickly assess the building envelope characteristics, such as the dimensions and U-values. The achieved results and comparison of both the energy performance simulation tools are presented in Tables 5 and 6 for the existing building and new building, respectively.

**Table 5.** Comparison between the Cypetherm REH results and REH spreadsheet results—existing building.

	Reference Model		Difference (%)	Optimised Model		Difference (%)
	Cypetherm REH	REH Spreadsheet		Cypetherm REH	REH Spreadsheet	
$N_{ic}$	201.21	200.68	0.26	38.61	38.54	0.18
$N_i$	49.00	45.97	6.18	49.00	45.97	6.18
$N_{vc}$	4.98	4.61	7.43	4.35	4.35	0.00
$N_v$	9.15	9.13	0.22	9.15	9.13	0.22
$N_{ac}$	28.56	28.56	0.00	28.56	28.56	0.00
$N_{tc}$	518.29	516.66	0.32	111.26	111.08	0.16
$N_t$	165.79	158.18	4.59	165.79	158.18	4.59

**Table 6.** Comparison between the Cypetherm REH results and REH spreadsheet results—new building.

	New Building		Difference (%)
	Cypetherm REH	REH Spreadsheet	
$N_{ic}$	27.12	26.78	1.27
$N_i$	68.07	65.36	4.14
$N_{vc}$	7.91	7.91	0.00
$N_v$	9.15	9.13	0.22
$N_{ac}$	28.56	28.56	0.00
$N_{tc}$	80.17	81.11	1.17
$N_t$	195.61	189.61	3.16

Concerning the calculated energy needs, both the Cypetherm REH and REH spreadsheet showed similar values, with deviations below 7.43%. However, the existing optimised model reached fewer differences with the validation engine than the existing reference model. The building performance maximum difference on the optimised model was only 0.18% ( $N_{ic}$ ), while, in the reference model, was 7.43% ( $N_{vc}$ ). A similar scenario was found for the new building project model, with a 1.27% difference between both methods' heating needs ( $N_{ic}$ ).

One of the most notorious difference was registered on the reference/limit value for the heating needs ( $N_i$ ) for both models—6.18% for the existing building and 4.14% for the new building. These values did not affect the simulation results, since they only represented the Portuguese reference value for this type of building. Although, by analysing the calculation methods, it was noticed that Cypetherm REH considers a reference U-value of 2.40 for exterior doors, while the REH spreadsheet considers 0.40. Thus, the calculation engine of Cypetherm REH considers that the heat transference by elements transmission is higher, and, therefore, the reference heating limit ( $N_i$ ) for the building is also higher. The reference U-value is given by REH; more specifically, from Portaria 379-A/2015 [85]. According to it, the reference U-value for the windows and doors for Porto's climatic zone (I2) should take a value of 2.40. Additionally, it also defines the reference U-value for opaque vertical and horizontal elements (0.40 and 0.35, respectively). Therefore, it can be concluded that the REH spreadsheet considers exterior doors as "opaque vertical elements". This leads to a more conservative value on the heating needs for the national reference/limit. With such a difference in the  $N_i$ -value, a difference of the same magnitude in the  $N_t$ -value was also expected, since it depends on it. Nevertheless, the difference was not so significant, reaching only 4.59% for the existing building and 3.16% for the new building.

Another significant difference was achieved in the cooling needs ( $N_{vc}$ ) only for the existing reference model (7.43%). To understand the reasons, once again, the calculation methods were carefully analysed. The problem was found in the windows' effective heating collection area. Since Cypetherm REH contains precise geometric data, the software can easily and accurately recognise which net glazed area is effectively facing south. Moreover, it also considers any existing obstructions or shading elements with higher accuracy. In the REH spreadsheet, the user must introduce all this data manually, and the orientations are fixed according to the cardinal axis. Overall, a slight difference of 0.1 m<sup>2</sup> on the solar collection was found between both methods. Since the existing reference model did not have any kind of insulation, this factor provided such a significant difference.

An additional setback was related to the number of decimal digits used in the calculations. Once again, the dimensions and U-values in Cypetherm REH are defined with several decimal digits (but only two or three decimal digits are displayed). At the same time, in the REH spreadsheet, it is the user's decision (according to availability and preference). This issue was the reason for the other small differences achieved between Cypetherm REH and the REH spreadsheet. As an example, Table 7 presents the same calculations but using Cypetherm REH and the REH spreadsheet. As it is possible to understand, the same calculation provided different results (0.1% difference).

**Table 7.** Rounding differences between Cypetherm REH and the REH spreadsheet.

	Cypetherm REH	REH Spreadsheet
Effective glazed area facing south (m <sup>2</sup> )	6.75	6.75
	×	×
Average south radiation (kWh/m <sup>2</sup> ·month)	130.00	130.00
	×	×
Heating season duration (months)	6.23	6.23
	=	=
Gross solar gains (kWh/year)	5466.83	5472.29

Nevertheless, some notes must be made regarding the input parameters. There are still some different inputs for the selected simulation tools, such as in the building exterior windows and building systems. For windows, Cypetherm REH allows defining some more simulation parameters, such as the frame type and performance, as well as different shading devices and their influence on the thermal performance of the window. For the building systems, Cypetherm REH also allows defining more types of efficiency, namely the seasonal Coefficient of Performance (COP) efficiency and the renewable energy system losses.

With these results, it is possible to provide an answer for RQ2. The identified BIM-based method can globally be accepted to carry out energy simulations and thermal projects in the Portuguese context. Moreover, the BIM-based process provides more reliable and precise results than the existing calculation spreadsheets. Still, there is some space for improvement, namely on the predefined reference U-values. Two calculation engines based on the same method must consider the same reference U-values for the exterior doors. Given that, and the small differences achieved, the BIM-based process can be successfully validated to be used in the assessment of the energy performance of residential buildings, according to the Portuguese thermal regulation.

### 5.3. Sustainability Assessment

Finally, it is possible to approach RQ3 and look for a sustainability assessment. Following the conceptual framework from Carvalho et al. [27], the energy simulation results from Cypetherm REH were used to assess the SBTool<sup>PT</sup>-H parameters P7—Primary Energy and P8—On-site energy production from renewables. With the energy simulation results, all the required information to assess the energy efficiency category is collected. The following sections present the assessment procedure for the SBTool<sup>PT</sup>-H parameters P7 and P8. For timesaving, the results were exported from Cypetherm REH to an XML document and then linked to the SBTool<sup>PT</sup>-H Excel spreadsheet.

#### 5.3.1. Parameter 7

The Cypetherm REH results were linked to the SBTool<sup>PT</sup>-H spreadsheet, and it was possible to reach an automatic assessment. For parameter P7—Primary energy demand, the required information for the evaluation is the total net floor area (74.92 m<sup>2</sup> for the existing model and 143.53 m<sup>2</sup> for the new building model), primary energy needs (and respective limit) and dwelling typology (three-bedroom dwelling). According to the SBTool<sup>PT</sup>-H evaluation guide, the building primary energy needs ( $P_{ENR} = N_t$ ) must be compared with two benchmarks: the national best ( $P_{ENR}^* = 0.25 \times N_t$ ) and conventional ( $P_{ENR} = N_t$ ) practice.

Therefore, using the Cypetherm REH results, these data assume the following values for the existing reference model:

$$P_{ENR} = N_{tc} = 518.29 \text{ kWh}_{PE}/(\text{m}^2 \cdot \text{year})$$

$$P_{ENR}^* = N_t = 165.79 \text{ kWh}_{PE}/(\text{m}^2 \cdot \text{year})$$

$$P_{\text{ENR}}^* = 0.25 \times N_t = 41.45 \text{ kWh}_{\text{PE}}/(\text{m}^2 \cdot \text{year})$$

The comparison against the benchmarks for the existing reference model is made using a normalised value, provided by Equation (1).

$$\overline{P}_{\text{ENR}} = \frac{518.29 - 165.79}{41.45 - 165.79} = -2.84$$

To reach the final score for P7, the normalised value must be converted into a qualitative scale, as presented in Table 8. The existing reference model achieved an E level for P7. This was an expected result for a non-insulated building.

The same assessment procedure was adopted for the existing optimised model, where the variables took the following values:

$$P_{\text{ENR}} = N_{\text{tc}} = 111.26 \text{ kWh}_{\text{PE}}/(\text{m}^2 \cdot \text{year})$$

$$P_{\text{ENR}^*} = N_t = 165.79 \text{ kWh}_{\text{PE}}/(\text{m}^2 \cdot \text{year})$$

$$P_{\text{ENR}}^* = 0.25 \times N_t = 41.45 \text{ kWh}_{\text{PE}}/(\text{m}^2 \cdot \text{year})$$

The normalised value for the existing optimised model is also provided by Equation (1).

$$\overline{P}_{\text{ENR}} = \frac{111.26 - 165.79}{41.45 - 165.79} = 0.4$$

Converting the normalised value into a qualitative score, the existing optimised model achieved a higher mark than the reference model—a B level for P7. Thus, the existing optimised model performance is between the national best and conventional practices for new buildings.

The same procedure was adopted for the new building to reach the analysis benchmarks.

$$P_{\text{ENR}} = N_{\text{tc}} = 80.17 \text{ kWh}_{\text{PE}}/(\text{m}^2 \cdot \text{year})$$

$$P_{\text{ENR}^*} = N_t = 195.61 \text{ kWh}_{\text{PE}}/(\text{m}^2 \cdot \text{year})$$

$$P_{\text{ENR}}^* = 0.25 \times N_t = 48.90 \text{ kWh}_{\text{PE}}/(\text{m}^2 \cdot \text{year})$$

By normalising the results using Equation (1) and converting them into a qualitative score, the new building model reached an A level for P7. The results from all the simulated models are presented in Table 8.

$$\overline{P}_{\text{ENR}} = \frac{80.17 - 195.61}{48.90 - 195.61} = 0.79$$

The results showed that, for parameter P7, all the required data for the assessment can be quickly obtained using BIM methodology. By exporting the BIM model from Autodesk Revit to Cypetherm REH, the building area elements (as walls, slabs, windows and doors) and material characteristics are automatically recognised. In the conventional assessment procedure, identifying all these characteristics is one of the most time-consuming tasks, which was almost instantaneous assessed using BIM. Then, just by adjusting/defining some simulation parameters, both the energy primary needs and limits are automatically calculated according to REH in the required units for SBTool<sup>PT</sup>-H use.

In what concerns the optimisation or adjustments of the building design, this task is also simple, since modifications in the BIM model (in Autodesk Revit) can be automatically updated in Cypetherm REH, allowing designers to compare the performances of different designs scenarios.

### 5.3.2. Parameter 8

Concerning SBTool<sup>PT</sup>-H parameter P8—On-site energy production from renewables, Cypetherm REH is not able to estimate the required renewable energy production (for

electrical use— $E_{ren}$ —or for DHW production— $E_{solar}$ ). An official spreadsheet from DGE was used to assess the minimum national requirements for renewable energy production, resulting in a value of 1366 kWh/year. All this energy was specified for the production of DHW— $E_{solar}$ .

The required data for SBTool<sup>PT</sup>-H to perform this evaluation are: dwelling typology (three-bedroom), total net floor area (74.92 m<sup>2</sup> for the existing model and 143.53 m<sup>2</sup> for the new building model), heating, cooling and DHW needs and energy production ( $E_{ren}$  and/or  $E_{solar}$ ). To assess parameter P8, the building energy production ( $P_{ER}$ )—calculated through Equation (4)—must be compared with the conventional national practice ( $P_{ER*}$ )—Equation (5)—and best practice ( $P_{ER*}$ )—Equation (6).

The following calculations were performed for the existing reference model:

$$P_{ER} = \frac{E_{solar} + E_{ren}}{A_p} \quad (4)$$

$$P_{ER} = \frac{0 + 1366}{74.92} = 18.23 \text{ kWh}_{PE} / (\text{m}^2 \cdot \text{year})$$

$$P_{ER*} = 0.5 \times \frac{Q_a}{0.95 \times A_p} \quad (5)$$

where:

$P_{ER*}$ —national conventional practice for P8;

$Q_a$ —building DHW needs (kWh/year);

$A_p$ —building total net area (m<sup>2</sup>).

$$P_{ER*} = 0.5 \times \frac{2139.85}{0.95 \times 74.92} = 14.35 \text{ kWh}_{PE} / (\text{m}^2 \cdot \text{year})$$

$$P_{ER*} = N_{tc}' = 1.2 \times \left( \frac{N_{ic}}{1} \times 2.5 + \frac{N_{vc}}{2.8} \times 2.5 + \frac{Q_a}{(0.95 \times A_p)} \times 1.0 \right) \quad (6)$$

$$P_{ER*} = 1.2 \times \left( \frac{201.21}{1} \times 2.5 + \frac{4.98}{3} \times 2.5 + \frac{2139.85}{(0.95 \times 74.92)} \times 1.0 \right) = 644.69 / 2.5 = 257.88 \text{ kWh}_{PE} / (\text{m}^2 \cdot \text{year})$$

With all the variables, it is possible to compare the building's renewable energy production with both benchmarks using Equation (2). As a normalised value of 0 corresponds to the conventional national practice, the analysed building is slightly better than that.

$$\overline{P_{ER}} = \frac{18.23 - 14.35}{257.88 - 14.35} = 0.016$$

Converting the normalised score into a qualitative scale, the existing reference model achieved a D level for parameter P8, as presented in Table 8.

The same procedure was adopted to assess parameter P8 for the existing optimised model. As the renewable energy production was kept the same, as well as the DHW needs, both calculations for the building energy production ( $P_{ER}$ ) and the conventional national practice ( $P_{ER*}$ ) were equivalent. It was only necessary to calculate the national best practice ( $P_{ER*}$ )—Equation (6)—by introducing the existing optimised model heating and cooling needs.

$$\begin{aligned} P_{ER} &= 18.23 \text{ kWh}_{PE} / (\text{m}^2 \cdot \text{year}) \\ P_{ER*} &= 14.35 \text{ kWh}_{PE} / (\text{m}^2 \cdot \text{year}) \end{aligned}$$

$$P_{ER*} = 1.2 \times \left( \frac{38.61}{1} \times 2.5 + \frac{4.35}{3} \times 2.5 + \frac{2139.85}{(0.95 \times 74.92)} \times 1.0 \right) = 156.26 / 2.5 = 62.50 \text{ kWh}_{PE} / (\text{m}^2 \cdot \text{year})$$

The comparison between the building renewable energy production and both benchmarks was performed by using the normalisation Equation (2).

$$\overline{P}_{ER} = \frac{18.23 - 14.35}{62.50 - 14.35} = 0.081$$

The qualitative score for the existing optimised model is presented in Table 8. Only by improving the thermal insulation of the building envelope was it possible to improve the classification of this parameter slightly. Even though the existing optimised model achieved a D level, the classification was closer to the bottom border of the upper qualitative level. The results were as expected, since the renewable energy production was set according to the regulation reference (minimum requirements). The same amount of renewable energy production was considered for both models.

Finally, the energy simulation results from the new building model were also linked to SBTTool<sup>PT</sup>-H for the assessment of P8. As the building area is different, the benchmarks must be defined again.

$$P_{ER} = \frac{E_{solar} + E_{ren}}{A_p}$$

$$P_{ER} = \frac{0 + 1366}{143.53} = 9.52 \text{ kWh}_{PE} / (\text{m}^2 \cdot \text{year})$$

$$P_{ER*} = 0.5 \times \frac{Q_a}{0.95 \times A_p}$$

$$P_{ER*} = 0.5 \times \frac{2139.85}{0.95 \times 143.53} = 7.85 \text{ kWh}_{PE} / (\text{m}^2 \cdot \text{year})$$

$$P_{ER*} = N_{tc}' = 1.2 \times \left( \frac{N_{ic}}{1} \times 2.5 + \frac{N_{vc}}{2.8} \times 2.5 + \frac{Q_a}{(0.95 \times A_p)} \times 1.0 \right)$$

$$P_{ER*} = 1.2 \times \left( \frac{27.12}{1} \times 2.5 + \frac{7.91}{3} \times 2.5 + \frac{2139.85}{(0.95 \times 143.53)} \times 1.0 \right) = 108.1 / 2.5 = 43.24 \text{ kWh}_{PE} / (\text{m}^2 \cdot \text{year})$$

The normalised value for P8 is given by the application of Equation (2). The conversion into a qualitative score resulted in a D level for the new building model. Since the renewable energy is the same as for the existing building, a similar result was also expected. All the sustainability scores are presented in Table 8.

$$\overline{P}_{ER} = \frac{9.52 - 7.85}{43.24 - 7.85} = 0.05 \quad (7)$$

**Table 8.** Final score for parameters P7 and P8.

Qualitative Level	Quantitative Value	P7			P8		
		Existing Building		New Building	Existing Building		New Building
		Reference	Optimised		Reference	Optimised	
A+	$p > 1.00$						
A	$0.70 < p \leq 1.00$			X			
B	$0.40 < p \leq 0.70$		X				
C	$0.10 < p \leq 0.40$						
D	$0.00 \leq p \leq 0.10$				X	X	X
E	$p < 0.00$	X					

The use of Autodesk Revit and Cypetherm REH can provide almost all the necessary data for the assessment of parameter P8. The exception goes for renewable energy production that needs to be previously calculated, which is the main setback. Nevertheless, Cypetherm REH allows designers to assess quickly (and simultaneous with the primary

energy needs for P7) the building heating, cooling and DHW needs according to REH, which are necessary for the P8 assessment.

However, the fact that Cypetherm REH cannot estimate the amount of renewable energy production only allows optimising parameter P8 by reducing the building energy needs. To further improve the P8 evaluation, it was necessary to select, for example, a higher area of solar thermal collectors to estimate the impact of a possible increase on renewable energy production. However, it was not the goal of this research, and therefore, the renewable energy production was kept constant.

Overall, a positive reply can be given to RQ3, as the simulation results from Cypetherm REH can be directly used in the assessment of the energy efficiency category of SBTool<sup>PT</sup>-H.

## 6. Conclusions

The use of BIM in the construction industry may be an essential path to optimise buildings' energy performances and the occupants' comfort requirements. BIM can significantly minimise the resources of Building Energy Modelling to analyse different design alternatives and improve building performances. This research validated a BIM-based process to carry out energy analyses and develop building thermal projects in the Portuguese context. The simulation results were also linked to the energy efficiency category of the Portuguese BSA method SBTool<sup>PT</sup>-H to analyse how the results can be used to assess the sustainability of buildings. This study analysed the possibility of using a BIM-based framework to improve buildings' energy performances and to develop mandatory thermal projects while improving buildings' sustainability. Designers can compare the impact of different energy solutions on the sustainability level of their buildings during the early design stage without spending too much time, money and other resources. As a case study, the presented framework was applied, discussed and validated in the Portuguese context but can, however, be extrapolated to other countries. This research also contributed to improving the knowledge about the integration of BSA in the BIM project workflow, providing new insights for complete implementation. BIM can significantly reduce the efforts for BSA application in project early design stages, bringing the opportunity to create more sustainable buildings.

When faced with the conventional assessment procedure, the applied BIM process improved the assessment of the building energy needs in terms of reliability and time. Less human errors are expected in assessing the building characteristics, in selecting simulation parameters according to REH and in defining thermal bridges. Less time was also required, as most of the building features were automatically recognised, the primary energy needs and limits were automatically calculated and information extraction happened faster. Moreover, it automatically provided mandatory documentation for the building thermal project. The simulation results were also revealed to be reliable. The differences from the REH spreadsheet were only noticeable due to the number of decimal digits considered for the several parameters, data accuracy and a predefined reference U-value for the exterior doors. Regarding the sustainability assessment, a single energy simulation in Cypetherm REH provided results for both of the SBTool<sup>PT</sup>-H energy efficiency criteria. It reduced the required efforts and time to carry out the BSA, encouraging designers to apply it in their projects.

Still, some limitations were also found during the BIM-based process. Renewable energy production must be assessed before the energy simulation using external tools. Some interoperability constraints were also noticed in the transmission of the building features (as presented in Table 3), which required a double-check revision with the energy simulation tool. Nevertheless, by using IFC builder, designers can check and correct the model's geometry and data before exporting to the energy simulation tool. Other issues were related to the model materials, which were not possible to transmit; the simulation results must always be connected to the SBTool<sup>PT</sup>-H spreadsheet, and the improvement measures must be manually introduced in Autodesk Revit. Overall, the

BIM-based process to carry out the energy analysis and thermal projects for Portuguese buildings was successfully validated, but it still requires further maturity.

It must be noted that this study was conducted with region-specific factors, which were established considering the Portuguese context. A specific oriented simulation tool was used, as well as a suitable BSA method. Nevertheless, SBTool<sup>PT</sup>-H is the adaptation to the Portuguese context of the international SBTool method, which has already been adapted to other countries' specificities. Additionally, Cype software (or other equivalent software) is also available in several countries, which make it possible to retain and export valuable insights about the applied process in other regions, especially about the interoperability between Autodesk Revit and Cype software. Nevertheless, other BIM platforms may be used, as long as they allow exporting the model IFC for BIMServer.center. This same procedure can also be applied for service buildings (using Cypetherm RECS instead of Cypetherm REH) and different parameters of SBTool<sup>PT</sup>-H, e.g., in the assessment of the acoustic performance (using Cypesound RRAE).

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## Appendix A

**Table A1.** SBTool<sup>PT</sup>-H list of categories and parameters.

Dimension	Category	Parameters	Category Weight (%)	Dimension Weight (%)
Environment	C1—Climate change and outdoor air quality	P1—Construction materials embodied environmental impact	12	40
		P2—Urban density		
	C2—Land use and biodiversity	P3—Soil sealing index of the development	19	
		P4—Use of precontaminated land		
		P5—Use of native plants		
		P6—Heat-island effect		
	C3—Energy Efficiency	P7—Nonrenewable primary energy consumption	39	
		P8—In situ energy production from renewables		
		P9—Materials and products reused		
	C4—Materials and waste management	P10—Use of materials with recycled content	22	
		P11—Use of certified organic materials		
		P12—Use of cement substitutes in concrete		
		P13—Waste management during operation		
	C5—Water efficiency	P14—Water consumption	8	
		P15—Reuse of grey and rainwater		

Table A1. Cont.

Dimension	Category	Parameters	Category Weight (%)	Dimension Weight (%)
Social	C6—Occupant’s health and comfort	P16—Natural ventilation efficiency	60	30
		P17—Indoor air quality		
		P18—Thermal comfort		
		P19—Natural lighting performance		
		P20—Acoustic comfort		
	C7—Accessibilities	P21—Accessibility to public transport	30	
		P22—Accessibility to urban amenities		
		P23—Occupant’s awareness and education regarding sustainability issues		
C8—Education and awareness of sustainability	P24—Capital costs	100		
	C9—Life cycle costs		P25—Operation costs	30

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