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Automating building sustainability assessment using building information modelling: A case study

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ABSTRACT

Facing the increasing pursuit of sustainable buildings, the construction industry has been adopting new project technologies. Building Sustainability Assessment (BSA) methods are a key tool to evaluate building sustainability, but their use is hindered by the time-consuming assessment process and required data. With the emergence of Building Information Modelling (BIM), new potentialities have been found, such as continuous data storage and integrated building design. Facing the opportunity to integrate BSA into BIM, this research aims to automate the assessment of a BSA scheme by creating a BIM-based application for the project's early stages. Visual Programming Language (VPL) was used to translate SBTool^{PT}-H criteria requirements into computable rules and create the SBTool^{BIM} application. Results show the feasibility of automating BSA with BIM, by integrating 19 criteria into SBTool^{BIM} and identifying BIM connections for the remaining 6 criteria. The applied procedure has established a novel framework to carry out BSA within the BIM environment in a faster and more reliable way using fewer resources. It offers a decision support tool for the design process able to provide valuable contributions to enhance building sustainability and meet decarbonisation and climate goals.

Abbreviations

AP	Acidification Potential
BIM	Building Information Modelling
BSA	Building Sustainability Assessment
CAD	Computer Aided Design
CSAT	Rainwater Satisfaction Coefficient
EP	Eutrophication Potential
FFDP	Fossil Fuels Depletion Potential
GWP	Global Warming Potential
IDF	Input Data File
IFC	Industry Foundation Classes
LCA	Life Cycle Assessment
LOD	Level of Development

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ODP	Ozone Layer Depletion Potential
POCP	Photochemical Ozone Creation Potential
PVC	Polyvinyl Chloride
REH	Portuguese thermal regulation
RRAE	Portuguese acoustic regulation
VOC	Volatile Organic Compound
VPL	Visual Programming Language

1. Introduction

General society and worldwide authorities are increasingly looking for more sustainable buildings [1]. Up to date, in Europe, buildings are responsible for 40% of the energy consumption, 36% of CO_2 emissions, 25% of the waste produced and 50% of the raw material consumption [2,3]. To turn buildings more efficient and sustainable, there is a need to act since the early project stages by introducing and analysing different sustainability measures, to effectively enhance building sustainability [4]. To support decision-making regarding effective sustainable measures and to monitor building's sustainable performance, Building Sustainability Assessment (BSA) methods have been developed all over the world and adapted to the specific conditions of each location and building. BSA must be properly adapted to region-specific aspects, to be in line with the local climate, society, culture, traditions, and building objectives and priorities [5,6]. They provide the opportunity for buildings to demonstrate their environmental, social, and economic benefits to the local community [7]. However, carrying out a BSA is currently a time-consuming and complex process, requiring the knowledge of interdisciplinary data and a long manual calculation procedure. Thus, BSA is commonly used in the project's later stages after finishing the project design, where modifications are unbearable or too expensive [8,9]. Furthermore, BSA is a voluntary approach with an absence of mandatory regulation and, together with the remaining setbacks, they have established a scenario for its reduced adoption [10]. There is a need to develop a more expedited method to perform BSA, with a real-time and dynamic evaluation, able to support project improvements and modifications, instead of the traditional static approach [11].

Buildings also need to comply with several requirements and criteria, such as normative standards, comfort and safety specifications, industry guidelines, and project requirements [12–14]. BSA can be related to existing requirements, as it also demands deep knowledge about the building, which is often difficult to obtain. With the deployment of digitalisation in the construction sector, building requirements are being translated into computer rules, to accelerate and guarantee building compliance in a faster and more reliable way [15]. BSA is based on a set of key performance indicators, which can also be represented by computer rules. Therefore, the opportunity arises to translate BSA methods into computable rules and effectively integrate them into existing computer software.

Building Information Modelling (BIM) is a novel methodology which is slowly replacing CAD and has emerged to support designers in managing all the project data and improving project efficiency [16,17]. BIM creates an excellent opportunity to incorporate sustainable measures throughout the design process, especially during the project's early stages, promoting the development of high-performance buildings [18]. It allows to store multidisciplinary information and encourages real-time collaboration among all the stakeholders [8,19,20]. BIM potential for automated rule checking has already been recognised and, together with Visual Programming Language (VPL), several compatible rules have been developed, creating better, faster, and more comprehensive assessment procedures [15].

Despite the existing research on the connection of BIM with BSA, a proper framework for this integration has not been established [21]. Authors tend to develop theoretical methods, which allow gathering BSA data through BIM, but any automatic evaluation has been made yet. With the possibility of translating BSA criteria into computable rules and facing the increased use of BIM, the opportunity for sustainability assessment automation arises. By automating BSA methods, they will eventually be an integral part of the common design process, providing a decision support tool to enhance building sustainability.

Thus, this research aims to establish a novel procedure for the automation of the Portuguese residential version of the BSA method $SBTool^{PT}$. By translating the BSA scheme into a computer application integrated into the Open BIM environment, a fast and reliable sustainability analysis can be performed during the project's early stages. Designers will be provided with an intuitive tool to analyse their building's sustainable performance, allowing them to introduce and compare improvement measures with few resources. Moreover, by creating an automated assessment procedure for the project's early stages, BSA application will be encouraged and coordination with all project disciplines enhanced. VPL will be used to translate the BSA requirements into computable rules and the application will be hosted in a BIM platform to fit into the BIM environment.

2. Literature review

2.1. Building sustainability assessment methods

Following the need to achieve more sustainable buildings, BSA methods have been developed worldwide by public authorities, international organisations, and private consultancy companies [6,22]. Usually, BSA schemes are developed according to a specific location or construction needs, but there are others which have the flexibility to be adapted to each region's requirements [23,24]. Moreover, more than 600 assessment schemes have been developed globally for BSA [24], addressing environmental, social, and economic aspects [25]. BSA methods aim at implementing and evaluating the building's sustainable performance by assessing a set of partial building features and aggregating the results into a sustainability score [6,25]. These rating systems are organised into

evaluation categories, which include criteria and multiple indicators on several topics, such as energy, waste, water, material impacts, transport, accessibility, social aspects, Life Cycle Assessment (LCA) or indoor environment [22,23,26]. BSA has an important role in sustainable building development, providing support for designers and building owners when dealing with the building life cycle design, construction, and operation [11]. Among some of the most known BSA methods are BREEAM, LEED, SBTool, CASBEE, DGNB, Green Star, HQE and BEAM [27,28]. The first three assessment schemes – BREEAM, LEED, and SBTool – have been considered the basis for all other approaches [29].

Currently, BSA is used as a voluntary approach taken by owners and/or developers to demonstrate their building's sustainable features [26]. However, authors have been discussing that nowadays, green building schemes are being seen as market-oriented tools to increase the building's value instead of focusing on sustainable-related aspects [11]. Furthermore, BSA is usually applied during the project's later stages or even after the construction itself, where improvement changes are often unfeasible [30]. Such a problem is related to the required amount of multi-disciplinary data for the assessment, as well as the required time to carry out the analysis. Due to the short deadlines of design teams, they are usually not able to spend resources and time performing BSA during the project's initial stages [10,31]. Moreover, improvement modifications will require the repetition of the assessment procedure, discouraging designers to do it [32]. Zhang et al. [30] have also reached similar conclusions about BSA status, suggesting the need for a real-time and dynamic assessment, which would be able to be applied in the project's initial stages in order effectively optimise the building final score. Different authors have also highlighted some other constraints of BSA methods, such as data collection, calculation mistakes, user-friendly restrictions and complex credit structures [33–35].

2.2. BIM and applications for building sustainability

With the growing digitalisation of the construction sector [36], BIM has emerged as a working methodology capable of managing the project design and all the building data with a virtual model through the building life cycle [37]. It is an integrated process where the building characteristics and data are digitally represented to improve interoperability and real-time collaboration among stakeholders [38]. BIM provides decision support data for designers and allows them to easily identify errors and incompatibilities, resulting in a more efficient process and result.

The BIM methodology implies the creation of a Building Information Model, which consists of a realistic and enriched representation of the building through a virtual model [13]. It is created based on a parametric and object-oriented approach, where parameters are defined to characterise the relation between the model objects [39]. The BIM model can store several multi-disciplinary data throughout the entire building life cycle, and it creates the opportunity to virtually construct and simulate the building performance before the construction itself [40]. The BIM model is classified according to its content and information through the Level of Development (LOD). The LOD specifies and articulates the content and reliability of a BIM model, facilitating stakeholders' communication, as well as supporting them in understating the BIM model's usability and limitations [41]. The LOD identifies the specific minimum content requirements for a certain use, and it is defined according to the objects graphic and data information [19]. For instance, the United States General Services Administration [42] has defined the minimum capabilities of the BIM model at different development stages. A LOD 200 is enough to estimate costs, while a LOD 300 is required to carry out building performance simulations. For sustainability purposes, a LOD 100 allows to integrate sustainable principles, a LOD 200 allows to get approximate quantities of materials and a LOD 300 allows for the extraction of precise quantities and other sustainable data such as recycled content or locally produced materials.

To create a BIM model, it is required to use a BIM authoring platform, which generates multiple uses information and allows to create and edit BIM models. Examples of BIM platforms are Autodesk Revit, ArchiCAD and Bentley MicroStation. To fully explore BIM method potentialities, virtual models are usually exported to BIM tools – software that performs a specific type of analysis, such as building performance analysis [8]. Autodesk Insight, IESVE or Solibri are examples of BIM tools. Interoperability between BIM platforms and tools is often made through an Industry Foundation Classes (IFC) model. The IFC is commonly readable by all BIM platforms and tools, being a platform-neutral and object-based structured format that describes building and construction industry data [43].

The use of BIM for sustainability purposes has also gained exponential attention in the past years [44,45]. Designers and stakeholders are increasingly looking for more efficient and ecological buildings and new approaches have been developed to support decision-making and enhance building sustainability. BIM has been recognised as an effective method to address building's environmental, social, and economic performance, with different applications throughout the building life cycle [21,46]. Authors [47,48] have identified the preconstruction and project phases as key stages to act on building sustainability. As BIM benefits are also more noticeable during the same phases, BIM influence on building sustainability becomes clear [26]. Among the most known BIM-based sustainable applications, the following stand out: life cycle analysis, energy analysis, daylight and lighting analysis, sustainability assessment, acoustic analysis, water consumption analysis and waste management.

A set of investigations have been made addressing the use of BIM to assess BSA methods, with credits directly calculated and documented in a short period of time with few resources [49]. Moreover, BSA exploits the full potential of the BIM method, requiring building multi-disciplinary data and building performance simulation results [32]. Direct benefits of BIM application regard decision support, automatic data extraction, automatic assessment, process efficiency and resource-use reduction. In a systematic review from Carvalho et al. [32], LEED has been identified as the most addressed BSA method regarding BIM integration. Several authors [50–53] have used BIM to assess LEED credits and prerequisites, mainly in the categories of Energy and Atmosphere and, Materials and Resources. Research has also been made on the integration of BIM with other schemes such as BREEAM, SBTool, BEAM Plus, Green Star and Green Mark [21,34,54–58]. The majority of these approaches have developed a theoretical framework where the assessment data can be gathered from BIM models and tools. A couple of practical applications can also be found but with limited focus on some BSA

criteria, especially regarding the site analysis, indoor environment and building performance.

A common conclusion among authors is that BIM is still not properly oriented for building sustainability and its full potential was not reached yet [21,34,43]. There is a need to extend current research, by including all sustainability dimensions and topics, as well as comprehensively integrating BIM for sustainability assessment [7,59]. BIM software should also embrace more sustainability issues and improve interoperability between them, avoiding the need for model checking and remodelling [51,54,59,60]. It is also frequently necessary to use several software to gather assessment data for the evaluation of only one BSA scheme [32]. Consequently, investigators [55,56] argue that BIM-based sustainability assessment requires the development of BIM coordination and execution plans to address and guide building certification, as well as the need to include BSA in BIM national standards [60].

2.3. Visual programming

VPL has been successfully recognised as an easy-to-learn codification mode when compared with traditional coding languages, which are commonly text-based programming languages [12,61]. It allows programming with a two-dimensional notation using visual elements instead of textual ones, providing faster and easier interpretation [12,17,27]. By being integrated with several BIM platforms, VPL presents a high degree of control and customisability of BIM models due to its geometric modelling functionalities and ability to create algorithms [44,62]. VPL provides transparency, flexibility and portability as design rules are machine and human-readable [12].

VPL has been commonly applied in different types of research, including building sustainability. Rule checking is one of the main topics when using VPL during the last few years, as the process consists of repetitive tasks that can be automatically performed with proper codification [12]. Burggraf et al. [15] have created an automatic system for checking semantic data of BIM-based factory designs through Dynamo. Cavalliere et al. [62] have proposed a novel approach to evaluate the flexibility of buildings during the design process phases. By automating design rules into six criteria through VPL, they have reached a real-time method to provide data for decision-making regarding flexible and sustainable choices. Ghannad et al. [12] have also automated rule checking by introducing a new modularised framework that integrates LegalRuleML with VPL. It encompasses a compliance checking process from the interpretation of natural language-based requirements to machine-readable rules, categorisation, and execution. VPL codes have been commonly developed for automatic extraction and process of quantities from BIM models [36] and, they can be used to rapidly define Life Cycle Inventories. Villaschi et al. [63] have successfully developed a VPL framework on Dynamo to automate the verification of Brazilian design rules for buildings, providing a novel tool for designers and authorities to evaluate building compliance. Furthermore, Dynamo has been used both to collect LCA data, as well as to perform the calculation itself, allowing for the direct assessment of the building and material's environmental impacts [62,64]. BSA methods have also been addressed with VPL. Kensek et al. [52] have evaluated if a building should earn LEED Pilot credit 55 – Avoiding Bird Collisions with a software-assisted approach based on Dynamo.

Other BIM-based VPL approaches concern the use of Dynamo to handle and correct faulty analytical data from BIM geometries, enhancing the procedure of obtaining a Finite Element Model [17]. Sheikhkhoshkar et al. [28] have shown other applications for building structural analysis, by using VPL, Matlab and Excel to extract spatial data regarding construction joints from BIM models. Banfi and Previtali [65] have used VPL and a 3D real-time platform to obtain extended reality for the analysis of archaeological sites and heritage buildings. Scan-to-BIM and digital photogrammetry methods have also been used. Likewise, VPL is emerging for topics such as facility management, with several links between BIM models, databases, and sensors data [13,61]. Moreover, Thai [66] has suggested that VPL should be included in architecture, design, and engineering classes to facilitate the programming learning process. VPL has a steeper learning curve than text-based languages, lowering the barriers when entering into programming [17].

Among the most recognised VPL tools are Grasshopper for Rhinoceros3D, Dynamo for Autodesk Revit, Marionette for Vectorworks, Generative components, Digital Project, and Yeti [17,67].

2.4. SBTool

This research will be focused on the Portuguese residential version of SBTool. SBTool has influenced several rating systems, including for Austria, Spain, Japan, South Korea, Italy, Czech Republic, and Portugal, due to its flexibility to be adapted to the local conditions of each region. SBTool covers a wide range of sustainable issues, and its scope can be modified to be as narrow or as broad as desired, from more than 100 criteria to half a dozen [6,68,69]. Such criteria are usually selected when transposing the international SBTool system to each location, according to the local standards, practices, customs, and priorities. Moreover, criteria weights are also adjusted to region-specific and site-specific factors, by using a multi-variable method to define the weighting system, which is detailed in Ref. [6]. In the Portuguese version of SBTool ($SBTool^{PT}$), each sustainability criterion is classified with a quantitative score that

Table 1
$SBTool^{PT}$-H conversion scale.

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

results from the comparison between two benchmarks: national best and conventional practices. The quantitative score is then normalised through equation (1) and turned into a qualitative score through a linear evolution according to Table 1. The aim is to establish a dimensionless value and to easily express the building score to non-experts. In the qualitative scale, D corresponds to the national conventional practice, while A corresponds to the national best practice. After weighing and aggregating all the parameters, a final sustainable classification is given to the building [6].

$$\overline{P_i} = \frac{P_i - P_{*i}}{P_i^* - P_{*i}} \forall_i \tag{1}$$

$\overline{P_i}$ – Result of the normalisation of parameter i
P_i – Case study quantification of parameter i
P_i^* – National best practice for parameter i
P_{*i} – National conventional practice for parameter i

The transposition of SBTool for the Portuguese context was made at different levels for residential buildings, service buildings, and urban areas, among others [70–72]. Between the local versions, SBTool^{PT}-H stands out as it focuses on new and existing residential buildings. The aim was to develop a method to assess the sustainability of residential buildings and to raise awareness about the benefits of adopting more sustainable solutions [6]. SBTool^{PT}-H has a total of 25 criteria, sorted by 9 categories, which are divided into three sustainability dimensions, as presented in Table 2. The calculation procedure follows the international systems, where each criterion has a different weight and it is classified with a quantitative score, resulting from the benchmark comparison and normalisation.

Up to date, carrying out a manual sustainability assessment is a very time-consuming process, requiring multi-disciplinary data about the building and a set of pre-defined calculations, as part of an inefficient interactive assessment process. The application of BSA methods is also usually incompatible with project short deadlines and project modifications also require the repetition of the assessment process. Therefore, there is an urgent need to optimise and automate BSA, so they can be easily applied during the project's early stages – supporting eventual modifications with few resources – and effectively enhancing building sustainability.

3. Material and methods

3.1. Methodology

Facing the capabilities of BIM for sustainability purposes and the current nonexistence of an established BIM-based method to automate BSA evaluation, this research aims to establish a procedure and a BIM-based application to automate sustainability assessment during the project's early stages. Moreover, it is also intended to efficiently integrate BSA into the BIM environment, to effectively enhance building sustainability. The Portuguese residential version of SBTool (SBTool^{PT}-H), which is based on Key-Performance Indicators will be used as a case study and the BIM-based application will be named SBTool^{BIM}. The following specific objectives are intended for the SBTool^{BIM}:

- Simple and intuitive method to promote and encourage BSA implementation by designers;
- Applicable in the project's early stages to effectively act on building sustainability, where modifications are still feasible and more cost-effective;
- Provide real-time feedback to act as a decision support tool for designers, allowing them to constantly understand the sustainability level of their projects and solutions;
- Allow to quickly introduce and analyse improvement measures to optimise building sustainability;
- Integrated into the Open BIM concept to effectively include BSA in the common BIM project workflow. The aim is to promote BSA use when adopting the BIM methodology for project development;
- Include as many criteria as possible to fully automate the evaluation process and avoid parallel processes (and rework) when assessing non-covered criteria.

Based on the research objectives, this study will develop a BIM-based application for end-users to support project design and increase building sustainability. Thus, SBTool^{BIM} needs to be applied during the building design and modelling stage and, to successfully

Table 2
SBTool^{PT}-H list of categories.

Dimension	Dimension weight (%)	Category	Number of criteria	Category weight (%)
Environment	40	C1 – Climate change and outdoor air quality	1	12
		C2 – Land use and biodiversity	5	19
		C3 – Energy Efficiency	2	39
		C4 – Materials and waste management	5	22
		C5 – Water efficiency	2	8
Social	30	C6 – Occupant's health and comfort	5	60
		C7 – Accessibilities	2	30
		C8 – Education and awareness of sustainability	1	10
Economic	30	C9 – Life cycle costs	2	100

create a link with BIM methodology, it must be related to a BIM authoring platform. Given the capabilities of Autodesk Revit, which are described in the next section, it was chosen as a BIM platform to host the SBTool^{BIM} application.

The method to develop SBTool^{BIM} itself will be based on an automated code checking procedure [15]. The research methodology will consider the four main aspects of automated code checking with slight deviations, assumptions, and extra works, according to the research needs:

1. Rule interpretation – SBTool^{PT}-H assessment requirements and calculation procedures will be carefully analysed to identify all the necessary inputs and workflow. Moreover, for each SBTool^{PT}-H criterion, all the input data will be identified, as well as a possible way to include it in the sustainability analysis. According to the data type, different integration methods and data collection procedures will be suggested. This data will then be translated into a computer-processable language to be later programmed.
2. Based on the previous analysis, a research process map will be established for the development of the SBTool^{BIM} application, defining all the information flow and required software. Different assessment stages will be identified, highlighting the key data for each phase and which software is intended to be used.
3. BIM model preparation – After the theoretical establishment of the assessment procedure, a BIM model will be created as a case study to test the developed theory. The model will be created in Autodesk Revit with all the identified required data for the assessment and a set of modelling guidelines will be followed. The model will be a simple and small building, as the goal is only to test and validate SBTool^{BIM} functionality. Less complex and sized models allow for faster analysis of SBTool^{BIM}, granting quicker programming and validation. The case study will be used to manually assess SBTool^{PT}-H for validation purposes, and it is described below.
4. Rule execution – All the established "rules" during the interpretation phase and the identified research procedure will be programmed through VPL by using Dynamo. This phase consists of the development of the SBTool^{BIM} application, which will reflect SBTool^{PT}-H criteria. Moreover, the application will gather and group the required assessment data from the BIM model and the user to perform the assessment calculations and display the building score. During this phase, SBTool^{BIM} template will also be created to establish a set of new shared parameters, according to the sustainability assessment requirements.
5. Rule report and validation – SBTool^{BIM} rule report consists on the building sustainable evaluation, which will be the analysis output. The application itself will display the "rule report" by presenting the individual score of each criterion, as well as the building global score. Such output will be provided directly into the Autodesk Revit environment – to function as a real-time decision support tool – and through an Excel spreadsheet – which will serve to carry out the full and final assessment of SBTool^{PT}-H. During this stage SBTool^{BIM} will also be validated, confronting the results of the BIM application, with the manual application of SBTool^{PT}-H.
6. BIM additional linkage – As it is expected that Dynamo will not be able to automate the assessment of all SBTool^{PT}-H criteria, especially the ones that require performance analysis data, an additional BIM linkage will be proposed to gather the remaining assessment information. Such linkage will be made by exporting the created BIM model to specific BIM tools, where building performance analysis can be carried out. The BIM model specifications, the export stage and the required BIM tools will be identified, as well as the specific data that should be collected from each tool. These data can later be grouped with the SBTool^{BIM} results to achieve a final sustainability score for the building.

Fig. 1 presents the summarised method adopted for the development of SBTool^{BIM}.

3.2. Software

The following section summarises and justifies the software selection for the research. As stated, Autodesk Revit will be used as a BIM platform, both to create the BIM model and to host the SBTool^{BIM} application. Autodesk Revit is a frequently used platform in BIM-sustainability related fields [66]. It has the capacity to import and export several file formats, including IFC (allowing to frame

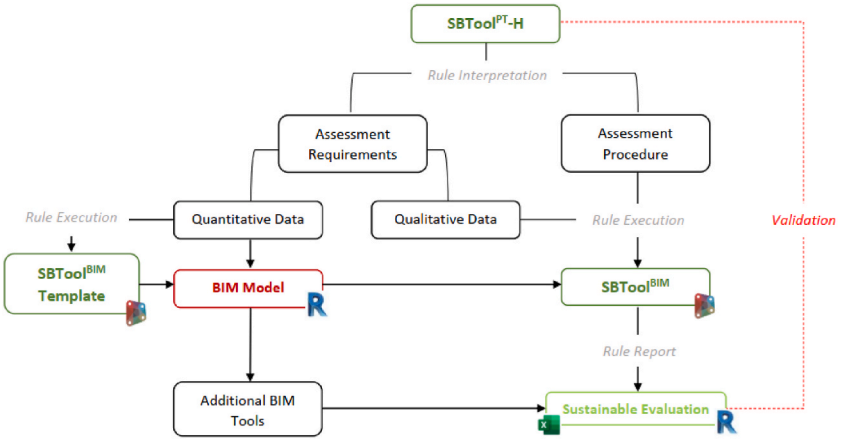


Fig. 1. Summarised method for SBTool^{BIM} development.

SBTool^{BIM} into the Open BIM environment) and, to develop personalised interfaces to perform specific tasks through Dynamo. Software capabilities have been found appropriate for SBTool assessment [32] and fully meet the research needs, allowing to fit for the following requirements:

- Ability to create and import BIM models;
- Ability to characterise the BIM model with sustainability requirements;
- Ability to host the application to avoid interoperability issues;
- Ability to export the model for building performance simulation.

The application will be made through VPL in Dynamo, which provides a convenient and automated data exchange procedure with a BIM model in Autodesk Revit [28]. Dynamo provides a user-friendly workspace where the code is presented as nodes connected with wires [13,17]. Personalised interfaces can be created for querying and manipulating the BIM model data [15]. With SBTool^{BIM} necessities in line with Dynamo capabilities, this tool was chosen to develop the application. BIM model characteristics can be instantly assessed and processed according to the application requirements, allowing the user to introduce external inputs, as well as display the final scores in the Autodesk Revit environment. Furthermore, Dynamo can also export data through an Excel spreadsheet with the analysis results.

According to a couple of requirements of some SBTool^{PT}-H criteria, building performance analysis will be required to have a full sustainability evaluation. Such requirements concern building energy and acoustic performance, which must be made in specific BIM tools. These tools' calculation engines must consider Portuguese thermal (REH) and acoustic (RRAE) regulations. In this context, Cype software was found appropriate to carry out building performance analysis. Cype is a Spanish company that develops computer software to support the construction industry stakeholders and is adequately adapted to Portuguese standards. Cype has a link to Autodesk Revit, which allows importing BIM models through an intermediary platform – BIMServer.center. The following Cype software will be used for the research approach:

- Cypetherm REH, which performs energy analysis according to REH;
- Cypesound RRAE, which performs acoustic analysis according to RRAE.

Finally, according to SBTool^{PT}-H, a single assessment requirement must be gathered from Energy Plus software. For this sake, Autodesk Revit allows exporting a readable file (IDF) for Energy Plus by using Autodesk Insight as an intermediary platform. For these reasons, both have been selected for the research approach.

3.3. Case study

To test and validate the SBTool^{BIM} application, a case study was developed as a BIM model in Autodesk Revit. It was properly created and characterised to meet SBTool^{BIM} requirements, according to the following description.

The case study is located in Braga (Portugal), and it's inserted in a 635 m^2 site, according to the characterisation of Table 3. Following the local regulation, the Maximum Land Use Index for the building is 0.75. For analysis purposes, no previous site area was reused or treated.

The building itself consists of a single-family detached dwelling with 90 m^2 of gross area divided by 3 bedrooms, kitchen, bathroom, living room, corridor, and pantry. Only two bedrooms have 2 windows – allowing cross ventilation – and the building's total glazed area is 7.25 m^2. The ceiling height is 3.00 m, including slab thickness. The building floor plan is presented in Fig. 2.

An important requirement for SBTool^{BIM} concerns the building materials characteristics, which go beyond Autodesk Revit base parameters. All the model materials must be correctly characterised, especially for the considered elements – floors, roofs, walls, windows, floors, and stairs. The overall material characterisation for SBTool^{BIM} is presented in Table 4, as well as the adopted construction solutions.

Moreover, some additional specific attributes for materials were also considered:

- Interior doors and windows frames have been previously recycled;
- Wood floor finishing has been made of certified wood;
- The binder uses 400 kg of cement per cubic meter (m^3) with 100 kg/m^3 of cement substitutes;
- No ventilation grills were considered in door and window frames;
- Interior painting and wood floor are low Volatile Organic Compound (VOC) materials;
- The materials with recycled content are presented in Table 5. This table also presents the market best and conventional practices for the recycled content of each material, as well as the recycled content of the applied material.

Table 3
Case study topography characterisation.

Site surface	Area (m^2)	Sealed soil	Reflectance ≥60%
Grass	416.8	No	Yes
Native plants	21.4	No	Yes
Sidewalks	15.4	Yes	Yes
Building footprint	97.8	Yes	No
Car access road	84.1	Yes	No

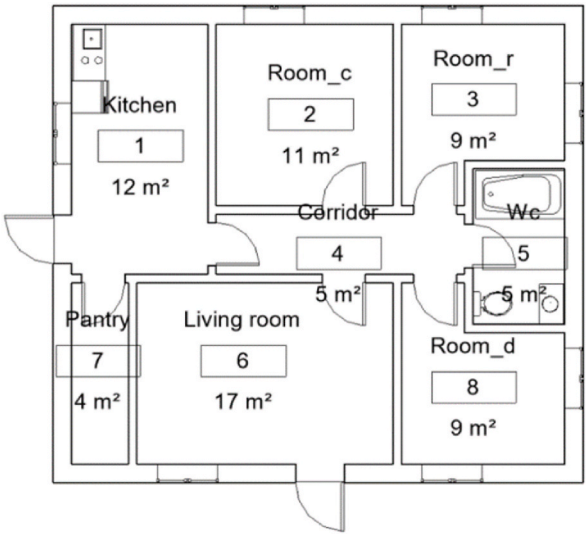


Fig. 2. Case study floor plan.

Although there is no requirement regarding the building systems modelling, plumbing fixtures should be placed and characterised. The case study plumbing fixtures are presented in Table 6 and the rainwater satisfaction coefficient (CSAT) was considered 100% for analysis purposes. Recycled water from the identified fixtures is used for irrigation purposes.

Some other general building features, which are also required for SBTool^{BIM} and are not available directly in the BIM model are listed in Table 7.

Specific neighbourhood data is also mandatory for SBTool^{BIM} analysis, such as public transportation data and amenities distance. The building location was considered nearby a district capital city, with the public transport services and amenities presented in Tables 8 and 9, respectively.

All the presented data must be provided for SBTool^{BIM} to carry out the sustainability analysis. Some of it can be introduced through building modelling, making it part of the BIM model. Materials data can also be stored in a database and imported for the model when needed. Although, some other data is not possible to be stored by the BIM model and it should be directly introduced in the SBTool^{BIM} application, namely the information from Tables 5 and 7–9.

4. Results

4.1. Input requirements and assessment model

Following the proposed methodology, the first step was to proceed with the assessment analysis of SBTool^{PT}-H criteria. To do so, the data requirements and the assessment procedure of all SBTool^{PT}-H criteria were identified. As SBTool addresses a wide range of criteria categories, different type of data is required for the assessment. The assessment process of some criteria lies only in geometric quantitative data from the model. Other criteria require the knowledge of several specific local data or even the results of building performance simulations. Therefore, different input types are expected, and they have been grouped into three sections:

- BIM Model – Data intrinsic to the model (identity and geometry data) or data that can be introduced into the model through shared parameters (mainly quantitative data);
- User interface – Specific local data and qualitative data that the user must provide to SBTool^{BIM} through an interface;
- BIM tools – Data that requires the use of additional tools (performance simulation tools) for model simulation.

As SBTool^{BIM} will be a Dynamo-based application, both the BIM model data and the user interface data will be available inside the Autodesk Revit environment. The BIM tools data will require to export the BIM model for additional software to carry out performance simulations and data will not be directly available in the Autodesk Revit environment.

All the requirements and weights of each criterion from the Environmental, Social and Economic dimensions are listed in Tables 10–12, respectively. Based on the requirement types, the SBTool^{BIM} assessment mode can also be selected. All the information inside the Autodesk Revit environment will be handled by Dynamo. For the external data, Cype software linkage will be used to export the model IFC to carry out performance simulations, as well as the direct connection with Autodesk Insight to get an Energy Plus model.

According to Table 10, for the environmental dimension, the data for 11 criteria will be intrinsic to the BIM model. Categories C1, C2 and C5 have all their criteria fulfilled, while C4 have 3 out of 5 criteria. The two remaining C4 criteria will require user inputs through an interface, namely for the material recycling content benchmarks and the building recycling exterior conditions. Category C3 is fully dependent on external tools, as it evaluates the building energy efficiency and renewable energy production, which are beyond Autodesk Revit capabilities. Overall, 13 out of 15 environmental criteria will be directly addressed by the SBTool^{BIM}

Table 4
Case study material characterisation.

Material			Area (m^2)	Environmental impact categories quantification (per m^2)						Cost	Density (kg/m^3)
				GWP	ODP	AP	POCP	EP	FFDP		
				($kgCO_2$)	(kgCFC-11)	($kgSO_2$)	(kgC_2H_4)	($kgPO_4$)	(MJ)		
			–	–	$x10^{-07}$	$x10^{-02}$	$x10^{-04}$	$x10^{-04}$	–	–	–
Exterior walls		Common brick 15.0 cm + 11.0 cm	198.8	0.220	0.158	0.055	0.400	0.671	2.58	4.75 €/m^2	700
		Rigid insulation 4.0 cm	99.4	4.140	1.100	1.500	67.500	12.400	105	4.00 €/m^2	23
	Finishing	Cement plaster (1.5 cm each side)	198.8	0.195	0.080	0.032	0.129	0.487	1.31	17.00 €/m^2	1100
		Painting (1.0 cm each side)	198.8	2.460	3.690	1.700	7.720	42.300	47.8	8.00 €/m^2	1188
Interior walls		Common brick 11.0 cm	91.2	0.220	0.158	0.055	0.400	0.671	2.58	4.75 €/m^2	700
	Finishing	Cement plaster (1.5 cm each side)	182.3	0.195	0.080	0.032	0.129	0.487	1.31	17.00 €/m^2	1100
		Painting (1.0 cm each side)	182.3	2.460	3.690	1.700	7.720	42.300	47.8	4.50 €/m^2	1188
Floor slab	Finishing	Oak floor	90.0	−1.200	0.128	0.081	0.729	1.290	1.98	65.00 €/m^2	750
		Cement plaster 2.0 cm	90.0	0.195	0.080	0.032	0.129	0.487	1.31	17.00 €/m^2	1100
		Rigid insulation 4.0 cm	90.0	4.140	1.100	1.500	67.500	12.400	105	4.00 €/m^2	23
		Reinforced concrete 40.0 cm	90.0	0.148	0.036	0.056	0.528	0.576	1.24	70.00 €/m^2	1300
Windows		Glass	13.2	0.973	0.801	0.850	2.860	6.530	11.5	440.00	2480
		Sash/wood	48.5	−1.200	0.128	0.081	0.729	1.290	1.98	€/un	560
Doors		Aluminium	12.6	4.280	18.400	3.800	22.300	12.100	62.8	432.00 €/un	2700
		Wood panel	26.4	−1.200	0.128	0.081	0.729	1.290	1.98	432.00	560
		Wood frame	14.9	−1.200	0.128	0.081	0.729	1.290	1.98	€/un	560
Roof	Finishing	Concrete tile	98.2	0.212	0.111	0.045	0.234	0.764	1.73	25.00 €/m^2	1300
		Rigid insulation 5.0 cm	98.2	4.140	1.100	1.500	67.500	12.400	105	4.00 €/m^2	23
		Flexible membrane with bitumen	98.2	0.581	7.270	0.730	19.400	3.020	53.3	6.00 €/m^2	1700
		Steam PVC barrier	98.2	1.970	0.028	0.540	3.120	7.590	46.9	13.00 €/m^2	1500
		Reinforced concrete 20.0 cm	98.2	0.148	0.036	0.056	0.528	0.576	1.24	70.00 €/m^2	1300

Table 5
Adopted recycled content and benchmarks.

Product	Recycled content (% of mass)		
	Conventional	Best	Used
Concrete	15	90	35
Thermal insulation	0	25	25
Bricks and blocks	0	30	50
Glass	0	10	10

Table 6
Case study plumbing fixtures characterisation.

Fixture	Instances	Liters per use	Rainwater use	Water recycling
Sink	1	12.0		
Dishwasher	1	25.0		
Toilet	1	8.0	X	
Tap	1	1.0		X
Bath tube	1	52.5		X

Table 7
Complementary data for SBTool$^{BI.M}$.

Building user's guide content	Interior recycling conditions	Local economy data	Mechanical ventilation
Sustainability measures report	Bin volume of 30L	Site cost – 20 000 €	The building does not have mechanical ventilation
Recyclable waste guide	Includes oil and batteries recycling	Construction labour percentage (function of material cost) – 40%	
Non-recyclable waste guide		Selling profit percentage (function of material and labour cost) – 20%	
Building rehabilitation and maintenance guide	Distance to recycling public bin of 150 m	Average selling price of 10 similar and nearby dwellings – 105 000 €	
Emergency information		Average selling price of 3 lowest similar and nearby dwellings – 96 000 €	

Table 8
Case study public transport stations.

Station	Distance (m)	Number of services
Bus	150	4
Bus	300	10
Train	2000	8

Table 9
Case study nearby amenities.

Amenity	Distance (m)
Garbage collection point and public recycling bin	150
Bakery, grocery, butchery, cafe, restaurant, prayer place and Post office march	300
Exterior public space, pharmacy, bank and sports center	500
Service/industrial zone, bike lane and medical center	1000
Kindergarten, elementary school, recreation center, police station and post office	1500
High school	2000
Firefighters and Shopping center	2500

application.

When concerning the social dimension in Tables 11 and it can be noticed a higher requirement for qualitative data, as only 2 out of 8 criteria can gather the assessment inputs from the BIM model. The 2 criteria from the C7 category and the criterion from the C8 category will require the use of an interface, while the remaining 3 criteria will need the use of external tools. For this case, thermal, visual, and acoustic performance results are necessary for the assessment. Overall, 5 out of 8 social criteria will be directly assessed through SBTool^{BIM}.

Finally, the two criteria from the economic dimension in Table 12, will have different assessment modes. The first one will be fulfilled with the model data and the user inputs through the SBTool^{BIM} interface. The last one is once again dependent on external tools. Although, it requires the same data as other SBTool^{PT}-H criteria (as P7 and P14), so it depends on their prior assessment.

Considering all the dimensions, it is expected that SBTool^{BIM} will directly embrace a total of 19 criteria. For the remaining 6 criteria, a BIM linkage will be identified and detailed to allow the complete assessment automation.

Based on the adopted software capabilities, the identified input requirements, and the assessment method, the SBTool^{BIM} process map was established, and it is presented in Fig. 3. As stated, SBTool^{BIM} will be Dynamo based, so all its functionalities will be only available in Autodesk Revit. Therefore, to start the process it is necessary to create a new model in Autodesk Revit or import one existing model from Autodesk Revit or another authoring platform (through IFC). Then, the first part of SBTool^{BIM} will act, by creating the SBTool^{BIM} template. This will be made automatically by running the respective Dynamo file and can be made before or after the model creation. SBTool^{BIM} template aims to create new shared parameters that will be filled with the required data for the SBTool^{PT}-H assessment.

After characterising all the new building parameters, the SBTool^{BIM} application can be used to carry out the automatic sustainability assessment. Once again, this is made automatically by running the respective Dynamo file. SBTool^{BIM} will first gather the required assessment data from the BIM model and then it will display an interface in the Autodesk Revit environment. Such an interface will ask for user data inputs, according to the previous Tables. All input data will be grouped and processed to reach a final sustainability assessment for the building. The outcomes of the SBTool^{BIM} application will be made in two different ways:

- Individual qualitative score of 19 criteria and global qualitative building score, displayed in Autodesk Revit environment;
- Individual qualitative and quantitative scores of 19 criteria and global qualitative and quantitative building scores, extracted through an Excel spreadsheet.

The first outcome is intended to be used as a fast decision support method during project design. It provides a reliable and real-time sustainability assessment for users to compare the performance of different solutions. The second outcome is intended to be used for

Table 10
SBTool^{PT}-H environmental criteria requirements.

Cat.	Criterion	Weight (%)	Inputs			Assessment mode
			BIM model	User interface	BIM tool	
C1	P1 - Construction materials embodied environmental impact	12.0	Materials weights and impacts			Automated assessment through Dynamo
C2	P2 - Urban density	7.2	Site and construction areas; Max Land Use Index			
	P3 - Soil sealing index	1.0	Sealed and non-sealed soil area; Site area			
	P4 - Use of pre-contaminated land	1.1	Pre-contaminated land area; Site area			
	P5 - Use of native plants	4.6	Green Area, Native plants area; Site area			
	P6 - Heat-island effect	5.1	Site area; Green area; Reflectance >60% area			
C3	P7 - Primary energy consumption	19.5			Building primary energy needs; Maximum primary energy needs;	BIM linkage to Cype
	P8 – Renewable energy production	19.5			Building primary energy needs; Renewable energy production	
C4	P9 - Reused materials and products	5.5	Total material cost; Total reused material cost.			Automated assessment through Dynamo
	P10 - Use of materials with recycled content	5.5	Materials quantities	Percentage of recycled content per material and benchmarks		
	P11 - Use of certified organic materials	6.2	Certified organic material cost; Total organic material cost.			
	P12 - Use of cement substitutes in concrete	4.0	Weight of cement substitutes; Total binder weight in concrete.			
	P13 - Waste management during operation	0.8		Interior recycling bin type, number and volume; Exterior bin distance; Waste Collection system		
C5	P14 - Water consumption	4.0	Plumbing fixtures Water consumption per fixture			
	P15 - Reuse of grey and rainwater	4.0	Reused water fixtures; Toilets water consumption; Total water consumption; Satisfaction coefficient.			

the full SBTool^{PT}-H evaluation. The extracted Excel spreadsheet will be connected with the existing SBTool^{PT}-H spreadsheet through macros functions. By automatically filling in the scores of the assessed 19 criteria, the user will only need to collect the data for the remaining 6 criteria to achieve a full evaluation. To do so, the BIM model must be exported from Autodesk Revit to additional software, where performance simulations can be made. For five out of six criteria, the BIM model is exported to Cype software by using the existing IFC plug-in, sending the BIM model to BIMServer.center, which makes it available for Cype software. For the other criterion, the BIM energy model is generated in Autodesk Revit and exported to Autodesk Insight cloud, where an EnergyPlus file (IDF format) can be automatically obtained to carry out dynamic simulations. After performing all the required simulations, results must be manually gathered and introduced in the SBTool^{PT}-H spreadsheet. Both software provides the simulation results directly on the screen or through reports and, therefore, no automated connection will be possible at this stage. Nevertheless, all the required data is easily identified and should be directly introduced in the SBTool^{PT}-H spreadsheet, with no intermediary calculations or efforts.

4.2. SBTool^{BIM} template and model characteristics

Autodesk Revit has a set of base templates with common transversal parameters to characterise the BIM model. Some of the common model characteristics, which are required for the SBTool^{PT}-H assessment, are:

- Elements (walls, floors, roofs, doors, windows, exterior surfaces, among others) dimensions;
- Element's cost;
- Material cost, density, class, and function.

This data is usually intrinsic to the model and is shared by all the templates. Despite none of the templates was found suitable for sustainability issues, Autodesk Revit allows to create and edit templates according to the user's requirements. Facing the need to properly describe a BIM model for the sustainability evaluation, the SBTool^{BIM} template was developed. In short, the template was

Table 11
SBTool^{PT}-H social criteria requirements.

Cat.	Criterion	Weight (%)	Inputs			Assessment mode
			BIM model	User interface	BIM tool	
C6	P16 - Natural ventilation efficiency	7.2	Natural ventilated areas Floor and opening areas Ventilation devices integrated in window and door frames			Automated assessment through Dynamo
	P17 - Indoor air quality	7.2	Quantity of finishing materials containing low VOC; Total quantity of finishing materials			
	P18 - Thermal comfort	19.2	.		Running mean external temperature Thermal comfort levels Winter number of months	BIM linkage to EnergyPlus
	P19 - Natural lighting performance	15.0			Horizon angle, horizontal obstruction angle, glazed area and characteristics and, interior surface area	BIM linkage to Cype
	P20 - Acoustic comfort	11.4			Airborne sound insulation, impact sound insulation and collective equipment noise evaluation	
C7	P21 - Accessibility to public transport	16.5		Building location type; Distance to public transportation stations; Types of public transportation; Number of services		Automated assessment through Dynamo
	P22 - Accessibility to urban amenities	13.5		Building location type Distance to amenities.		
C8	P23 - Occupant's awareness and education for sustainability	10.0		Building user guide availability and content		

Table 12
SBTool^{PT}-H economic criteria requirements.

Cat.	Criterion	Weight (%)	Inputs			Assessment mode
			BIM model	User interface	BIM tool	
C9	P24 - Capital costs	50.0	Materials price	Labour and profit percentage; Site cost; Selling price of ten similar buildings nearby.		Automated assessment through Dynamo
	P25 - Operation costs	50.0			Energy, water, and solid waste unitary costs; Energy and water consumption; Volume of solid waste production.	BIM linkage to Cype

developed in Dynamo (VPL language) considering the architectural template as a basis. New shared parameters are automatically created according to the identified input requirements for SBTool^{PT}-H. Table 13 identifies all the programmed parameters, as well as their type and applicable category. In total, 28 shared parameters were created to make available the assessment of 13 criteria. Four types of parameters are used, with number type and yes/no type being the most common. The parameters address six Autodesk Revit categories. The template can be saved as an Autodesk Revit template and marked as standard to create and develop models, avoiding the need to run the Dynamo file for every project.

All the created parameters are mandatory to be filled for a successful evaluation, as well as guarantee that the model fulfils a set of other characteristics. The BIM model should be developed through a parametric modelling and should include the site topography and constructions. Each topography zone – such as green zone, sidewalks, entrance, among others – should be defined as an individual topography surface, to define different characteristics between them. Topography surfaces should also be considered for construction areas. Fig. 4 a) presents the mandatory topography characteristics for the analysis (red square), which must be filled for every model topography surface. Simultaneously, the building general data must also be defined in the "Project Information" section (Fig. 4 b), red square, under Autodesk Revit manage tab.

With the site characteristics defined, the building itself can be added to the model. Note that all elements must be properly defined, so SBTool^{BIM} will be able to group all the building data accordingly. Thus, the ground slab and between levels slabs must always be defined as "Floors", while the building top slab should be modelled as "Roof". This is an important issue, as the application will

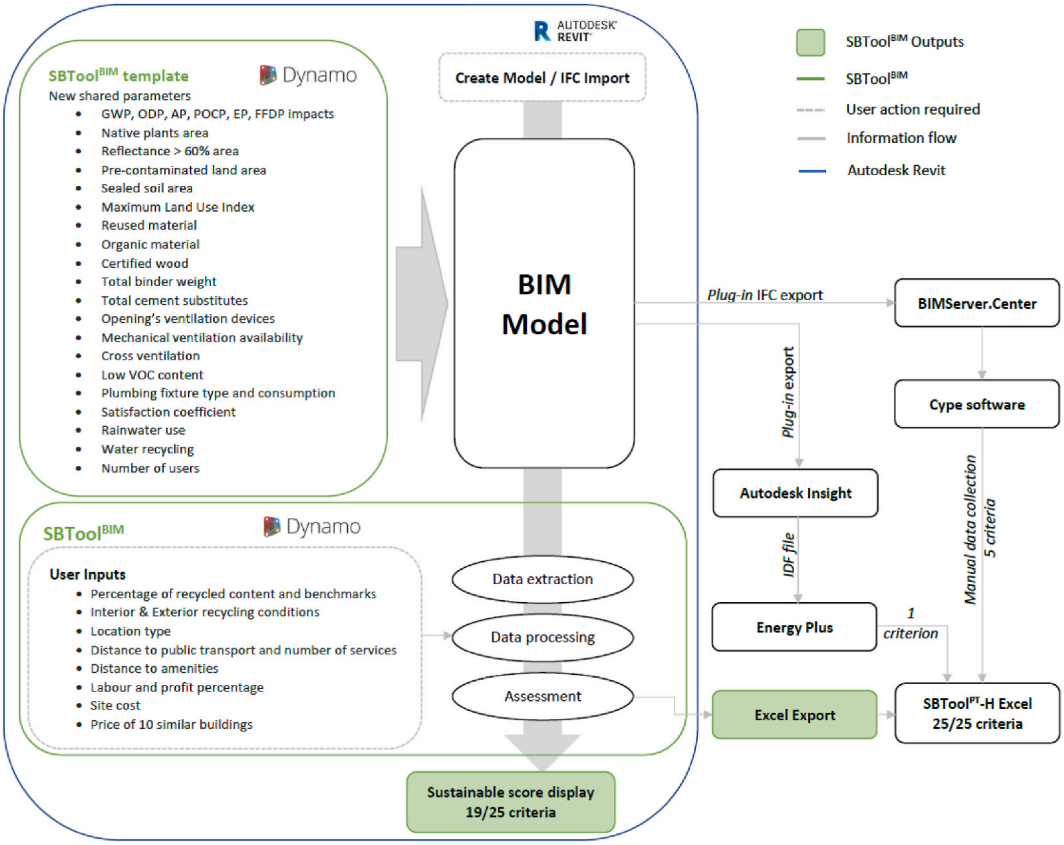


Fig. 3. SBTool[BIM] process map.

Table 13
Created parameters for SBTool[BI.M.].

Parameter name	Parameter type	Created for criterion	Applies to Category
GWP	Number	P1	Materials
ODP	Number		
AP	Number		
POCP	Number		
EP	Number		
FFDP	Number		
Maximum Land Use index	Number	P2	Project Information
Sealed soil	Yes/No	P3	Topography
Pre-contaminated area	Area	P4	Project Information
Native plants area	Yes/No	P5	Topography
Reflectance >60%	Yes/No	P6	Topography
Reused material	Yes/No	P9	Materials
Organic material	Yes/No	P11	Materials
Certified wood	Yes/No		
Total binder weight	Number	P12	Materials
Total cement substitutes	Number		
Select type	Text	P14	Plumbing Fixtures
Liters per utilisation	Number		
Water recycling	Yes/No	P15	Plumbing Fixtures
Rainwater use	Yes/No		
Number of users	Number		Project Information
CSAT	Number		
Ventilation grille/Range-stop	Yes/No	P16	Doors
Ventilation grille/Range-stop	Yes/No		Windows
Out of P16 scope	Yes/No		Rooms
Cross ventilation	Yes/No		
Mechanical ventilation	Yes/No		Project Information
Low VOC content	Yes/No	P17	Materials

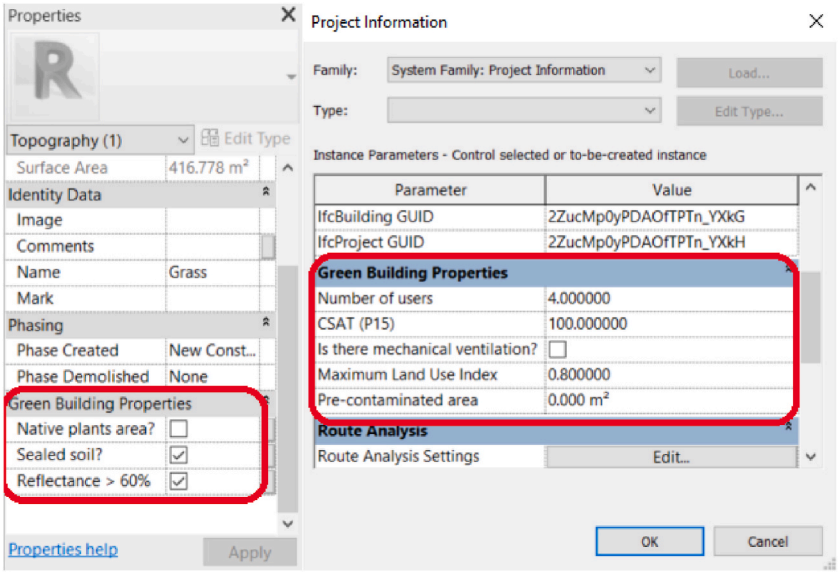


Fig. 4. (a) Topography characteristics and (b) Project Information data.

specifically look for "floors" and "roofs" to carry out the assessment. Walls must be defined accordingly, as well as their construction materials and function (exterior or interior). Note that Walls must be modelled through stacked walls instead of compound layers.

Every building element is composed of materials. Thus, the following step consists in selecting the element's materials and defining their main characteristics for the sustainability assessment, as presented in Fig. 5. Most of these characteristics must be collected by the user, according to the material type. Although, a material database can also be used, where all the material characteristics are already defined, and it is just necessary to import them for the current model. Note that the parameters from Fig. 5 were created for all the existing materials but SBTool^{BIM} will be able to distinguish them and disregard unnecessary data. For instance, if the user state that a wood product will have cement substitutes, the application will notice the incoherence and ignore it. SBTool^{BIM} analyses every material class and for the cement substitutes parameter only concrete-class materials are considered.

The building's interior and exterior openings (windows and doors) must also be modelled and characterised. Besides the material

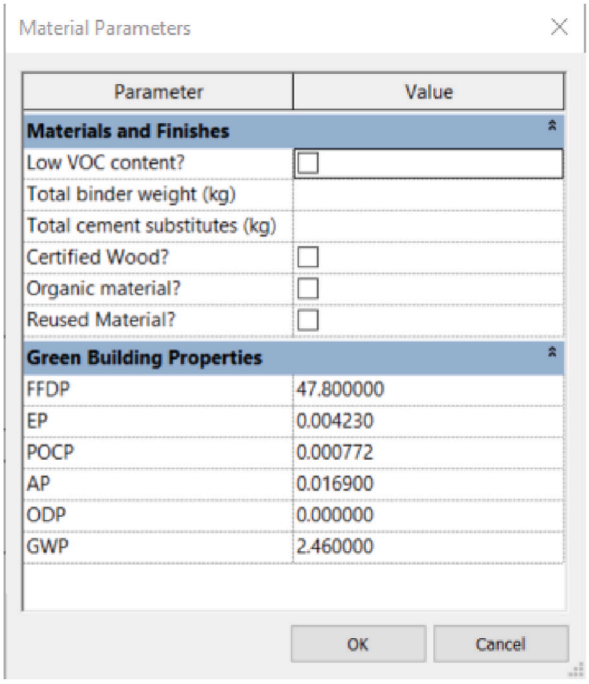


Fig. 5. Material characteristics.

selection (and characteristics definition), openings must also have their cost (per window or door) and information regarding integrated ventilation devices.

Finally, the building interior should be defined, especially the finishing materials (if not defined already) and the plumbing fixtures. All finishing materials should have data about the VOC content and plumbing fixtures must be characterised according to Fig. 6 a). For every plumbing fixture, the user should select the type (toilet, sink, bathtub, tap, dishwasher, or laundry machine), the liters per utilisation, if the fixture reuses rainwater and if it recycles water. At last, for every building compartment the "room" function should be used to characterise each space, according to Fig. 6 b). Moreover, the "room" function will also be mandatory when exporting the BIM model for the additional BIM tools. When finished, the BIM model can be specified as a LOD 300. The model elements are graphically represented in terms of quantities, size, shape, location, and orientation. Sustainability data has been included as non-graphic information, with precise quantities and properties for a sustainability assessment [42,73]. According to different authors [16,74], the LOD 300 is also the minimum specification to proceed with building performance analysis.

4.3. SBTool^{BIM}

4.3.1. Structure

To extract and process data from the BIM model, the SBTool^{BIM} application was developed through VPL in Dynamo. It automatically assesses the required building data for the sustainability evaluation and provides an interface for the user to complete the analysis information. By interpreting the assessment procedure of each SBTool^{PT}-H criteria, calculations were programmed in Dynamo, as well as different output methods.

SBTool^{BIM} code is based on the collection of the BIM model categories data. All elements of each category are assessed and filtered according to each criterion scope. Fig. 7 presents an example of the basic nodes that start the Dynamo algorithm and how data is collected from each category. Overall, criteria P1, P2, P3, P4, P5, P6, P9, P10, P11, P12, P13, P14, P15, P16, P17 and P24 use this same method to collect the assessment requirements, as data is intrinsic to the model.

However, SBTool^{BIM} also requires additional information which is not available in the model. Dynamo was used to create user interfaces during the analysis, where the designer can introduce the remaining required data for the assessment. After starting SBTool^{BIM}, a set of pop-up windows will consecutively appear on the Autodesk Revit environment. The aim is to collect external and local data for the analysis and the coding procedure is presented in Fig. 8. Specific popup windows were developed for criteria P10, P13, P21, P22, P23 and P24.

After collecting the required data for each criterion, SBTool^{BIM} performs the assessment calculations, normalisations, and qualitative quantification, as presented in Fig. 9.

Finally, SBTool^{BIM} displays a pop-up window in the Autodesk Revit environment with the individual qualitative score of each criterion, as well as a global sustainable score for the building. The global score was achieved by equally splitting the excluded 6 criteria weights for the remaining criteria of their respective categories. Simultaneously, SBTool^{BIM} produces an Excel spreadsheet with the quantitative and qualitative scores of each criterion, as well as the building global score. This spreadsheet will later be related to the SBTool^{PT}-H spreadsheet to automatically fill the assessed criteria with SBTool^{BIM}.

SBTool^{BIM} has a set of assumptions and exclusions for the building model, which were not possible to program or are not relevant to the research scope:

- 19 SBTool^{PT}-H criteria have been successfully automated;

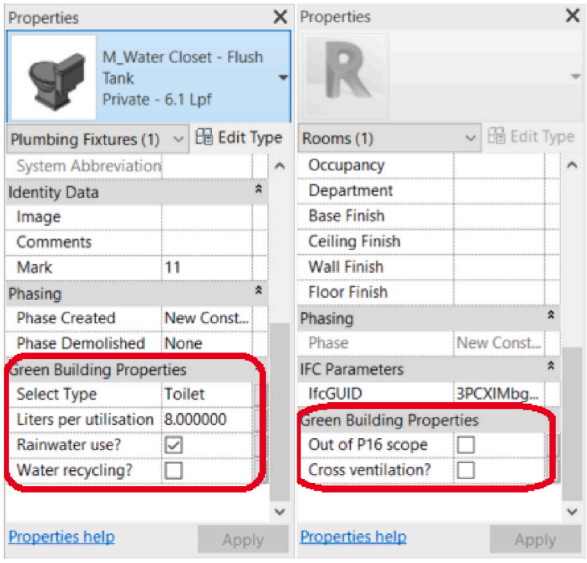


Fig. 6. (a) Plumbing fixtures characterisation and (b) Room characterisation.

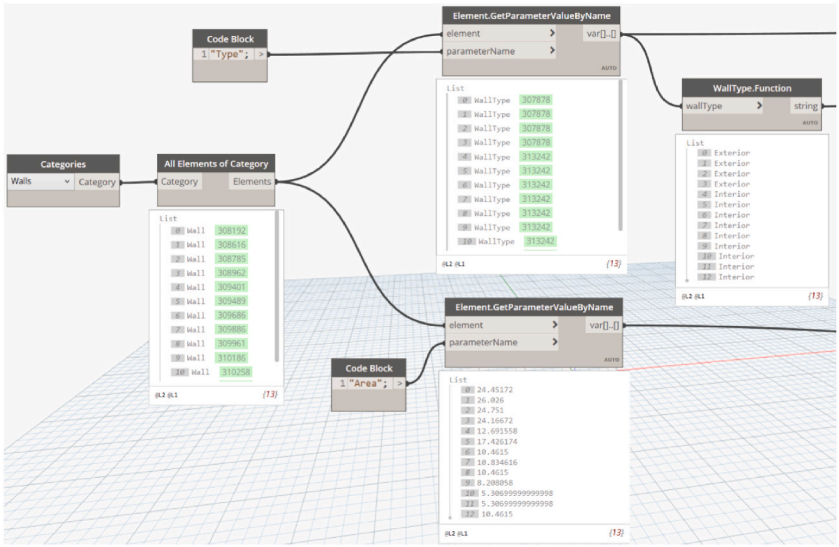


Fig. 7. Collecting and processing data in Dynamo.

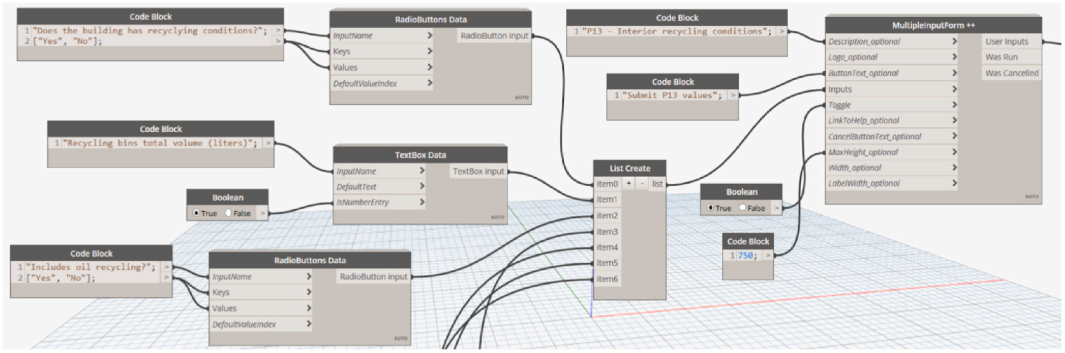


Fig. 8. User interface creation in Dynamo.

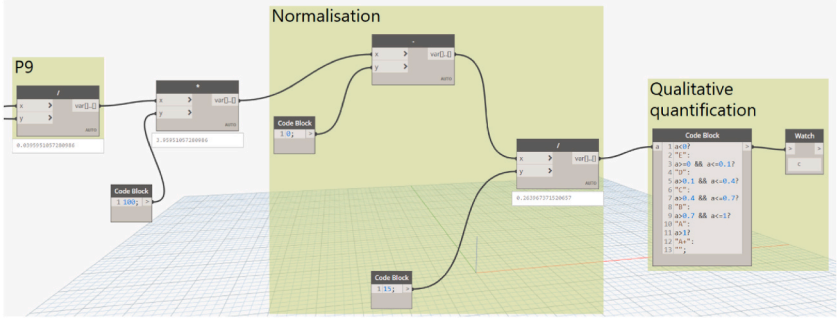


Fig. 9. Result normalisation and qualitative quantification.

- Building architectural elements such as Walls, Floors, Roofs, Windows, Doors and Rooms are considered for the sustainability analysis;
- Structural slabs must be modelled under the Roofs or Floors categories. Structural walls must be modelled under the Walls category. Structural columns are not considered for the sustainability analysis;
- Furniture is not considered;
- Green roofs are not considered as 50% of sealed soiled;
- Every non-sealed soil area is considered a green area.

4.3.2. Case study application

The case study presented in section 3.3 was modelled in Autodesk Revit under the SBTool^{BIM} template and according to the procedure presented in section 4.1. All the stated characteristics from the case study description have been included in the model. After characterising all the required parameters, SBTool^{BIM} was started by selecting its respective file in the Dynamo player and pressing the play button, as presented in Fig. 10.

After a couple of minutes, the application starts by showing some pop-up windows for the user inputs, requiring the assessment data for criteria P10, P13, P21, P22, P23 and P24. Fig. 11 presents different examples of the input forms that the user must answer to proceed with the analysis. P10 interface shows a table with all the BIM model materials (and total weights – column 1), where the user must introduce the recycled content (%) of each material (column 4), as well as the national benchmarks (columns 2 and 3). P13 and P23 show a kind of checklist with pre-defined options that correspond to different sustainable evaluations. P21, P22 and P24 are mainly based on number entrances, where distances and/or costs must be introduced. Note that all the direct inputs into the application must be collected earlier by the user, as the information is not contained in the BIM model.

Combining and processing the introduced data with the BIM model data, SBTool^{BIM} proceeds with the assessment and normalisation of all 19 criteria, displaying the final case study result in the Autodesk Revit environment (Fig. 12). Both the individual score of each criterion and the global building score are presented, indicating a B mark for the building sustainability score.

Simultaneously, an Excel is produced and exported with the detailed building score, as presented in Fig. 13. Both the qualitative and quantitative score of each criterion is presented to further allow the full evaluation of SBTool^{PT}-H. This procedure is explained in the next section.

To introduce improvement measures, designers must only change the building design or the characteristics of the materials directly in the BIM model. Then, SBTool^{BIM} must be used again, to achieve the sustainability score of the improved design. Note that the user inputs in the SBTool^{BIM} application (Fig. 11) are saved from the previous analysis, sparing the user from double work. The input data is saved in a local file, which is then assessed by SBTool^{BIM} to automatically fill in the required information. Modifications in the inputs are still available. Therefore, only a few efforts in editing the BIM model are required to compare the sustainability performance of different building scenarios.

All the simulation process was validated by performing a manual application of SBTool^{PT}-H in the same building. Validation results are shown in Table 14, where the quantitative score of each criterion is faced. SBTool^{BIM} results were gathered from the extracted Excel spreadsheet (Fig. 13). The slight differences in criteria P1 and P10, concern rounding issues when assessing the building element's mass. SBTool^{BIM} is able to extract quantitative data from the model with high precision (up to 8 decimal places), while the manual assessment has only considered 2 decimal units. Regarding P11, SBTool^{BIM} considers a single cost for the whole opening (frame plus window), while the SBTool^{PT}-H manual assessment has considered the frame and the window cost individually. Overall, a positive validation has been reached, with minor results differences in 3 criteria, which do not affect the building score. The remaining 16 criteria have achieved identical scores.

4.4. BIM linkage for the remaining criteria

As building performance simulations are out of the capabilities and scope of Autodesk Revit, a set of SBTool^{PT}-H criteria requires the use of additional BIM tools to find the necessary information for the assessment. Cype software and Energy Plus were found appropriate to deliver such data and their current capabilities provide strict collaboration with Autodesk Revit.

For the assessment of criteria P7, P8, P19, P20 and P25, the BIM model was exported through IFC to the BIMServer.center, by using the available plug-in for Autodesk Revit. Then, the following Cype software was selected to carry up performance analysis:

- Cypetherm REH – provides data for the assessment of P7, P8, P19 and P25;
- Cypesound RRAE – provides data for the assessment of P20.

The BIM model is directly imported from the BIMServer.center when starting a new project. In Cypetherm REH, the user must complete some building data before the simulation and gather the horizon angle and obstruction angle of each window, as well as the room's surface areas (required for the assessment of P19). The Portuguese minimum renewable energy production requirements for each building type can be considered for the assessment of P8. After the simulation, the building's primary energy needs and national limits can be collected for the assessment of P7 and P25. Note that P25 also requires data from the assessment results of P14. A similar procedure is necessary for Cypesound RRAE, where the user must complete a couple of building data to perform the analysis. Simulation results provide the sound insulation levels for the assessment of P20. More details about the BIM linkage can be found in past research [75].

For the assessment of criterion P18, the BIM model must reach Energy Plus software to determine the building's thermal comfort level and the hourly operational temperature. This is made by exporting the BIM model for Autodesk Insight, which allows to extract the model in IDF or DOE-2 format. The file must then be uploaded into Energy Plus to perform dynamic simulations and reach the required data for the assessment.

This data must be manually assessed by the user and introduced in the SBTool^{PT}-H spreadsheet, which is already connected with SBTool^{BIM}. The manual requirement concerns the need to assess data from the BIM tools environment and/or simulation reports, which are not available to be further connected. Cype software provides direct data for the complete evaluation of P7, P8, P19 and P20, allowing to fully automate 23 criteria. Concerning P18 and P25, some extra information is still required for the assessment, namely:

- Running mean external temperature for P18;
- Solid waste production, energy, water, and waste disposal costs for P25.

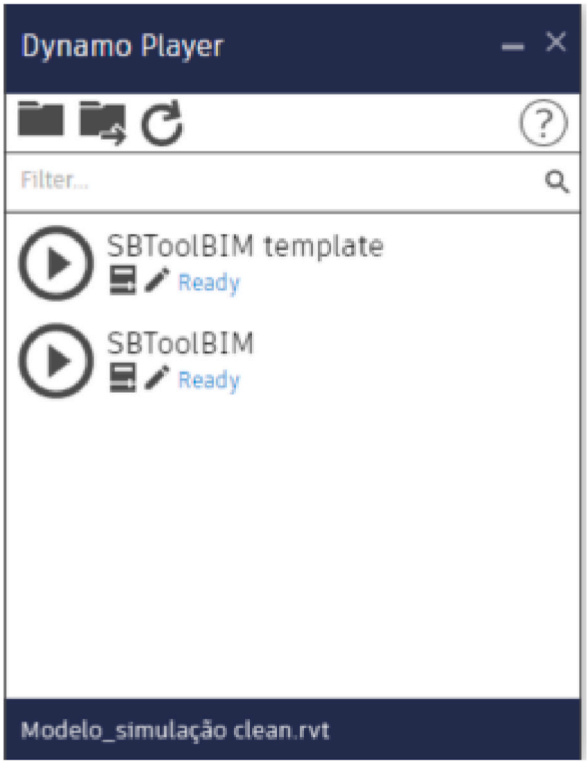


Fig. 10. Dynamo player in autodesk revit.

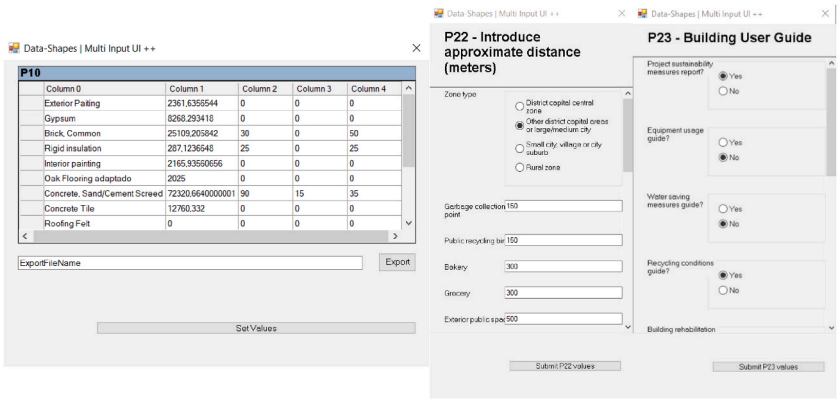


Fig. 11. Input forms through user interfaces in Autodesk Revit.

By collecting the above information, the building sustainability score can be reached, and it is shown on the SBTool^{PT}-H spreadsheet.

5. Discussion

Assessing a building's sustainability is usually a time-consuming procedure, where different types of information are required to carry out the evaluation. By introducing BIM, BSA methods can significantly benefit from it, by automating data collection and calculation procedures. Therefore, this research has developed a unique BIM-based approach capable of automatically assess 19 out of 25 sustainable criteria from SBTool^{PT}-H and has proposed an additional BIM linkage to evaluate the remaining 6 criteria. Overall, it is the first BIM-approach to automatically assess a wide range of sustainability criteria with minor user interference and resources, allowing to optimise the building performance during the early project stages.

By interpreting SBTool^{PT}-H assessment requirements, different input methods have been proposed according to the information type: direct inputs in the BIM model, application-specific inputs and performance simulation inputs. Depending on the input type,

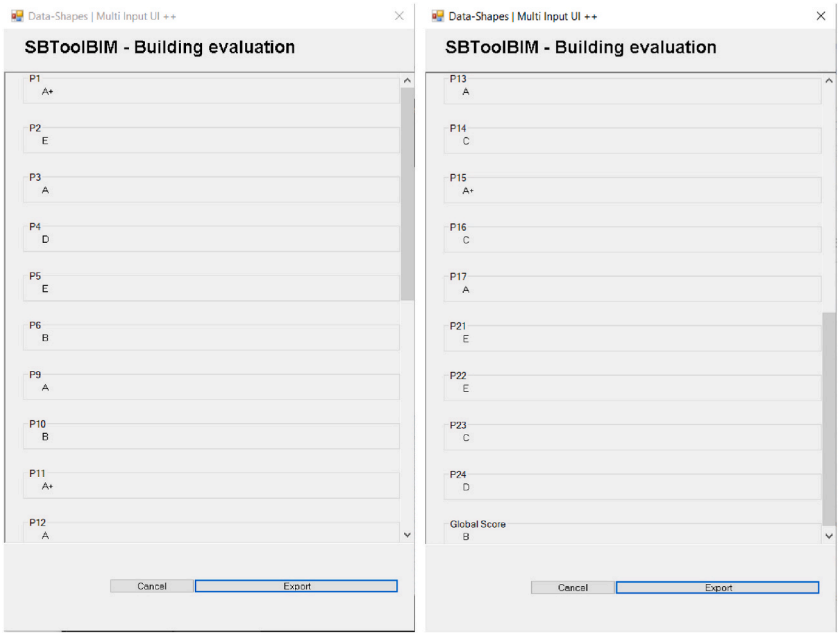


Fig. 12. SBTool^{BIM} results in Autodesk Revit.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	P1	P2	P3	P4	P5	P6	P9	P10	P11	P12	P13	P14	P15	P16	P17	P21	P22	P23	P24	Global Score	
2	A+	E	A	D	E	B	A	B	A+	A	A	C	A+	C	A	E	E	C	D	B	
3	1,308554	-0,77788	0,964994	0	-0,41879	0,527507	0,787561	0,480851	9,547903	0,826292	0,75	0,179148	1,779167	0,333333	0,743836	-0,09081	-0,03731	0,333333	0,062055	0,668991	

Fig. 13. Excel report produced by SBTool^{BIM}.

Table 14
Validation results.

Criteria	SBTool^{BIM}	SBTool^{PT}-H	Difference (%)
P1	1.31	1.32	0.76
P2	−0.78	−0.78	–
P3	0.97	0.97	–
P4	0.00	0.00	–
P5	−0.42	−0.42	–
P6	0.63	0.63	–
P9	0.78	0.78	–
P10	0.47	0.48	2.08
P11	9.54	9.50	0.42
P12	0.83	0.83	–
P13	0.75	0.75	–
P14	0.18	0.18	–
P15	1.78	1.78	–
P16	0.33	0.33	–
P17	0.74	0.74	–
P21	−0.09	−0.09	–
P22	−0.04	−0.04	–
P23	0.33	0.33	–
P24	0.06	0.06	–

different procedures have been established. For the direct inputs in the BIM model, which are related to building quantitative data, an Autodesk Revit template was developed. The template creates a total of 28 new shared parameters, which allows the user to characterise the building elements, materials, and general features with the required data for SBTool^{BIM} assessment. The template was developed in Dynamo, it can be saved as an Autodesk Revit template and defined as standard to open and create BIM models. All the BIM model inputs are then collected and processed by the SBTool^{BIM} application, which was programmed according to the assessment procedure of SBTool^{PT}-H. Overall, BIM model inputs provide the necessary information to fully assess 13 criteria. Besides data collection and treatment, SBTool^{BIM} also allows the user to introduce some additional data, mainly local specific data or building qualitative information. The application inputs must be collected by the user to proceed with the analysis. In total, application inputs

are required for 6 criteria, allowing the complete evaluation of 5 criteria. For the remaining criterion, application inputs are combined with BIM model data to reach an assessment.

After these inputs, SBTool^{BIM} performs automatic calculations to achieve the building individual score for 19 criteria, as well as the building global score (based on those 19 criteria with a redistribution of weights). SBTool^{BIM} provides two different outputs: (i) Automatically displays the building qualitative score in the Autodesk Revit environment and (ii) creates an Excel spreadsheet with both qualitative and quantitative scores. The goal of the first output is to provide designers with a real-time sustainability assessment of their projects during the early stages, allowing for building design optimisation. Although it does not assess all SBTool^{PT}-H criteria, the application analysis relies on 75% of its criteria and can be seen as a key indicator for the building sustainability score. Nevertheless, SBTool^{BIM} second output allows the user to perform SBTool^{PT}-H full evaluation. By connecting the extracted Excel spreadsheet with the SBTool^{PT}-H spreadsheet, 19 criteria are automatically filled. The user must then collect and fill in the data from the remaining six criteria to achieve the building's final score. This information can be gathered from identified BIM tools – Cype and Energy Plus – by exporting the BIM model through different procedures.

SBTool^{BIM} was validated by comparing results with SBTool^{PT}-H manual assessment. Differences of less than 2% were noticed in only three criteria, which did not affect the building score. Time savings were noticed when collecting the building data and performing the assessment calculations. SBTool^{BIM} gathers and groups all the available data according to the criteria requirements and automatically performs the sustainability assessment. It takes a couple of minutes to run and can be applied in early project stages, acting as a decision support tool for project sustainability optimisation. Improvement measures are easily introduced and analysed, providing designers with reliable data for decision-making. SBTool^{BIM} can be included in the Open BIM concept as it is hosted by the BIM platform Autodesk Revit. Articulation of building sustainability with other project disciplines is enhanced, as well as information share. Besides the capability to read models from other software, Autodesk Revit also allows exporting the model for BIM tools to carry out the required performance analysis.

Despite the automatic assessment, SBTool^{BIM} requires a properly characterised model and prior knowledge about the input data. Some of the assessment data still need to be manually gathered by the user and introduced into de model or application. Although, the major limitation concerns the impossibility of automatically assessing the 25 criteria of SBTool^{PT}-H. Six criteria require performance analysis results, which are not available in Autodesk Revit. A BIM linkage to specific software was established to easily gather the remaining data within the BIM environment. Such linkage uses the same BIM model and considers Autodesk Revit as a starting point, sparing the user from rework with the model and establishing a straightforward method to collect the remaining data and conclude the evaluation. New shared parameters could be included in the SBTool^{BIM} template, to fill building performance data directly in the Autodesk Revit environment. However, the evaluation would not be complete without the building performance results, which would always require additional BIM tools. This kind of data is usually available in the project later stages, i.e., the building thermal comfort is only known when all the building envelope and systems are well defined. To act in the project's early stages with real-time feedback, the SBTool^{BIM} application does not consider such building performance criteria but offers additional BIM links to assess them. Nevertheless, the results from the 19 criteria can already provide a strong prediction of the building performance. SBTool^{BIM} does not consider some details from SBTool^{PT}-H. Only building elements such as walls, floors, roofs, stairs, windows, and doors are considered. All exterior permeable areas are considered as "grass" for the building sealed soil evaluation. Building structural elements can be considered if modelled as walls, floors or roofs and building furniture is not considered. However, both were not expectable to be included, as SBTool^{BIM} aims to act in the project's early stages, where such data is usually unavailable.

Regarding its applicability, SBTool^{BIM} is hosted on paid software – Autodesk Revit and Dynamo – which can restrict its general adoption. The absence of mandatory regulation and the low awareness of building owners are also important factors that can hinder SBTool^{BIM} applicability. SBTool^{BIM} was mainly developed for Portuguese single-family buildings but is also applicable in multi-family buildings, being only able to provide a global assessment of the building. However, SBTool^{BIM} applicability is strongly dependent on the BIM model complexity and computer features. The application requires a couple of minutes to start, freezing Autodesk Revit during this time. Complex and large models will extend the freezing time, as well as less powerful computers. This fact can also hinder SBTool^{BIM} use in complex and/or large buildings. In this matter, there is still a need to optimise the application algorithm in order to reduce the number of commands and speed up the assessment time. Moreover, an additional and improved interface is also required both to facilitate comparisons when analysing modification measures and to provide more user-friendly outputs (such as graphic results). Note also that major modifications on Dynamo software may also require reviewing the SBTool^{BIM} algorithm.

SBTool^{BIM} can be applied to all residential buildings by creating and characterising the respective BIM model. It can be developed directly in Autodesk Revit or imported through IFC from another platform. SBTool^{BIM} considers the Portuguese version SBTool^{PT}-H, which is adapted for the Portuguese context. Foreign buildings can still be submitted and evaluated according to Portuguese standards to understand the building sustainability level. Nevertheless, process replicability for other building types or locations was found very accessible. SBTool^{BIM} file can be edited in Dynamo and new criteria can be introduced using similar established procedures. Benchmarks are located at the end of each criterion evaluation and can also be changed according to local standards. As SBTool^{BIM} is also based on the SBTool international system, the same benefits are applied, such as flexibility in criteria consideration and location applicability. The replication for other BSA schemes is also feasible if they are also based on key performance indicators. The research ideology can be replicated for other BSA schemes, only by translating their criteria into computable rules.

6. Conclusions

The research outputs have presented a novel BIM-based application for end-users which provides an automatic assessment of building sustainability using SBTool^{PT}-H. By providing real-time feedback about the performance of 19 key performance indicators,

SBTool^{BIM} offers a cutting-edge decision support tool to enhance building sustainability during the project's early stages. Different designs and improvement measures can be easily analysed and compared with fewer resources, creating the opportunity to develop highly efficient and ecological buildings.

SBTool^{BIM} was found very reliable and can reduce the sustainability assessment time from a week to a couple of days when performing the first project analysis, including data collection, BIM model creation and characterisation and, specific building performance evaluations. Subsequent analysis on the same project only takes a couple of minutes. When integrated into a BIM environment, the prior existence of a BIM model can further reduce the assessment time, as well as avoid double work.

The main limitation of SBTool^{BIM} is the impossibility to automate all the 25 criteria of SBTool^{PT}-H. Six criteria require specific input data, such as building performance simulation results, which are out of Autodesk Revit scope. An alternative BIM procedure was identified to collect the required information, with a straightforward connection with the BIM model. Besides the need to include all the 25 criteria, SBTool^{BIM} will also require the development of a more user-friendly interface and a more efficient algorithm to deal with more complex buildings. As future research, it is proposed to improve the existing limitations, as well as to extend the SBTool^{BIM} approach to other building types, locations and sustainability rating schemes, to effectively increase BIM integration and enhance buildings sustainability.

Overall, it is expected that SBTool^{BIM} will be an essential tool to evaluate and optimise building sustainability, providing valuable contributions to meet worldwide decarbonisation and climate targets. SBTool^{BIM} has demonstrated a future path for BIM integration in BSA, providing designers and researchers with an innovative approach to perform building analysis and frame BSA in future BIM standards.

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CRediT authorship contribution statement

José Pedro Carvalho: Conceptualization, Methodology, Software, Writing – original draft, Validation, Formal analysis, Investigation, Writing – review & editing, Visualization, Funding acquisition. **Luís Bragança:** Supervision, Validation, Writing – review & editing, Visualization, Validation. **Ricardo Mateus:** Supervision, Validation, Writing – review & editing, Visualization, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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