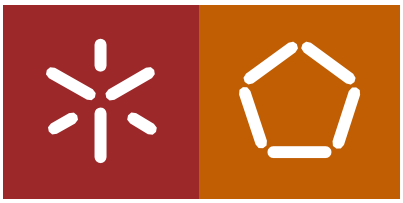
Universidade do Minho
Escola de Engenharia

José Pedro Almeida Carvalho

Integration of BIM in Building Sustainability Assessment methods

junho de 2023

Integration of BIM in Building Sustainability Assessment methods
José Pedro Almeida Carvalho
UMinho | 2023



Universidade do Minho
Escola de Engenharia

José Pedro Almeida Carvalho

Integration of BIM in Building Sustainability Assessment methods

Tese de Doutoramento

Trabalho efetuado sob a orientação do
Professor Doutor Luís Bragança
Professor Doutor Ricardo Mateus

Junho de 2023

DIREITOS DE AUTOR E CONDIÇÕES DE UTILIZAÇÃO DO TRABALHO POR TERCEIROS

Este é um trabalho académico que pode ser utilizado por terceiros desde que respeitadas as regras e boas práticas internacionalmente aceites, no que concerne aos direitos de autor e direitos conexos.

Assim, o presente trabalho pode ser utilizado nos termos previstos na licença abaixo indicado.

Caso o utilizador necessite de permissão para poder fazer um uso do trabalho em condições não previstas no licenciamento indicado, deverá contactar o autor, através do RepositórioUM da Universidade do Minho.

Licença concedida aos utilizadores deste trabalho



Atribuição-NãoComercial-SemDerivações
CC BY-NC-ND

https://creativecommons.org/licenses/by-nc-nd/4.0/

Acknowledgements

This research is the result of a comprehensive stage of my life, which demonstrates my constant pursuit of knowledge. During the past years, different people have positively and directly or indirectly influenced my life and, therefore, this investigation. I am grateful to all of them as they have pushed and shaped my current knowledge, as well as shared good and less positive experiences.

First, I would specifically like to express my gratitude to my supervisors, Professor Luís Bragança and Professor Ricardo Mateus for their valuable advice, support, guidance, patience, and availability during the past years. Their contribution was fundamental to carrying out this research and to all my academic achievements.

I would like to thank my parents and sister for their unconditional support and advice in all my decisions.

I have no words to express my gratitude to Joana Carvalho, who was always there to motivate me no matter what.

At last, I would like to thank all my friends who have always supported my decisions.

This research has been supported by the Portuguese Foundation for Science and Technology (FCT), under the doctoral grant SFRH/BD/145735/2019. This grant was co-financed by the European Social Fund (FSE) through the Northern Regional Operational Program.

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

Abstract

The Architecture, Engineering and Construction (AEC) industry is highly responsible for several environmental impacts and worldwide authorities and societies are increasingly looking for more sustainable buildings. Given the ambitious targets of climate neutrality and decarbonisation, there is an urgent need to develop specific strategies to act in the building sector, as it has been recognised as a key industry to reverse environmental impacts. Among the existing tools, Building Sustainability Assessment (BSA) methods stand out as a pathway to evaluate and promote the integration of sustainability principles in buildings. However, such methods often require multi-disciplinary information about the building and significant resources such as time, money, and human labour. Consequently, and in the absence of mandatory legislation, BSA is usually neglected or applied in project later stages just to provide a sustainable evaluation of the building. With the deployment of Building Information Modelling (BIM), the opportunity for BSA to adopt and benefit from BIM functionalities arises. Currently, BIM has not been used comprehensively in the evaluation process of BSA but the potential for process automation and simplification are well known. To effectively integrate BSA into BIM environment, this research aims to develop a BIM integration framework for the Portuguese residential BSA method SBTool^{PT}-H. Moreover, such framework will be materialized by the creation of an end-user BIM-based application – SBTool^{BIM} – which will act as a decision support tool regarding building sustainability for the project's early stages. SBTool^{BIM} will automate and accelerate the assessment of SBTool^{PT}-H by reflecting its criteria through computable rules. Results show the attractiveness of SBTool^{BIM}, as well as the possibility to have real-time feedback about the building sustainability level in early project stages, allowing for the introduction and comparison of different sustainability measures with few resources. SBTool^{BIM} has established a novel and common approach which can be used as a systematic framework to apply BIM in other BSA schemes, representing a pathway to reduce the building sector impacts and provide valuable contributes to reach worldwide climate neutrality and decarbonisation targets.

Keywords: Building Sustainability Assessment (BSA); Building Information Modelling (BIM); Sustainability; Sustainable built environment

Resumo

A indústria da Arquitetura, Engenharia e Construção (AEC) é responsável por diversos impactes ambientais, levando as autoridades e sociedades mundiais à procura por edifícios mais sustentáveis. Perante os ambiciosos objetivos da neutralidade climática e descarbonização, surge a necessidade de desenvolver estratégias específicas para o setor dos edifícios, dado ser uma indústria chave para a reversão dos referidos impactes. Entre as ferramentas existentes, destacam-se os métodos da avaliação da sustentabilidade de edifícios (BSA, do inglês Building Sustainability Assessment) como forma de avaliar e promover a integração de medidas sustentáveis. No entanto, a sua utilização requer informações multidisciplinares do edifício, bem como recursos significativos, tais como tempo, custos e mão de obra. Consequentemente e na ausência de legislação obrigatória, os BSA são geralmente negligenciados ou aplicados em fases finais de projeto, apenas para identificar o nível de sustentabilidade do edifício. Com a implementação do Building Information Modeling (BIM), surge a oportunidade dos BSA adotarem e beneficiarem das suas funcionalidades. Atualmente, o BIM ainda não é integralmente utilizado no processo de avaliação dos BSA, mas as suas potencialidades para automação e simplificação do processo já foram reconhecidas. De modo a integrar os BSA em ambiente BIM, este trabalho visa desenvolver uma estrutura de integração BIM para o método BSA residencial português SBTool^{PT}-H. A estrutura será materializada através da criação de uma aplicação BIM – SBTool^{BIM} – que irá atuar como uma ferramenta de apoio à decisão em fases iniciais de projeto. O SBTool^{BIM} irá automatizar e acelerar os processos de avaliação da sustentabilidade através do SBTool^{PT}-H, refletindo os seus critérios através de regras computacionais. Os resultados demonstram a utilidade do SBTool^{BIM}, bem como a possibilidade de fornecer feedback em tempo real sobre o nível de sustentabilidade do edifício nas fases iniciais de projeto, permitindo a introdução e a comparação de diferentes medidas de sustentabilidade, utilizando poucos recursos. O SBTool^{BIM} estabelece uma nova abordagem sistemática para aplicação do BIM noutros métodos BSA, representando um caminho para a redução dos impactes do setor e dando valiosas contribuições para alcançar as metas de neutralidade climática e descarbonização.

Palavras-Chave: Métodos de avaliação da sustentabilidade; Building Information Modelling (BIM); Sustentabilidade; Sustentabilidade do ambiente construído

Contents

1. Introduction 1
1.1 Research background and motivation 2
1.2 Research aim and objectives 4
1.3 Research methodology 5
1.4 Thesis outline 7
2. Literature Review 10
2.1 Building Sustainability 11
2.1.1 Building's context 11
2.1.2 Sustainability in the building sector 13
2.1.3 Building Sustainability Assessment (BSA) 16
2.1.4 SBTool 18
2.2 Building Information Modelling (BIM) 20
2.2.1 Concept, context, and benefits 20
2.2.2 BIM model and LOD 24
2.2.3 BIM dimensions 26
2.2.4 Software and interoperability 29
2.2.5 Automated rule checking and Visual Programming Language (VPL) 30
2.2.6 Limitations and setbacks 32
2.3 BIM and building sustainability 35
2.3.1 Context and applications 35
2.3.2 BIM and BSA 40
2.3.3 Benefits and limitations 43
2.4 Concluding remarks 45
3. A Systematic Review of the Role of BIM in Building Sustainability Assessment Methods 46
3.1 Introduction 47
3.2 Building Sustainability Assessment Methods 50
3.2.1 BREEAM 50
3.2.2 LEED 51

3.2.3 SBTool 52
3.3 Methodology 52
3.4 Results 55
3.4.1 Related Review Studies – Idea Validation 55
3.4.2 Publications for consideration 58
3.4.3 BIM Application in BREEAM 59
3.4.4 BIM Application in LEED 61
3.4.5 BIM Application in SBTool 63
3.5 Discussion 69
3.6 Conclusions 75
4. Optimising building sustainability assessment using BIM 78
4.1 Introduction 79
4.1.1 Sustainability and building sustainability assessment (BSA) methods 79
4.1.2 SBTool^{PT}-H 80
4.1.3 Building information modelling (BIM) 82
4.1.4 Sustainability of the construction sector and BIM 84
4.1.5 Autodesk Revit's application programming Interface (API) 86
4.2 Methodology 88
4.3 Results and discussion 89
4.4 Conclusions 104
5. Sustainable building design: Analysing the feasibility of BIM platforms to support practical building sustainability assessment 106
5.1 Introduction 107
5.1.1 SBTool^{PT}-H 108
5.1.2 Building Information Modelling (BIM) 110
5.1.3 BIM and BSA methods 112
5.1.4 Autodesk Revit 113
5.2 Material and methods 114
5.3 Results 117
5.3.1 Category C1 120
5.3.1.1 P1 – construction materials embodied environmental impacts 120

5.3.2 Category C2 125
5.3.2.1 P2 – urban density 125
5.3.2.2 P3 – soil sealing index development 125
5.3.2.3 P4 – use of pre-contaminated land 126
5.3.2.4 P5 – use of native plants 126
5.3.2.5 P6 – heat-island effect 127
5.3.3 Category C4 128
5.3.3.1 P9 – reused material 128
5.3.3.2 P10 – use of materials with recycled content 128
5.3.3.3 P11 – use of certified organic materials 129
5.3.3.4 P12 – use of cement substitutes in concrete 130
5.3.3.5 P13 – waste management during operation 130
5.3.4 Category C6 131
5.3.4.1 P16 – natural ventilation efficiency 131
5.3.4.2 P17 – indoor air quality 132
5.4 Discussion 133
5.5 Conclusions 135
6. BIM-based energy analysis and sustainability assessment – application to Portuguese buildings 138
6.1 Introduction 139
6.2 Literature Review 141
6.2.1 Buildings Energy Performance 141
6.2.2 BIM and BEM 141
6.2.3 Building Sustainability Assessment 144
6.2.3.1 Overview 144
6.2.3.2 BIM integration 145
6.2.3.3 SBTool^{PT}-H 146

6.3 Materials and Methods 149
6.4 BIM Model for Energy Simulation 153
6.4.1 Building Modelling 153
6.4.2 IFC upload Using Open BIM Collaboration Add-in 154
6.4.3 Building Envelope, Systems and Thermal Bridges 154
6.5 Results and Discussion 156
6.5.1 BIM-Based Energy Simulation 156
6.5.2 BIM-Based Energy Validation 159
6.5.3 Sustainability Assessment 162
6.5.3.1 Parameter 7 162
6.5.3.2 Parameter 8 164
6.6 Conclusions 168
7. Automating Building Sustainability Assessment 171
7.1 Introduction 172
7.2 Literature Review 174
7.2.1 Sustainability and building sustainability assessment (BSA) methods 174
7.2.2 BIM and applications for building sustainability 175
7.2.3 Visual Programming 177
7.2.4 SBTool 178
7.3 Material and methods 180
7.3.1 Methodology 180
7.3.2 Software 183
7.3.3 Case study 184
7.4 Results 189
7.4.1 Input requirements and assessment model 189
7.4.2 SBTool^{BIM} template and model characteristics 194
7.4.3 SBTool^{BIM} 199
7.4.3.1 Structure 199
7.4.3.2 Case study application 202

7.4.4 BIM linkage for the remaining criteria 205
7.5 Discussion 206
7.6 Conclusions 210
8. Conclusions, contributions and future work 211
8.1 Conclusions and main contributions 212
8.2 Further research 216
References 218
Publications 249
Appendix 251
Appendix A. SBTool[BIM] User Guide 251

List of Figures

Figure 1 – Types of LOD [107] 25
Figure 2 – BIM dimensions [120] 28
Figure 3 – BIM learning curve, adapted from [148] 33
Figure 4 – Shanghai tower [207] 44
Figure 5 – Systematic review procedure 54
Figure 6 – PRISMA flow diagram [217] 59
Figure 7 – BREEAM categories assessed with BIM 60
Figure 8 – Applied software to assess BREEAM criteria 61
Figure 9 – Addressed LEED versions 61
Figure 10 – Addressed LEED categories 62
Figure 11 – Applied software to assess LEED criteria 63
Figure 12 – Total articles published per year (LEED, BREEAM and SBTool) 70
Figure 13 – Preferred journals (BRREAM, LEED and SBTool) 71
Figure 14 – Commonly assessed categories (BREEAM and LEED) 72
Figure 15 – Commonly used software (BREEAM and LEED) 73
Figure 16 – Number of LEED, BREEAM and SBTool criteria that is possible to assess with BIM 75
Figure 17 – Traditional approach vs a BIM approach, adapted from [236]. 83
Figure 18 – Research Procedure 89
Figure 19 – Basis for SBTool^{BIM} organisation framework 95
Figure 20 – Information flow – SBTool^{BIM} – Phase 1 99
Figure 21 – Information flow – SBTool^{BIM} – Phase 2 99
Figure 22 – Information flow – SBTool^{BIM} – Phase 3 100
Figure 23 – Assessment of SBTool^{PT}-H criteria P2 and P5 101
Figure 24 – Assessment of SBTool^{PT}-H criteria P7 and P8 102
Figure 25 – Assessment of SBTool^{PT}-H criteria P21 and P22 103
Figure 26 – Research procedure 116
Figure 27 – Case study 116
Figure 28 – Created Shared Parameters in Autodesk Revit 119

Figure 29 – Topography and Room Schedules 119
Figure 30 – Project Information and Material Take-off Schedules 120
Figure 31 – Simulation procedure 151
Figure 32 – Floor plan of the case studies: existing model and new building model 151
Figure 33 – Case study floor plan 185
Figure 34 – SBTool^{BIM} process map 194
Figure 35 – (a) Topography and (b) Project Information data 197
Figure 36 – Material characterisation 198
Figure 37 – (a) Plumbing fixtures characterisation and (b) Room characterisation 199
Figure 38 – Collecting and processing data in Dynamo 200
Figure 39 – User interface creation in Dynamo 200
Figure 40 – Result normalisation and qualitative quantification in Dynamo 201
Figure 41 – Dynamo Player in Autodesk Revit 202
Figure 42 – input forms though user interfaces in Autodesk Revit 203
Figure 43 – SBTool^{BIM} results in Autodesk Revit 203
Figure 44 – Excel report produced by SBTool^{BIM} 204
Figure A1 – SBTool^{BIM} process map 251
Figure A2 – Dynamo Player 255
Figure A3 – Topography surface characterisation 255
Figure A4 – Instructions for parameter selection 256
Figure A5 – Project Information characterisation 256
Figure A6 – Material characterisation 257
Figure A7 – Openings characterisation 258
Figure A8 – Plumbing fixtures characterisation 258
Figure A9 – Room characterisation 259
Figure A10 – SBTool^{BIM} interface for P10 assessment 260
Figure A11 – SBTool^{BIM} interface for P13 assessment 260
Figure A12 – SBTool^{BIM} interface for P21 assessment 261
Figure A13 – SBTool^{BIM} interface for P22 assessment 262
Figure A14 – SBTool^{BIM} interface for P23 assessment 262

Figure A15 – SBTool[BIM] interface for P24 assessment 263
Figure A16 – SBTool[BIM] results....263
Figure A17 – Results exportation for SBTool[BIM] Excel spreadsheet 264
Figure A18 – SBTool[BIM] Excel Spreadsheet....264
Figure A19 – Simulation results in Cypetherm REH....265
Figure A20 – Horizon and horizontal obstruction angle in Cypetherm REH 265
Figure A21 – Simulation results in Cypesound RRAE....265
Figure A22 – Plug-in to Insight in Autodesk Revit....266
Figure A23 – IDF export in Insight 266
Figure A24 – Importing data in SBTool[PT]-H Excel spreadsheet....267

List of Tables

Table 1 – SBTool^{PT}-H criteria overview 20
Table 2 – Related review studies 56
Table 3 – BIM integration on BREEAM 65
Table 4 – BIM integration on LEED 66
Table 5 – SBTool^{PT}-H list of categories 81
Table 6 – SBTool^{PT}-H criteria evaluation 91
Table 7 – Assessment phases for the SBTool^{BIM} framework according to the assessment procedure 98
Table 8 – SBTool^{PT}-H list of categories 109
Table 9 – SBTool^{PT}-H qualitative scale 110
Table 10 – Sustainability criteria of SBTool^{PT}-H under analysis 115
Table 11 – Case study characteristics 117
Table 12 – Created Shared Parameters in Autodesk Revit 118
Table 13 – Case study materials environmental impacts 122
Table 14 – Conventional and best practice benchmarks 123
Table 15 – Environmental impacts normalisation 124
Table 16 – Result of the Category C1 124
Table 17 – Results of the Category C2 127
Table 18 – Results of the P10 criterion 129
Table 19 – Results of the Category C4 131
Table 20 – Criteria evaluation – Category C6 132
Table 21 – Conversion from the quantitative to the qualitative performance scales in SBToo^{PT}-H 148
Table 22 – Construction solutions and systems 153
Table 23 – Interoperability synthesis 155
Table 24 – Cypetherm REH results 158
Table 25 – Comparison between the Cypetherm REH results and REH spreadsheet results – existing building 159
Table 26 – Comparison between the Cypetherm REH results and REH spreadsheet – new building 160
Table 27 – Rouding differences between Cypetherm REH and the REH spreadsheet 161

Table 28 – Final score for parameters P7 and P8 167
Table 29 – SBTool conversion scale 179
Table 30 – SBTool^{PT}-H list of categories 180
Table 31 – Case study topography characterisation 184
Table 32 – Case study material characterisation 186
Table 33 – Adopted recycled content and benchmarks 187
Table 34 – Case study plumbing fixtures characterisation 187
Table 35 – Complementary data for SBTool^{BIM} 188
Table 36 – Case study public transport stations 188
Table 37 – Case study nearby amenities 188
Table 38 – SBTool^{PT}-H environmental criteria requirements 191
Table 39 – SBTool^{PT}-H social criteria requirements 192
Table 40 - SBTool^{PT}-H economic criteria requirements 192
Table 41 – Created parameters for SBTool^{BIM} 196
Table 42 – Validation results 205
Table 43 – SBTool^{BIM} vs traditional assessment 215
Table A1 – SBTool^{BIM} considered criteria and weighting system 252
Table A2 – SBTool^{BIM} template parameters 254

Symbols

AEC	Architecture, Engineering and Construction
AIA	American Institute of Architects
API	Application Programming Interface
BAMB	Buildings As Material Banks
BEM	Building Energy Modelling
BIM	Building Information Modelling
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
BSA	Building Sustainability Assessment
CAD	Computer Aided Design
CDW	Construction and Demolition Waste
CEAP	Circular Economy Action Plan
CEN	European Committee for Standardization
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CSAT	Rainwater satisfaction coefficient
DGEG	Portuguese Directorate-General for Energy and Geology
DHW	Domestic Hot Water
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene insulation
EU	European Union
FM	Facility Management
GBI	Green Building Index
GBS	Green Building Studio
gbXML	Green Building XML

GDP	Gross Domestic Product
GHG	Green House Gas
GIS	Geographic Information Systems
GSA	United States General Services Administration
IESVE	Integrated Environmental Solutions Virtual Environment
IFC	Industry Foundation Classes
iiSBE	international initiative for a Sustainable Built Environment
ISO	International Organization for Standardization
kWh	kilowatt-hour
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
LNEC	Portuguese national civil engineering laboratory
LOD	Level of Development
Na	National limit for the building DHW needs
Nac	Building DHW needs
Ni	National limit for the building heating needs
Nic	Building heating needs
Nt	National limit for the building primary energy needs
Ntc	Building primary energy needs
Nv	National limit for the building cooling needs
Nvc	Building cooling needs
NIBS	United States National Institute of Building Sciences
OECD	Organisation for Economic Co-operation and Development
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PV	Photovoltaic
RECS	Services and Commercial Buildings Energy Performance Regulation
RED	Renewable Energy Directive

REH	Residential Buildings Energy Performance Regulation
RQ	Research Question
RRF	Recovery and Resilience Facility
SBTool	Sustainable Building Tool
SCE	Buildings Energy Certification System
U	Heat Transfer Coefficients
UI	User Interference
UK	United Kingdom
UN	United Nations
USA	United States of America
USGBC	United States Green Building Council
VOC	Volatile Organic Compounds
VPL	Visual Programming Language
WGBC	World Green Building Council
XPS	Extruded polystyrene insulation

1. INTRODUCTION

Chapter 1 presents the background of the research. The aim and objectives, research scope, methodology and outlines of the thesis are referred to.

1.1 Research background and motivation

The relation between buildings and environmental impacts has already been proved and accepted by the scientific community [1]. Worldwide governments and societies are increasingly looking for a more sustainable, green, efficient, and low-carbon environment. In Europe, the building sector has extreme importance on decarbonisation to reach the current goals of climate neutrality by 2050, which is also required to meet the Paris Agreement objectives [2,3]. Currently, buildings are responsible for 36% of the energy consumption, which is 80% powered by fossil and, responsible for 37% of Green House Gas (GHG) emissions [2]. The European Union (EU) is also highly dependent on energy, with a dependency rate of over 58% in 2020 [4]. Most of this energy is oriented towards buildings use, since 97% of European buildings are not energy efficient, highlighting the urgent need to improve building energy performance [5]. In order to act near buildings, the EU has established different initiatives (Green Deal, Renovation Wave, Fit for 55, among others) to reduce building energy demand, associated emissions, resource consumption and general environmental footprint [3]. Therefore, it becomes extremely important to act in the building sector, which together with the food and mobility sectors, could have a significant contribute to reach the targeted sustainability goals. There is a need to act since the early project stages by introducing and analysing different sustainability measures to effectively address building sustainability.

A way to enhance buildings sustainability is to monitor and evaluate their sustainability levels through the application of Building Sustainability Assessment (BSA) methods. They provide a useful tool to support the introduction of sustainability measures and to demonstrate and communicate to the community the environmental, social, and economic benefits of the project of a building [6]. Among the most known BSA methods are LEED, BREEAM and SBTool [7,8], which will be explored in this research. The application of BSA methods is traditionally a time-consuming procedure, requiring multidisciplinary data from the building and a tedious calculation process, being an iterative procedure seeking for the best sustainability scenario. Consequently, they are usually applied in the project later stages only to provide a classification for the building, excluding their potentialities during the project early stages [9,10]. Moreover, BSA is usually a voluntary approach, which also contributes to a narrow adoption, with less than 0.4% of buildings in the EU being certified [11]. There is a need to develop a more expedited framework to carry BSA, providing a real-

time evaluation in the project early stages, where project modifications to improve sustainability are still available at a reduced cost [12,13].

With the deployment of construction digitalisation, Building Information Modelling (BIM) has shown up as a new paradigm to design, build and manage constructions. BIM can be described as a working methodology which allows managing the project design and data through a virtual model during its lifecycle. It allows the development of high-performance buildings, by creating and simulating the building in a virtual environment before the construction itself [9,14,15]. BIM has been used for building sustainability, as it provides the opportunity to store multi-disciplinary data about the building, allowing to analyse and introduce different sustainability measures [16].

The application of BIM for BSA methods is also an emerging subject among building sustainability topics [17–19]. With the noticeable benefits from BIM in the project early stages, the opportunity arises for BSA methods to benefit from it and streamline process efficiency [20]. Assessment time can be reduced and BSA can become a decision support tool for designers to effectively enhance building sustainability. Different approaches have been made in several BSA methods, by establishing frameworks to gather assessment data from BIM models and software [9,16,21–25]. However, authors have agreed that a proper connection of BIM with BSA has not been established and BIM potential can be further explored [20,22,26]. Moreover, the role of digitalisation has been recognised by the World Business Council for Sustainable Development for improving sustainability performance and supporting the development of new processes, services, and markets [2].

Facing the need to develop an expedited method for BSA and to address the identified research gap, this research aims to expand the integration of BIM in BSA methods by developing a BIM-based application to automate sustainability assessment in the project early stages. SBTool^{BIM} application will be created to translate SBTool^{PT}-H assessment requirements into computable rules and automate the assessment procedure, providing a real-time decision support tool for designers. They will be provided with the project's sustainability score in the very early stages, allowing for the introduction and comparison of new sustainability measures, resulting in more efficient and ecological buildings. The outcomes from this PhD thesis will provide a cutting-edge framework for the integration of BIM in BSA methods, marking the beginning of a new approach for carrying out BSA. SBTool^{BIM} provides the opportunity to effectively improve buildings sustainability and can act as an important tool to achieve Europe's goals for the building industry.

1.2 Research aim and objectives

The need to develop more sustainable buildings together with the narrow application of BSA methods and the lack of knowledge on the integration of BIM in BSA methods has led to the definition of the research aim. In this context, the main objective of this research is to develop a BIM-based application for designers to automate and simplify BSA in the early project stages. Despite the existing studies, a direct link between BIM and BSA has not been properly established yet to effectively benefit from digitalisation. Therefore, SBTool^{BIM} application will be developed to translate the Portuguese residential version of SBTool – SBTool^{PT}-H – to computer language and optimise data collection and the assessment procedure. SBTool^{BIM} specific objectives are:

- Automate BSA to reduce the assessment time and efforts, as well as to shift the assessment phase to early project stages, where decisions regarding building sustainability should be made;
- Provide a decision support tool for designers regarding the application of sustainability principles, with real-time outputs for analysing project sustainability with few resources;
- Define an integration framework for BSA into the BIM environment, to benefit from BIM potentialities (such as data storage, process automation and collaboration) and to include sustainability assessment as part of a BIM project work process. It is also intended to enhance sustainability assessment coordination with other project disciplines;
- Promote BSA application with a faster and more intuitive tool for designers to effectively enhance building sustainability;
- Reduce the building sector impacts and provide contributions to reach EU and United Nations sustainability goals.

Simultaneously, it is also intended to evaluate the current state of the art regarding the application of BIM in the main BSA methods, such as LEED, BREEAM and SBTool, as well as to evaluate BIM potential and attractiveness for scheme automation. This task will provide valuable insights about existing BIM approaches, which will serve as the basis to define SBTool^{BIM} conceptual framework. Moreover, based on this analysis the attractiveness of a BIM-based application will be evaluated for the three studied BSA methods.

1.3 Research methodology

To achieve the intended goals, the research will begin with a theoretical analysis of the current state of the art regarding key aspects of BSA, BIM, as well as the integration of BIM in BSA. The focus will be given to the three following BSA methods: LEED, BREEAM and SBTool. A systematic review will be made through the definition of research parameters, databases and search engines. This way, it will be possible to develop a broad, concise, and detailed review concerning the integration of BIM in the referred BSA methods. This analysis will provide valuable insights for the achievement of the research objectives, by exploring existing BIM approaches to evaluate BSA criteria, as well as the current research gaps. As the research goal is focused on SBTool, this BSA scheme will be carefully analysed, especially the Portuguese residential version, SBTool^{PT}-H. This scheme was selected as it is adapted to the Portuguese context and the research team has a deep knowledge about its structure and assessment process. Furthermore, SBTool is a flexible method which has been used in other countries, facilitating the replicability of the research method and outcomes on different context from the Portuguese one. All of its criteria will be studied to identify the assessment data requirements and calculation procedure.

Then, a conceptual framework will be developed to use BIM for the automation of SBTool^{PT}-H. By identifying the required data for each criterion, a BIM approach will be selected for its direct or indirect evaluation according to the assessment needs. The suggested framework will address the BIM model details for each evaluation stage, the need to collect external information, the tasks and processes sequence, the interoperability between software, the predicted limitations, and indications on how to aggregate the results from different BIM software. Moreover, a critical analysis will be made about process optimisation and simplification, as well as about the capabilities and restrictions of BIM and BSA methods.

To test the developed theory, the framework will be used to assess the sustainability score of a case study. A Portuguese single-family residential building – under SBTool^{PT}-H scope – will be selected and assessed to understand the benefits and restrictions of this approach to designers and the built environment. The model will be a simple and small building, as the goal is only to test and validate the developed theories. During this stage, a BIM software will be used both to store the assessment data and carry out building performance simulations. Less complex and sized models allow for faster analysis, granting quicker programming and

validation. The results will allow the understanding of the framework restrictions in order to optimise and adapt the conceptual structure for the next stage.

The conceptual structure will then serve as basis to proceed with the creation of a BIM-based end-user application – SBTool^{BIM}. By using Visual Programming Language (VPL), the application will be created to extract, filter, and process the necessary information for BSA from the BIM model. Information such as building and site dimensions, materials characteristics, costs, rooms, and plumbing fixtures, among many other data will be quickly assessed and forwarded for the respective criteria. Additionally, SBTool^{BIM} will display an interface both to collect external data from the user and to present the building sustainability score in real-time. The aim is to provide a decision support tool with enough reliability to help designers in introducing and comparing different sustainability measures in the early project stages. The building assessment results will also be produced in an Excel spreadsheet, which will be connected to SBTool^{PT}-H Excel spreadsheet through macros to automatically fill the results. The goal is to use SBTool^{BIM} results for a full sustainability assessment in project later stages, where building performance results are already known. Overall, an automated rule checking process [27] will be adapted to create and use the application:

- Rule interpretation – Analysis of SBTool^{PT}-H assessment requirements and calculation procedures;
- Model preparation – Creation and characterisation of a BIM model, according to the assessment requirements;
- Rule execution - All the established "rules" will be programmed through VPL into an algorithm. This phase consists of the development of the SBTool^{BIM} application, which will reflect SBTool^{PT}-H criteria;
- Rule report – Building sustainability assessment, which consists on the building score, will be available through a user interface and Excel spreadsheet.

Finally, an additional BIM linkage will be proposed to gather building performance data. SBTool^{BIM} will not be able to carry out detailed building performance simulations and such data is usually available in project later stages when other project disciplines have already started. Thus, the additional linkage will provide the opportunity to use SBTool^{BIM} results from the project early stages, together with building simulation results from specific project disciplines to reach a complete sustainability assessment. Such linkage will be made by exporting the created BIM model to specific BIM tools, where thermal and acoustic simulations can be

carried out. Model requirements and interoperability will be presented, as well as which data should be collected from each tool. Results are then linked to the SBTool^{PT}-H spreadsheet that already contains the results from SBTool^{BIM} and a final sustainability score can be achieved. This way, SBTool^{BIM} can still be used in the project early stages to guide and support designers, as well as in the project later stages to complete the evaluation.

SBTool^{BIM} and all BIM linkages will be tested and validated in a controlled case study, confronting the results with the manual/traditional assessment of SBTool^{PT}-H.

1.4 Thesis outline

This thesis is organised into different chapters, starting by presenting the research background and the motivation that leads to the origin of this thesis, as well as the global research methodology and the thesis organisation. Then, the current state of the art on the research relevant topics is addressed and the SBTool^{PT}-H sustainability assessment requirements are identified, together with possible different procedures to carry out the sustainability evaluation. Next, the main results of this research are presented, by demonstrating the development of the SBTool^{BIM} application, which is validated and applied to a case study. Moreover, the integration of BIM in BSA is discussed and clearly established. Finally, the investigation main findings and contributions are Identified, as well as a set of approaches for future research. The content of each Chapter is summarised as follows:

- Chapter 2 presents an analysis of the current State of Art, with a focus on building sustainability, BSA methods and BIM. The main topic concepts will be addressed, as well as the relations between them. The analysis will provide valuable insights to develop a concise BIM framework for the automatic assessment of BSA methods;
- Chapter 3 presents a systematic review of the role of BIM in BSA methods, where the current application of BIM for the assessment of LEED, BREEAM and SBTool criteria is investigated. An analysis is made to determine which method can currently take more advantage of BIM and the attractiveness of a BIM-based assessment application is studied. This chapter is based on the article *"Carvalho, J.P.; Bragança, L.; Mateus, R. A Systematic Review of the Role of BIM in Building*

Sustainability Assessment Methods. Appl. Sci. 2020, 10, 4444. https://doi.org/10.3390/app10134444";

- Chapter 4 explains how BIM can be used to optimise the assessment of BSA methods, with a focus on the Portuguese residential version of SBTool. Moreover, the conceptual framework for SBTool^{BIM} is established, where the assessment requirements are identified and BIM-based approaches are proposed to create the virtual model, gather the required data and automate the assessment calculation. This Chapter is based on the article *"J.P. Carvalho, L. Bragança, R. Mateus, Optimising building sustainability assessment using BIM, Automation in Construction. 102 (2019) 170–182. https://doi.org/10.1016/J.AUTCON.2019.02.021";*

- Chapter 5 is dedicated to the practical validation of the SBTool^{BIM} framework by analysing the feasibility of BIM platforms to provide the assessment data of SBTool^{PT}-H. A template for Autodesk Revit is proposed, able to store and process sustainability data. By properly characterising the BIM model, a total of 13 out of 25 criteria were possible to evaluate by collecting assessment data from predefined schedules, validating the possibility of using Autodesk Revit to host the SBTool^{BIM} application. This Chapter is based on the article *"J.P. Carvalho, L. Bragança, R. Mateus, Sustainable building design: Analysing the feasibility of BIM platforms to support practical building sustainability assessment. Computers in Industry 127 (2021) 103400. https://doi.org/10.1016/j.compind.2021.103400";*

- Chapter 6 focuses on the additional BIM links to provide building performance data for the sustainability assessment. As BIM platforms are not properly adapted to carry out building performance analysis, supplementary software is identified to provide the additional data for the sustainability assessment. Model requirements and interoperability approaches are discussed, as well as the assessment data that should be collected and used. This Chapter is based on the article *"Carvalho, J.P.; Almeida, M.; Bragança, L.; Mateus, R. BIM-Based Energy Analysis and Sustainability Assessment–Application to Portuguese Buildings. Buildings 2021, 11, 246. https://doi.org/10.3390/buildings11060246";*

- Chapter 7 regards the programming, development, and validation of the SBTool^{BIM} application. SBTool^{BIM} process map is presented together with its model and requirements, as well as its main

contributions, functionalities and limitations. Moreover, SBTool^{BIM} is applied to a case study to validate the developed theory and additional BIM links are identified to collect building performance data. This Chapter is based on an article under submission process to *Journal of Building Engineering*;

- Chapter 8 summarises the main findings and contributes from the previous chapters regarding the development of the SBTool^{BIM} application. Furthermore, research perspectives for future studies are proposed.

2. LITERATURE REVIEW

This Chapter focus on the published literature on building sustainability and BIM, as well as explaining the actual developments in relation to the mentioned concepts. Moreover, the buildings context background in the European Union is identified, such as impacts, figures, existing policies and expected targets. Building sustainability tools, such as BSA methods are named and acknowledged as a pathway to enhance building sustainability. BIM concepts are explained, and the current implementation status and setbacks are identified. Finally, the connection between BIM and BSA is explored by reviewing the research and practical developments. The insights from this chapter will provide the basis for the research theory development, as well as for the clarification of the existing research gaps.

2.1 Building Sustainability

2.1.1 Building's context

Buildings are an important element of our societies and the backbone of all economic activity, representing the largest global asset. Dysfunctional, neglected or poorly designed buildings are a pathway for energy poverty, lower productivity and missed opportunities for social development, leading to distorted and disrupted communities. Buildings must provide services and functions according to the society necessities and answer to external effects such as environmental, societal, and economic drivers. Among them are the speeding up climate change, air pollution, increased urbanisation, construction and real estate prices, and rent affordability [28]. There is a need for sustainable and resilient buildings, which can withstand market volatility and provide a healthy, efficient, and comfortable environment for their users [5,29].

With the central role of the built environment on many economic sectors and quality of life, it requires a vast number of resources, accounting for half of all the extracted material [30,31]. The relation between buildings and environmental impacts has already been proved and accepted by the scientific community [1,32,33]. The construction sector is responsible for 35% of the waste generated in the EU and buildings account for 37% of the energy demand, which is 80% powered by fossil fuels [2,30]. The building sector is one of the main contributors to the EU energy dependency rate of 58%, increasing Europe's vulnerability in terms of energy import dependency [5]. Moreover, the building stock is also responsible for 37% of GHG emissions in the EU, which can reach up to 50% if combined with the emissions from materials and processes involved in their construction and demolition [3,5]. Social and economic impacts of the construction sector are also evident, with more than 18 million direct jobs in the EU, representing 9% of the Union's Gross Domestic Product (GDP), having a direct impact on the safety of persons and the quality of life [34].

Worldwide societies and public authorities have revealed a particular interest in more sustainable, efficient, and ecological buildings and building technologies. The building sector has been recognised as a key segment to achieving climate targets, such as the Paris Agreement or the EU climate neutrality objective for 2050 [2,3]. Buildings must have proper investment to boost both the rate and depth of building renovations. New buildings must be carbon neutral and existing buildings must be upgraded. Currently, the EU building stock has 97% of energy inefficient buildings, which will still be operational in 2050 [3,5]. Given their impacts and

energy demand, it becomes clear the need to proceed with specific renovations of the building stock, to turn them more efficient and make it possible to achieve EU objectives. Climate neutrality in 2050 will require a reduction of 60% in GHG emissions by 2030 (compared with 2015 levels) [3,5,31]. The actual energy-renovation rate is around 1% (0.2% deep renovation) and investigators have already highlighted the need to increase the annual deep renovation rate to at least 3% to have a minimal chance to reach the intended goals [3]. Moreover, increasing the renovation rate of the EU building stock will also promote local economies. The BPIE institute pointed out that for every €1 million invested in the energy renovation of buildings, an average of 18 local and long-term jobs are created [5].

Decarbonisation will overcome the environmental dimension and be a social challenge in the EU. Social policies, public funds for energy efficiency and political decision making will be required and often member states do not agree on energy-related policies. Up to date, in the EU it is estimated that over 37 million citizens cannot afford to properly heat and cool their homes. Social justice and climate action are two sides of the same coin [5,28].

In this regard and to effectively achieve the 2050 climate neutrality goal, the EU has established and updated existing legislation under the Clean Energy Package from 2018, where the Energy Performance of Buildings Directive (EPBD), the Energy Efficiency Directive (EED), the Renewable Energy Directive (RED) and Regulation on Governance are the main instruments [3]. The aim is to accelerate the energy transition in Europe and upgrade the existing regulatory framework to reflect higher ambitions and more pressing needs concerning climate and social action. Simultaneously, several initiatives have also been launched, where the EU Green Deal stands out, which encompasses the Renovation Wave and Fit for 55 packages. It is the strategy for driving the EU towards a sustainable and climate-neutral economy until 2050, addressing different sectors such as health, food, transport, jobs, or economy but also with a focus on the transition to a zero-carbon building stock. The fit for 55 package was released in 2021 with a set of legislative proposals to guide the EU in achieving the interim target of a 55% reduction in GHG emissions by 2030. The package also includes revisions on the main legislative instruments such as the EPBD, EED and RED. The Renovation Wave also aims toward European buildings, highlighting key areas to boost the renovation of buildings, through a wide range of policies, measures, and tools [3,5].

In addition, the COVID-related recovery plan for the EU also allocates funds to promote a sustainable and green recovery, including loans and grants for building renovation. A total of € 1.211 trillion has been

organised for a seven-year period to support economic recovery and promote a green and digital future in the EU. While more than € 806 billion were specified to fix countries' economies under the NextGenarationEU, the Recovery and Resilience Facility (RRF) makes available 90% of a 724 billion budget for building renovation. The principal objective is to support the achievement of climate targets while promoting economic recovery and mitigating the impacts of the coronavirus pandemic [3].

Nevertheless, there are still other pathways that can support the achievement of climate neutrality by 2050. Both new buildings and renovations require materials and construction/demolition procedures which generate CO_2 emissions. It is further necessary to decrease embodied emissions and energy from processes and materials [31]. The EU has released the Circular Economy Action Plan (CEAP) to provide "*a future-oriented agenda for achieving a cleaner and more competitive Europe in co-creation with economic actors, consumers, citizens and civil society organisations*" [30]. Among other sectors, the CEAP intends to increase material efficiency and reduce climate impacts from constructions and buildings, by developing a Strategy for a Sustainable Built Environment. Circular principles will be promoted such as improving the durability and adaptability of built assets, promoting soil sealing reduction and circular use of excavated soils, using Level(s) to integrate life cycle assessment and reviewing EU material recovery targets and Construction Product Regulation [30]. It is also expected a valuable contribution from the CEAP for the Renovation Wave, as it will be implemented in line with circular economy principles, which allows reducing the use of materials and embedded emissions in the renovation of existing buildings [30,31]. Still, the Strategy for a Sustainable Built Environment has been frontloaded to the RRF and Renovation Wave, and it is expected during 2022 [35].

Overall, building decarbonisation has still a long path to contribute to climate goals and the EU needs to accelerate the transition toward a regenerative growth model. The building sector will face different environmental, social, and economic challenges in an effective, consistent, and long-term manner, adopting sustainability and circularity principles to retain and increase buildings value for societies.

2.1.2 Sustainability in the building sector

The construction sector is one of the main economic sectors of our societies. However, it is still based on traditional construction systems, and it is responsible for resource scarcity, energy use, GHG emissions and production of waste. Building sustainability has been highly discussed in the past years, adapting the

concepts of sustainable development to the construction industry. Initial international discussion on the sustainability topic goes back to 1972 during the United Nations (UN) Conference on the Human Environment [36]. In 1987, the Brundtland report defined sustainable development as "*the development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" [37]. The UN conferences on Environment and Sustainable Development (Rio de Janeiro, 1992+2012 and Johannesburg, 2002) have also given a significant contribution to the concept expansion and goals, by establishing the three main dimensions for sustainable development, which must be tuned among them: environment, society, and economy [36,38].

Given the impacts of the traditional procedures of the building industry and the increasing authority and public pressure [29,39,40], sustainable development goals were adopted for the industry, adapting the sustainable building concept, which was first defined by Charles Kibert in 1994 as a "*responsible creation and management of a healthy building environment, considering the ecological principles and the efficient use of resources*" [41], during the First World Conference on Sustainable Construction. Moreover, Kibert has also identified six main principles for sustainable construction [41]:

- Minimisation of resources consumption;
- Reuse of resources;
- Use of renewable and recyclable resources;
- Natural environment protection;
- Creation of a healthy and non-toxic environment;
- Quality improvement.

To the Organisation for Economic Co-operation and Development (OECD) [42] a sustainable building has minimal adverse impacts on the built and natural environment. It has a set of building practices which strive for integral quality, where the whole building life cycle is considered, taking environmental quality, functional quality and future values into account. Moreover, the World Green Building Council [43] states that a sustainable building besides the minimal impact, also create positive impacts in climate and natural environment, reducing resource use and improving quality of life, enhancing economic and social aspects in local, regional and global levels. According to the UN Environment Programme [44], the ideal sustainable

building concerns an active process where policies and incentives should be provided by governments and where stakeholders are aware of sustainability considerations and encourage the adoption of such practices.

A building can only be considered sustainable if all the dimensions of sustainability are considered - environmental, economic, and social-cultural [6,42,45,46]. It is a wide and multidisciplinary research, which includes several project disciplines and the participation of different stakeholders, such as designers, owners, contractors, suppliers, and users. Among the key areas to act for a sustainable building the following stand out [6,42,43,47]:

- Optimise site and renewable production;
- Efficient use of energy, water and other resources;
- Pollution and waste reduction measures;
- Use of environmentally friendly materials;
- Promote a healthy and comfortable indoor environment;
- Planning building conservation and renovation, bearing for the preservation of cultural identity.

Building sustainability requires a systematic and integrated approach [6,42] apart from the identification of sustainability measures. There is a need to change the building paradigm by adapting stakeholders' attitudes, as well as existing processes and systems [48].

The optimal sustainable building must be shaped and adapted according to its location requirements and culture. Different countries and regions have different climates and traditions, which contribute to the local definition of sustainable building [6]. Overall, building sustainability can be influenced by four factors [6,48]: The considered criteria, the importance of each criterion, the building type, and the specific local cultural, social, and environmental characteristics.

The use of BSA methods is a possible pathway to promote buildings sustainability, allowing to balance the three dimensions of sustainability. BSA methods are explored in the next section.

Sustainable building and construction aspects have also been commonly addressed by the International Organization for Standardization (ISO). Currently, there are several ISO standards for sustainability in building

and construction works, which are the responsibility of the respective Technical Committee (ISO/TC 59/SC 17) since 2002 [49].

The potential of sustainable buildings has already been recognised. On the environmental dimension, the adoption of sustainability measures can reduce 50% of the sector energy demand until 2050, as well as reduce GHG emissions and water use. From an economic perspective, this energy reduction can represent savings of over € 280 billion. Furthermore, in Canada alone, the sustainable building industry represents $ 23 billion in the GDP. Together with the United States of America (USA), there are approximately 4 million full-time jobs related to sustainable buildings. Finally, social benefits will also be noticed, such as improved indoor quality and human well-being [50]. Despite the benefits, there are still some restrictions on the application of building sustainability, such as the fragmented value chain, the possibility to apply integrated design, the lack of knowledge and demand or the drawbacks in the marketing process [44].

2.1.3 Building Sustainability Assessment (BSA)

Given the demand for more sustainable buildings and the need for an integrated approach to dealing with multidisciplinary data, BSA methods have been developed for the past 30 years. BSA consist of a holistic approach that allows buildings to demonstrate their benefits for the community, taking into consideration the connection between the urban and natural environment [51–53]. BSA aims to implement and spread sustainable principles, evaluate, and monitor building performance and provide information for decision-making in the different stages of a project. Moreover, BSA intends to communicate to the market the building's commitment to sustainable development [54]. BSA methods must be in constant development to reach a balance between the different sustainability dimensions. They also need to be practical, transparent, and flexible enough for an easy adaption to different contexts and technological evolution [6].

More than 600 BSA frameworks have been developed worldwide by public authorities and private companies, adapted to their region-specific aspects and conditions [55,56]. Consequently, the building score is not a shared definition worldwide, as different countries have different rating systems according to their local priorities and traditions [11,47,51]. Nevertheless, authors have pointed out the need for a common global method to allow comparisons between buildings from different locations [57]. Among the most known BSA methods are LEED, BREEAM, SBTool, CASBEE, DGNB and Green Star [7,54,55,58]. They commonly assess

a set of building features and aggregate the results into an environmental rating or sustainability score, understandable for all the society [6].

BSA is an interdisciplinary approach that evaluates the impacts of products and processes from an environmental, social, and economic perspective simultaneously, acting in several fields [46]. Rating schemes are often organised in evaluation areas, such as architectural quality, reliability, energy efficiency, economic convenience, waste, transport, accessibility, indoor environment and reduced environmental impact [51,54,58–60].

Currently, BSA is a voluntary nature with narrow adoption, taken by owners and/or developers to demonstrate their building's sustainable features. They are usually focusing on the certification score for market benefits in the real estate sector instead of building whole life cycle optimisation [51,54,59].

Authors have argued that governments can provide key contributions to the promotion of sustainable buildings, both by requiring sustainability certification and by providing incentives for developers and owners. Additionally, by being the largest owner in the building sector, governments have considerable potential to promote the development of sustainable buildings [61,62].

BSA presents extra resources and complexity [11,60], which is usually incompatible with early project deadlines, where decisions regarding building sustainability should be made [63,64]. Thus, BSA is often used in project later stages to certify the building sustainability score for market purposes, and changes are often unfeasible [12]. There is a need to gather and process multidisciplinary data, as well as to carry out an iterative procedure seeking the best sustainable solution. If an improvement measure is introduced, the calculation procedure must be repeated, also contributing to the restricted adoption of BSA in the project early stages. Authors have been arguing about novel insights for BSA, such as real-time and dynamic assessment, less complex credit structures and more user-friendly environments [12,22,65,66]. This context is translated into only 0.32% of certified residential buildings and 0.04% of commercial buildings in Europe [11].

The benefits of the adoption of BSA are known. According to the World Green Building Council (WGBC) [50] certified buildings by Green Star Australia produce 62% fewer GHG emissions and use 51% less water. In India and South Africa, certified buildings by local schemes consume around 40% less energy and use 30% less water than other conventional buildings. LEED certified buildings in the USA present fewer effective

results, with buildings consuming 25% less energy and 11% of water. These facts are in line with the potentialities suggested for sustainable buildings, such as a 30–50% reduction in total energy use, 35% reduction of GHG emissions, 40% reduction in water use, and 70% savings in waste production [61].

In Portugal, BSA has already been addressed but there is still limited use of existing methods. As there is not any mandatory sustainable evaluation for buildings, designers often disregard sustainability assessment schemes and evaluations are only made upon the owner's request. To date, Portugal has not had an official BSA method, and only a couple of building sustainability rating schemes have been specifically developed for the country context: SBTool^{PT}, LiderA and Domus Natura [67,68]. Nevertheless, a couple of Portuguese buildings have also been submitted to foreign schemes, such as BREEAM and LEED [11].

Both SBTool and LiderA are the most popular schemes in Portugal. LiderA was the first developed method in 2005 and considers 22 different fields, where each criterion has the same importance under the same field. SBTool^{PT} was disclosed in 2011 and uses a life cycle approach in the evaluation. The criteria weighting system is adapted to meet local specific aspects, such as culture, traditions, and priorities. Moreover, SBTool directly considers economic aspects, while LiderA is more like LEED, considering economic issues indirectly [67]. Despite being voluntary, existing methods have already been adapted to embrace different Portuguese building types and urban areas [6,69–71]. The development of sustainable indicators in Portugal still lacks political commitment and vision, as well as higher stakeholder involvement and societal awareness [72].

2.1.4 SBTool

SBTool, promoted by the international initiative for a Sustainable Built Environment (iiSBE), together with BREEAM and LEED are considered the basis for all the other approaches for sustainability assessment [47]. SBTool is considered the most comprehensive BSA due to its flexibility to be adapted to the local requirements of each region, allowing the comparison of buildings from different countries [6,8]. Moreover, it can also be adapted to assess the sustainability of different building types, such as homes, offices, schools or medical facilities and even urban areas. SBTool has influenced the development of the national rating systems in Austria, Spain, Japan and South Korea, and custom versions have been introduced in Italy, Czech Republic, and Portugal [6,69,73,74]. The international structure of 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. Criteria selection and ponderation are usually defined when transposing the international system to each location according to region-specific and site-specific factors [6,64,73].

In Portugal, the SBTool has been adapted for different buildings, including residential, office, schools and health care. The first and most recognised was the residential building version – SBTool^{PT}-H – which was developed by the University of Minho, iiSBE Portugal and Ecochoice. The principal aim of this scheme was to create a common methodology to assess the sustainability levels of existing, new, and renovated residential buildings in Portugal. It was also intended to support design teams from the early project stages in selecting different sustainable measures, as well as to raise awareness of the construction market's stakeholders about the benefits of adopting more sustainable solutions [6].

SBTool^{PT}-H follows the structure of the international system and has a total of 25 criteria sorted by 9 categories, under the three dimensions of sustainability: Environment, Society and Economy. Table 1 presents an overview of SBTool^{PT}-H criteria. The number and nature of the criteria vary from one category to another according to the category itself and its importance to the Portuguese context. To carry out the assessment, each criterion is classified with a quantitative score that results from the comparison between the performance of the analysed building and two benchmarks: best and conventional national practice [75]. Each criterion score is then normalised to establish a dimensionless value that expresses the building performance in comparison to the benchmarks, as well as to avoid scale aggregation effects, and problems such as “bigger is better” or “bigger is worse”. The normalised value is finally converted into a quantitative scale to easily express the building score to non-experts, ranging from A+ to E, where A corresponds to the best national practice and D to the national conventional practice. After the assessment of all criteria, the weighting system is applied accordingly, and a sustainability score is reached [6].

Table 1 – SBTool^{PT}-H criteria overview

Dimension	Categoria	Number of criteria
Environment	C1 – Climate change and outdoor air quality	1
	C2 – Land use and biodiversity	5
	C3 – Energy Efficiency	2
	C4 – Materials and waste management	5
	C5 – Water efficiency	2
Social	C6 – Occupant's health and comfort	5
	C7 – Accessibilities	2
	C8 – Education and awareness of sustainability	1
Economic	C9 – Life-cycle costs	2

As with all the other BSA methods, the current assessment of SBTool^{PT}-H is a manual, time-consuming and complex process, requiring multi-disciplinary data about the building and a set of pre-defined calculations. It is also based on an inefficient interactive assessment process that pursues to find out the best building design to optimise the building sustainability level. When improvement measures are introduced, the entire assessment process must be repeated, discouraging designers to do so, and hindering the building sustainable potential. Due to the complex and inefficient process, the application of SBTool is also incompatible with the project short deadlines, leading to its application only in the project latter stages to classify the building. There is an urgent need for real-time and dynamic assessment in the early project stages, allowing for the comparison of different sustainability measures to improve the building performance and effectively enhance building sustainability [9].

2.2 Building Information Modelling (BIM)

2.2.1 Concept, context, and benefits

Digitalisation has increasingly been introduced in the Architecture, Engineering and Construction (AEC) sector as a new technology to handle the complexity of the industry [76,77]. Current procedures involve several operations that are carried out at the same time, which require proper management and are responsible for different challenges such as low productivity, poor quality, rising cost, construction waste, delays, and lack of information share [78,79]. BIM has the potential to support organisations in managing their work

efficiently, as well as to address the AEC challenges and improve sector performance [78–81]. BIM is increasingly emerging in the industry by slowly replacing CAD software and it can act as a catalyst for deeper adoption of digitisation [82,83].

The actual BIM concepts and approaches have been based on several studies and ideas from the past years [84]. The first industry milestone dates from the end of 1970 when Charles M. Eastman created the Building Product Model concept. It was a software containing a database of elements used in construction. Eastman marked the beginning of building modulation supported by databases, 7 years before the Autodesk foundation. Later, in 1975 Eastman also developed a working prototype, the Building Description System. The first time BIM was used in a construction project date from 1987, under Graphisoft responsibility, where a virtual model was created using ArchiCAD [85], which is stated as the first BIM-related software. With the deployment of Information Management and its combination with existing CAD technologies, the picture of BIM as we know it today has started to emerge [86]. With the surprising acceptability of BIM-related processes in the industry, new research, software and approaches have been developed, leading to the current understating of BIM [82,84].

The concept of BIM has a variety of understandings that complement each other [79]. The United States National Institute of Building Sciences (NIBS) defines BIM as "*a digital representation of the physical and functional characteristics of a facility which serves a shared knowledge resource for information*" [87]. BIM acts as a repository of project data to facilitate interoperability and exchange of information with related software applications and stakeholders. Eastman et al. [88] add that BIM is a modelling technology and process for producing, communicating, and analysing building models. Succar [15] has proposed a more concise definition affirming that BIM is a set of policies, processes, and technologies which conceive a working methodology to manage the 3D drawing and project data in a virtual format during the building life cycle. Overall, BIM is an innovative integrated approach to virtually design and manage construction projects, where the building characteristics and data are digitally represented to improve interoperability and real-time collaboration among stakeholders [79,89].

BIM can offer a high-accuracy representation of a project, giving the opportunity to simulate the real project construction before the actual construction itself, allowing for the production of high-performance buildings [81,82,90,91]. It also provides data for designer's decision support and provides real-time collaboration among stakeholders, allowing to easily identify errors and incompatibilities, resulting in better work efficiency,

effectiveness, and productivity [78,92]. BIM's essence lies in the information shared between all the project stakeholders, during the whole building life cycle, shifting the traditional disorganised and sequential procedures to a central model where all stakeholders can work individually but are always connected to each other. This paradigm change will have impacts and benefits for society in general, like better constructions which consume fewer materials, require less human and financial resources, and operate more efficiently [88].

The benefits of using BIM are well known and documented [78,82]. Several authors have highlighted that the most noticeable benefit regards process productivity and efficiency increase, which is achieved by integrating time and cost to support real-time updates and efficient tracking and monitoring [93]. In 2011, Azhar et al [94] have already identified the key areas where BIM could have important contributions: faster and more effective processes, better design, controlled life cycle costs and environmental data, better production quality, automated assembly, better customer service and life cycle data. Other authors have preferred to list BIM benefits by project phase, identifying the following main stages for acting: Pre-construction/design, construction, and post-construction [79,88]. The application of BIM can lead to significant savings during the building life cycle, resulting from reusing information, early decision-making information, and better early-phase analysis [84]. By collecting data from worldwide projects that have used BIM and from surveys with BIM experts, different researchers have tried to establish the general benefits of applying BIM, which are summarised below [77,79,84,93,94]:

- Cost estimation, control and reduction
- Time planning, control and reduction
- Increase productivity and efficiency
- Communication and coordination improvement
- Early detection of collisions and incompatibilities
- Design optimisation
- Quality increase and control
- Organisation improvement

- Monitor and track construction progress
- Efficient prefabrication and automated assembly
- Lifecycle data storage for facility management (FM)
- Risk reduction
- Scope clarification

BIM is considered the future way of designing and managing the built assets of construction industry, which will increasingly rely on BIM [84]. Despite the nearly universal awareness, the implementation rate of BIM is still at a low pace with inconsistencies between different countries [78,95]. Developed countries have witnessed a higher adoption of BIM, with the USA being one of the pioneer countries [79]. Since 2003 that the USA has started to establish a national program to gradually implement BIM for all major public projects, under the responsibility of the General Services Administration (GSA) [96]. To date, they have released a full BIM guide for construction projects, together with libraries and software guidelines [97]. In the EU, BIM has been promoted through the directive 2014/24/EU, which recommends the use of electronic tools for public works contracts [79]. Looking for specific European countries, for instance, in Denmark and the Netherlands, BIM is mandatory for public projects since 2007 and 2011, respectively [95]. A similar situation occurred in the United Kingdom (UK), as since the beginning of 2016 it is mandatory to use BIM in all public financed projects [98]. In other global areas, identical situations appear, such as in Singapore, South Korea or Hong Kong, where all public projects must be submitted using BIM [99]. According to Ullah et al. [79] who have conducted a study on the adoption of BIM in AEC companies, 79% of the USA companies are already using BIM, as well as 78% of Canadian companies. European frontrunners are Denmark (78%) and the UK (74%), while Australia has a lower adoption rate of 67%.

The application of BIM in Portugal is still far behind when compared to other European countries [95,100,101]. A survey made in 2016 pointed out that only 13% of Portuguese AEC companies have already used BIM, at least, in one project [85]. Moreover, only 52.5% of the respondents admitted to knowing BIM concepts and applications, stressing the need for an effective national implementation and awareness strategy, as well as an education plan. Up to date, only 13 high-degree courses address BIM in their curricular plans [101]. To answer this demand Silva et al. [95] have established a roadmap for BIM implementation in

Portugal for the next decade, both to catch up with the fast pace of the global adoption of BIM, as well as to maintain the competitiveness of the Portuguese AEC industry.

Besides that, Portugal is also represented in the European Standardization Commission by the CT 197 work group. They are working on the development of a common European BIM standard, as well as national standards and guides [100,101]. As it occurs in other European countries, a Portuguese BIM standard was identified as the first step for the proper implementation of BIM in Portugal, highlighting the government role in BIM promotion [95,101].

Note also for other initiatives, such as the BIM workgroup (GTBIM), the BIM forum Portugal or the national BIM congress (ptBIM), which have been making efforts to facilitate and accelerate the implementation of the BIM in Portugal [100,101]. Other private institutions have also recognised the usefulness of BIM, such as the National Palace of Sintra managers, which have decided to use a BIM model as a centralised resource for the integration and storage of multidisciplinary data about the palace [102].

Overall, Al-Ashmori et al. [93] have argued that there is still a need to promote information among practitioners, increase awareness, and enhance readiness to implement BIM. Moreover, they have also stressed the government role, as a major player in BIM promotion and adoption.

2.2.2 BIM model and LOD

The application of BIM methodology results in the development of a Building Information Model (BIM model) [84,97]. According to the GSA, a BIM model is a data-rich, intelligent, and parametric digital representation of a facility which is appropriate for all stakeholders. The BIM model is developed based on a parametric and object-oriented approach, where parameters are defined to characterise the relation between the model objects [81,103].

The model includes much more than 3D drawings, such as specific information on a wide range of building elements and systems associated with a building [97]. It stores multi-disciplinary data throughout the building lifecycle, and it creates the opportunity to virtually construct and simulate the building performance before the construction itself [104].

Among the main characteristics which are required for a BIM model are [78]: Digital representation and parametric modelling that allows for intelligent manipulation; Components and object data storage;

Automatic update of modifications in all views and assemblies and; Coordinated data. Overall, the American Institute of Architects (AIA) summarises the definition of the BIM model as a digital representation of the physical and functional characteristics of a project [105].

Depending on the detail of the BIM model characteristics, different classification is given to the models in order to provide information about the model content. According to the purpose of the model, it must have a certain Level of Development (LOD), which specifies and articulates the content and reliability of a BIM model, facilitating communication, as well as supporting the understating of the BIM model usability and limitations [106]. The LOD should be defined according to the information requirements and must allow simple and fast modelling that provides enough and reliable data [14,104]. The LOD ranges from 100 to 500, according to the specifications of Figure 1.

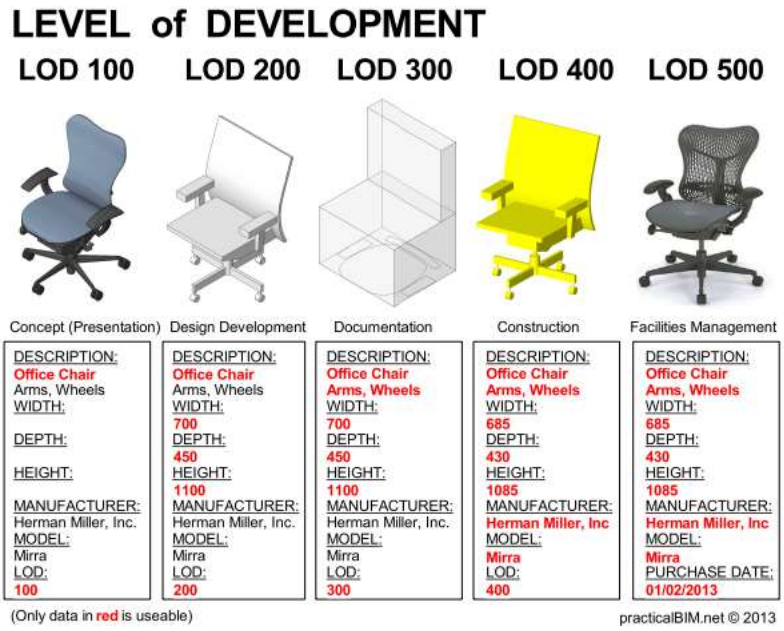


Figure 1 – Types of LOD [107]

In other to support and guide BIM implementation in the USA, the GSA has established the minimum capabilities of the BIM model at different development stages [108]. Based on those BIM guides and existing literature, the following descriptions have been developed for the different LOD [108–110]:

- The LOD 100 concerns the conceptual model, representing the beginning of a project. At this stage, the model has the overall design of the building, and it is possible to carry out preliminary simple

analysis, such as building orientation. During this stage it is also possible to start the introduction of sustainability measures;

- The LOD 200 represents the schematic design, where the approximate geometry is already available, as well as basic generic information about the model objects, such as approximate quantity, size, location, and systematic relationships of most objects. Performance analysis as shading and solar exposure can be made at this stage, as well as precise cost estimations;
- The LOD 300 makes available precise geometry and specific information about the model objects, like quantity, size, shape, location, and orientation. The model information embedded is equivalent to the construction documentation. The LOD 300 has been identified as the minimal requirement to proceed with detailed energy performance analysis, as well as for the extraction of precise quantities and specific sustainable data from materials;
- The LOD 400 contains precise geometry that allows for fabrication and assembly. This LOD also marks the beginning of coordination among different project disciplines;
- The LOD 500 represents the post-construction as-built stage of a project. This model is often handled to the facility manager to use throughout the building operation and lifecycle.

2.2.3 BIM dimensions

BIM can impact throughout all the building life cycle as in visualisation, documentation, management, cost planning, maintenance, operation, detailed analysis, logistics or demolition [77,111]. It went beyond the 3D, allowing for several uses under its multiple dimensions [112].

The emergence of nD BIM has changed the meaning of “dimension”, more likely referring to application domains or uses [113]. BIM has several dimensions and associated functionalities for each of them, enhancing specific capabilities of the BIM model at the different lifecycle stages [78]. The topic has been highly discussed by researchers to establish a common understanding about the relation between nD and BIM applications to take full advantage of it [113].

The nD theory is an extension of the 3D BIM model applications by including different aspects of design information, required for different stages of a building life cycle [114]. The third dimension (3D) represents the visualisation capacity of BIM, through a spatial representation of the project [78].

The 4D appeared by adding a virtual representation of another dimension to the 3D model – time. This dimension allows the BIM process to be represented, viewed and analysed from a temporal perspective by including timing data in the model. Construction scheduling and planning are the main application domains of 4D [112–115]. For some authors, 4D is the last dimension of BIM as any higher dimension concerns the capacity to calculate other aspects based on the 4D BIM properties and data. Moreover, 3D and 4D are often considered the required information for any BIM application [112].

Nevertheless, most authors agree on the existence of the fifth dimension (5D), which is characterised by adding the cost aspect to the BIM model [112,113]. 5D provides real-time cost data, allowing for budgeting and cost control. It supports more efficient, cost-effective, and sustainable building development [115,116].

Beyond the fifth dimension, existing literature reveals a lack of consensus [112,114,117]. In order to fulfil BIM potential, other application domains have been investigated, such as sustainability, FM, accessibility, safety, energy saving, acoustic, lean construction, and site monitoring, among others. These activities provide new ways to view and utilise nD data, which brings new degrees of complexity and more input data, leading to the extension of nD [112–114].

Sustainability is the strongest candidate for the 6D. Moreover, it includes building performance aspects, such as environmental, acoustic or energy performance [78,115]. In an online survey made in 28 EU countries, 86% of the practitioners agreed on including sustainability as BIM 6D [114].

The 7D is commonly referred to as the FM domain, with a high acceptance rate near practitioners. It aims to control, maintain, and sustain the entire lifecycle of the facility [112,114,115].

In addition to the previous standard dimensions, new ones are being established. The 8D is less referred to in literature, however, some authors have pointed it out as related to the safety domain or accident prevention [78,118].

With even fewer references, 9D and 10D domains have been discussed as the implementation of LEAN construction and industrialisation, respectively. The 9D, under the scope of LEAN, aims to optimise and

streamline the implementation process of a project through process digitalisation. The 10D regards construction industrialisation to achieve a more productive sector through the integration of new technologies and physical, commercial, environmental, and other data [119,120].

Figure 2 presents an overview of all the known and established dimensions of BIM.



Figure 2 – BIM dimensions [120]

Nevertheless, the lack of clarity and understanding regarding BIM dimensions beyond the 5D, is still a reality, hindering the potential benefits of those BIM applications. There is a need to provide a consistent approach by developing appropriate standards, to eventually identify a common perception about all BIM dimensions.

2.2.4 Software and interoperability

BIM involves multiple applications for different uses. To create a virtual model, it is required to use a BIM authoring platform, which generates multiple uses information and allows the creation and edition of BIM models. BIM platforms provide enough data to support design operations, editing, and modifications. They allow the user to carry a parametric and object-based modulation [121]. Examples of BIM platforms are Autodesk Revit, ArchiCAD or Bentley MicroStation. Most of them internally incorporate interfaces to multiple other BIM tools, providing direct connections among them.

Such BIM tools are required to fully explore BIM potential and are usually used by exporting the virtual model from BIM authoring platforms. BIM tools concern software that performs a specific type of analysis, such as building performance analysis, lifecycle assessment or clash detection. BIM tools outputs are often standalone, as reports or drawings [9,121]. Some examples of BIM tools are Autodesk Insight, Integrated Environmental Solutions Virtual Environment (IESVE) or Solibri.

Data exchange – interoperability – between software can be made in different ways, as different BIM file schemas have been developed [9,122]. The most associated and adopted schema in the BIM industry is the Industry Foundation Classes (IFC) [26,123]. The IFC is the only open standard schema recognised by the ISO and the European Committee for Standardization (CEN) [124]. It consists of a platform-neutral and object-based structured format that describes building and construction industry data [26,124]. IFC has been widely used in the AEC industry to exchange quality data and BIM models, during the design, construction, and operation stages [123,125]. By sharing all information in one open format, project stakeholders can access relevant information whenever they need it, enhancing work efficiency and collaboration. The current version of IFC4 is expected to be replaced by IFC5 in the next years [122].

Other schemas are also emerging, such as the Green Building XML (gbXML). However, gbXML focus concerns mainly on green and sustainability analysis, due to its capacity to incorporate thermal descriptive data [126]. Unlike the IFC, several BIM software is still not capable to read gbXML files [122].

2.2.5 Automated rule checking and Visual Programming Language (VPL)

With the increased complexity of project design and the necessity to check several building codes, the manual compliance checking process has become a highly time-consuming, complex, and error-prone process, which usually requires multiple domain experts [127–129].

Automated rule checking is a process where well-defined rules can be applied automatically with minimum user intervention [89]. Moreover, it evaluates the design through its objects, attributes, and relations without modifying the building design. The aim is to validate the project according to the region or specific requirements, by returning a compliance report [127,130].

Facing the increased number of building codes and the reasons stated earlier, the need to integrate automated code compliance checking in the BIM environment has already been recognised [27,128]. This topic has been addressed in the past years, as one of the promising directions of BIM is to facilitate rule checking and simulations for evaluating building designs in the project early stages [127,129,131,132].

BIM-based rule automatic compliance is a multi-domain validation framework based on parametric rules, where the semantic information contained in BIM models provides the basis for automatic checking [27,133]. BIM allows the development of automated interfaces, which can provide compliance data in a faster and more reliable way [127].

Among the different uses of BIM-based rule checking, the main application concern the control and validation of modelling procedures and internal consistency of BIM models or the compliance of design proposals against national and international codes and regulations, like fire protection, safety, or accessibility standards [27,127,132,133]. A successful and known example of a BIM-based rule-checking application is Solibri Office, which offers the possibility to check IFC-based BIM models for geometric design errors or missing semantic information [27].

Under a BIM environment, automated rule checking is usually based on 4 different stages, as each of them holds different responsibilities and functions [27,127,128,134]:

- Rule interpretation – Interpretation of the requirements, logical structuring of rules and translation to computer-processable rules.

- Building model preparation – Creation and characterisation of a digital BIM model, ensuring that all the required properties are implemented in the building model. Model views may be required to carry out specific building performance simulations to extract subsets of data from a given building model. According to Solihin and Eastman [89], the BIM model should have, at least, a LOD 300 for code compliance checking.
- Rule execution – Execution of the established rules, usually using text format coding (Python or C#) or visual programming language through Dynamo or Grasshopper.
- Rule compliance report – Final result with building compliance results.

The rule execution stage involves the practical implementation of the identified rules, usually by devolving a specific oriented computational algorithm. It is described through a coding language which physically represents the translation of human-readable rules. Given the high knowledge requirements of text coding languages, specific tools have been developed to simplify the coding procedure by adding a user-friendly visual environment – Visual Programming Language (VPL) [129].

VPL is an easy-to-learn codification mode when faced with commonly text-based programming languages [83,135,136]. The visual elements of VPL allow for a faster and easier understanding of the coding procedure for non-expert users. Consequently, there was recent interest in AEC industry to explore VPL for automatic rule checking and software developers have introduced dedicated functions into their products [27,129,132]. BIM editors, such as Autodesk Revit, already contain APIs for add-on development with VPL – Autodesk Dynamo – allowing to access BIM models data and extending the use of BIM during the early design stages [129]. VPL presents a high degree of control and customisability of BIM models due to its geometric modelling functionalities and ability to create algorithms [24,137].

VPL has applicability and functionalities for different BIM domains. An approach to evaluate building design flexibility has been made by Cavalliere et. al [138] through the development of an automated rule checking for BIM models. Ghannad et al. [135] have also developed a compliance checking process for BIM models that integrates LegalRuleML with VPL. Villaschi et al. [134] have used Dynamo for an automated code checking of Brazilian design rules for buildings. Burggraf et al. [27] have automated the assessment of semantic data of BIM models through Dynamo. Automatic extraction and process of quantities is also another application of VPL near BIM models, to easily generate Life Cycle Inventories (LCI) [76]. Dynamo allows the

production of such LCA data itself, allowing for the assessment of the building environmental impacts [139]. Another sustainability approach regards the assessment of LEED Pilot credit 55 – Avoiding Bird Collisions based on VPL [137]. Khan et al. [132] have proposed an approach based on BIM and VPL for the excavation safety planning and modelling at the preconstruction stage. Sheikhkhoshkar et al. [140] have shown VPL applicability for structural analysis, by developing an algorithm for the extraction of spatial data from construction joints. Banfi and Previtali [141] have extended the use of VPL to explore 3D models of archaeological sites and heritage buildings, integrating scan-to-BIM and digital photogrammetry functions. FM is also a common field for VPL, both to maintain databases and BIM models and to process data from building sensors [136,142].

Some of the most recognised VPL tools are Grasshopper for Rhinoceros3D, Dynamo for Autodesk Revit, Marionette for Vectorworks, Generative components, Digital Project, and Yeti [83,129,143].

2.2.6 Limitations and setbacks

The deployment of BIM has promised to deliver several benefits to the industry. However, BIM has not reached its full potential for the construction industry, as a range of challenges have been hindering its general implementation [82,93,144]. BIM application has been much slower than anticipated and several authors have been discussing existing barriers to BIM implementation [84].

A review from Ahmed [145], has identified the main factors affecting the implementation of BIM: social and habitual change resistance was the most addressed factor, followed by traditional methods of contracting and training expenses. Other factors such as high software and hardware costs, the lack of awareness and professional experts and BIM licensing problems were also commonly identified by the industry professionals. Liu et al. [144] agree with the previous vision and also add the lack of national standards and organisational and legal issues inside companies as additional challenges for BIM integration. The same opinion is shared by Begic and Galic [82], highlighting the lack of knowledge, initial efforts and costs as the main barriers to the full use of BIM, as well as the industry traditionalism. Overall, BIM challenges can be classified into five categories: Technology, Cost, Management, Personnel and Legal [84,93].

Under the technology category, BIM challenges related to existing software are identified. Some of the main issues regard software restricted capabilities, lack of standardisation, scalability, interoperability, and support

for remote collaboration [79,82,94]. The need for national standards for sharing data between software and stakeholders has also been recognised [94,144,146]. Data inconsistency and compatibility are still a usual matter due to the lack of common process models to eliminate interoperability issues. The lack of protocols and standards to regulate the BIM industry can also be included as a legal challenge.

The cost category addresses the financial challenges of BIM, such as staff training, specialised software and hardware improvements [84]. The uncertainty of investment return for companies is a common setback for BIM implementation [79]. The costs and time for staff training are too expensive for companies, as besides the qualification costs, there is also a productivity loss during the adaption phase. Figure 3 presents BIM common learning curve, where a significant value lost is verified before BIM full implementation. To address this challenge, it was suggested that BIM should be integrated into the industry professional curricular plans, such as engineering and architectural courses, to endow future professionals with enough knowledge to use and deal with BIM [147].

Moreover, Liu et al. [144] have grouped costs challenges as education and training costs, administration and start-up costs, and transition and behavioural costs. The lack of knowledge and awareness of BIM has strengthened the system implementation failure [20,145].

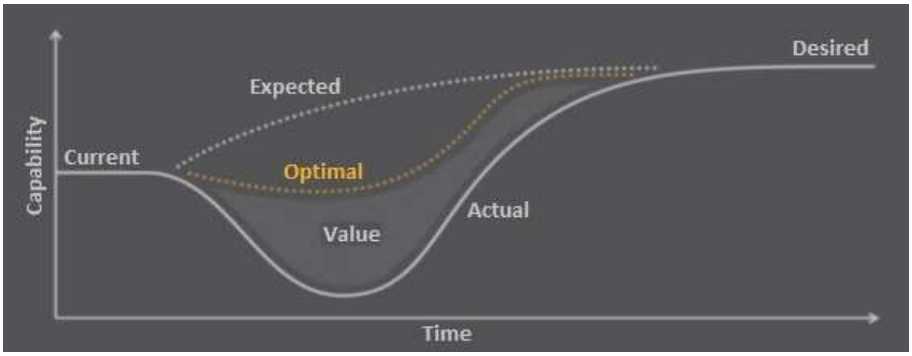


Figure 3 – BIM learning curve, adapted from [148]

Management challenges concern process and organisational issues, such as fragmented procedures, lack of business models, lack of managers/owner's awareness, workflow changes and lack of cooperation [84]. Stakeholders must relocate their roles in their project team and change traditional workflows, requiring suitable management support [145]. To encourage BIM implementation among practitioners and managers, there is a need to raise awareness, establish a standardised procedure and define guidelines for proper integration. Despite the development of some guidelines and standards, a formal and common standard is

still required to organise the industry practice [94,144]. Some authors have also identified the lack of interest near clients. Client awareness regarding BIM benefits would be a potential breakthrough for BIM implementation, as they could demand (or look for) the use of BIM. Cooperation issues appear when several companies are working on the same project, but their internal procedures are distinct. For instance, if a sub-contractor is not aware of BIM it will affect cooperation with other stakeholders [149,150].

Process changes require time and usually face some resistance due to a lack of knowledge and confidence, which lead to the personnel category issues. Besides the habitual resistance to change, this category also includes the required expertise to use BIM. There is a lack of skilled personnel and companies must hire or retrain existing staff, according to the new business model requirements. Once again, the introduction of BIM in university courses would support tackling this challenge [79,84,145,146,151].

Finally, legal challenges are commonly indicated by researchers and practitioners as a major barrier to BIM implementation. Licensing and responsibility are some of the most discussed topics, as different professionals are involved in the creation of a BIM model and responsibilities must be endorsed if some information loss occurs [84,151]. Moreover, all the involved stakeholders must also agree on who will control the access to the model data and be responsible for inaccuracies. Ownership and copyrights of the BIM model are also often discussed among the involved stakeholders and the client [84,144,146,151]. Another legal issue concerns government support. By being responsible for existing regulations, governments can play a key role to increase the implementation rate of BIM [93,145]. Additionally, governments can promote the development of national strategies for BIM implementation [144] or even provide start-up funding for companies [146].

There are several barriers limiting the further development and application of BIM. Is still necessary to promote information and increase awareness among all the involved parties, as well as to enhance the readiness to implement BIM. For smooth and proper implementation of BIM, progressive continuous participation of all stakeholders and governments is required [93,145].

2.3 BIM and building sustainability

2.3.1 Context and applications

With the emergence of BIM within the AEC industry, more activity has been witnessed about BIM and sustainable design strategies [53,152]. BIM is seen as a new paradigm to promote the sustainable construction industry, where BIM tools are efficiently used to achieve sustainable and high-performance buildings [78]. BIM and sustainability aim at efficient proposals for new architecture and engineering forms, preserving the natural environment and ecosystems. Both concepts intend to achieve a new lifestyle, a new environmental education, and a new perspective on human development's impact on the planet. BIM for sustainability can be used as a "*process of generating and managing coordinated and consistent building data during its project lifecycle that enhance building energy-efficiency performance and facilitate the accomplishment of established sustainability goals*" [53]. It creates an excellent opportunity to introduce sustainable measures throughout the project lifecycle, as it allows to overlay and group multi-disciplinary information into a single virtual model, as well as to carry out environmental performance analyses [16,20,53].

The integration of BIM during the early project stages allows designers to take more rational decisions, due to the increased quality, speed, and availability of design data, allowing them to balance and enhance environmental, social, and economic factors. By providing detailed information, designers can compare the impacts of different sustainable solutions and virtually construct the whole building model through simulations and analysis before the construction itself [81,152]. Moreover, several authors have also identified the preconstruction and project phases as the critical ones, where the main decisions regarding building sustainability are supposed to be made [63,153–155]. As these are also the stages when projects can most benefit from BIM, the influence that it can have in enhancing buildings sustainability becomes clear [20].

In 2008, Krygiel and Nies [156] listed seven aspects where BIM could have a potential impact to improve the sustainability level of a project:

- Building orientation;
- Building massing;

- Daylight analysis;
- Water harvesting;
- Renewable energy;
- Energy modelling;
- Sustainable materials.

Several authors have used the mentioned aspects to detail and identify specific BIM applications for building sustainability. Among the most addressed are energy analysis, daylight/solar analysis, building orientation analysis, massing analysis and site analysis [147,152,157]. Although BIM uses for sustainability are much broader, including renewable energy production and water use estimation, resource and waste management, wind analysis, acoustic analysis, sustainable materials selection (with life cycle analysis) or sustainability assessment [147,158–160].

BIM allows designers to reduce buildings mass by optimising the building shape and envelope [161]. Authors have been using a BIM-based process with computational fluid dynamics (CFD) calculations to improve the building design quality by integrating structural design and wind engineering analysis [162,163]. Moreover, mass analysis can also be combined with energy performance simulations, to enhance buildings thermal inertia and minimise energy needs.

Energy performance analysis is the most common BIM-sustainable analysis nowadays, with the combination of Building Energy Modelling (BEM) [152,164,165]. Different approaches have been made for energy performance analysis, such as Kim et al. [166] which have developed a BIM-based application to facilitate the exportation of BIM models to Modelica. Gourlis and Kovacic [167] have used EnergyPlus software to carry out energy simulations of a factory facility, highlighting the time and cost savings of the applied BIM method. Carvalho et al. [126] have used a BIM-based procedure to carry out energy simulations and thermal projects of Portuguese buildings using Autodesk Revit as an authoring platform to export BIM models for energy simulation tools from Cype software. They have pointed out that the main benefit of BIM was the decision support provided to designers in the early project stages. Montiel-Santiago et al. [168] have submitted a hospital BIM model to a set of analyses on Insight 360, achieving an energy renovation scenario able to save 47% of the current energy demand. Nevertheless, almost all the authors have recognised the

need to improve interoperability among BIM platforms and BIM tools, with considerable wasted time in double-checking and correcting geometry errors [165,166].

Daylight and lightning analysis are also common in BIM-related research. Besides supporting building implementation and orientation, it also allows for maximising solar gains. Díaz-Vilarino et al. [169] have made a procedure to generate 3D models to be subjected to lighting analysis based on laser scanning technology. Kota et al. [170] have developed a prototype to integrate the BIM method and lightning analysis using DAYSIM and Radiance software. Amoruso et al. [171] have performed a BIM-parametric renovation of a South Korean apartment, increasing the building daylight factor by 15%, the daylight autonomy by 30%, and the useful daylight illuminance by 15%.

Building orientation itself is also a specific analysis that can be easily performed with BIM in combination with daylight analysis. A proper orientation can have a considerable impact on the occupants' comfort, as well as on the energy bill. Abanda et al. [81] have proved that building orientation can have a positive impact on building energy consumption, with cumulative savings of around €1000 during a 30-year period. Furthermore, window orientation, size, and position can also have an impact in the building energy demand, with annual energy requirements variations of 1% for a small-scale dwelling [172].

Another application field of BIM is to estimate and minimise water use. BIM allows for improving the design process of building water supply and drainage [173], as well as supporting efficient rainwater harvesting and reuse [174]. On a city scale, Zhao et al. [175] have used BIM to develop an integrated BIM and Geographic Information Systems (GIS) method for the planning of water distribution systems.

Acoustic analysis is also another BIM-related application, which is usually made for specific and special buildings, like theatres, auditoriums, or concert halls, where the acoustics are a key aspect of the public experience [147]. Wu and Clayton [176] have created a software prototype for designers to quickly perform acoustic simulations to determine reverberation and sound intensity levels, in order to achieve better building designs. Tan et al. [177] have developed a BIM-based application to simulate and compare the acoustic performance of concert halls using Comsol software. The same authors [178] have also used a similar application to quantify and evaluate the noise impact over time on maintenance workers of offshore platforms.

BIM can also be used to perform site analysis, where contractors can analyse the site conditions, like wetlands or protected habitats, as well as efficiently plan the site utilisation [179]. BIM benefits are also evident for the demolition and renovation phases with regard to waste management. Cheng and Ma [180] have created and applied a BIM system prototype for the estimation and planning of Construction and Demolition Waste (CDW), including pick-up truck requirements and waste disposal fees. Won and Cheng [181] agree, stating that BIM can support managers in estimating the amount of generated CDW, to effectively calculate the number of pick-up trucks and bins required. Akinade et al. [182] add that BIM capabilities can certainly assist in achieving unprecedented analysis performance. Contractors can plan all their processes in advance, reducing waste and combining the transportation of different building materials to further reduce carbon footprints.

BIM is an emerging trend for the selection of sustainable materials [80]. By supporting Life Cycle Analysis (LCA), BIM allows designers to understand and compare the impacts of their materials. Authors agree that the integration of BIM-LCA provides the required data for stakeholders to perform LCA with few resources in the early design stages [14,77,183,184]. Rezaei et al. [185] agree and state that LCA must be performed since the early design stages to maximise its impacts. BIM can be linked to LCA in three different ways [14]: LCI; in addition to LCI, environmental information can be integrated into BIM software, and; automated process combining different data and software. Wang et al. [186] have used Ecotec to calculate the life cycle energy consumption and CO_2 emissions of different design options for a university building. Najjar et al. [153] have validated a framework for the integration of BIM and LCA, by using Autodesk Revit and Tally, easily achieving the environmental impacts of an office building. Hollberg et al. [187] have used Autodesk Revit and Dynamo to assess the embodied global warming potential (GWP) in the post-design assessment phase with few efforts. Naneva et al. [188] have proposed a decision-making support tool to continuously perform LCA in each building phase, avoiding constant re-work. Carvalho et al. [139] have used BIM and Dynamo to evaluate the environmental impacts of different building materials during the project design phase. Carvalho et al. [189] have also extended the use of BIM-LCA results, both to evaluate the building environmental impacts, as well as to assess a sustainability scheme criterion from SBTool^{PT}-H. A similar process was used by Jrade and Jalaei [190] to assess the LEED method criterion with Athena Impact Estimator. As LCA usually neglects social and cultural aspects [191], it should be made in combination with other multi-criteria

assessment tools to increase its usefulness [192]. Consequently, Hollberg et al. [187] suggest that LCA and sustainability certification should develop a common database for long-term use.

BIM has also been used to support BSA methods and it is a growing topic among researchers in the past years [60]. Several criteria from different methods have already been assessed, including from the most recognised schemes, like LEED, BREEM or SBTool. With the thesis focus on the integration of BIM and BSA methods, this topic is further explored in the next section.

A review from Chong et al. [90] have grouped BIM applications according to the project life cycle stage, as they argued that social, economic, and environmental dimensions have an effect on each other and cannot be dissociated. Thus, they have listed the following categories:

- Planning – where sustainable decisions have a higher impact and BIM can improve the effectiveness and efficiency of project development processes, avoiding re-works and re-planning;
- Design – BIM enables optimum design through the use of building performance simulations and enhances coordination among multidisciplinary stakeholders;
- Construction – BIM allows early 3D visualisation to predict costs and draw the project schedule. It also minimises construction errors and improves productivity;
- Operation and Maintenance – BIM virtual environment and data storage allow for efficient facility management and maintenance;
- Refurbishment and demolition – BIM can support renovation and demolition works by properly quantifying materials, waste and costs. Moreover, it allows for efficient CDW management.

A set of interviews made by Azhar et al. [157] have reached similar conclusions, where practitioners have divided BIM uses for sustainability according to the project stage. Most of the responders have admitted using BIM during the design (67%) and planning (63%) phases, while the construction (30%) and post-construction (10%) stages have witnessed a narrow BIM application. Cao et al. [193] have reviewed BIM implementation for green building construction with a different approach and have grouped them into the following categories:

- project quality improvement;
- lifecycle data storage and management;
- collaboration optimisation;
- planning and schedule management optimisation.

BIM can provide significant contributions to the whole project lifecycle, with significant potential benefits and improvements for green building construction. However, a common conclusion among authors is that BIM is not commonly used for sustainability purposes, but it has great potential. The adoption rate in AEC companies is still very limited, mainly due to the lack of awareness and knowledge from stakeholders [20,53,193].

The EU has recognised BIM potential and a set of research projects have been funded, such as Buildings As Material Banks (BAMB), where BIM was used to extend the usability of BAMB tools. BIMcert project was also funded by the EU, with the objective of developing BIM learning tools to enhance information exchange and collaboration for green and passive building design. More recently, the Circular EcoBIM/SECClasS project has been funded by Iceland, Liechtenstein, Norway, and EEA Portugal grants. The project aim is to further develop a BIM standard product data template for BIM objects, as well as to identify BIM applications to produce circularity passports for buildings and components, considering the integration of Environmental Product Declarations (EPD) and Levels system for buildings [147].

Overall, it can be stated that BIM development for sustainable buildings has only started to scratch the surface, yet its potential has already been recognised and it is expected to be in extensive use in the near future [19,53].

2.3.2 BIM and BSA

There has been increasing research interest in BIM integration into sustainability assessment, as its positive impact has become a proven and accepted fact by the AEC community [17,19,25,194,195]. BSA methods exploit the full potential of BIM, as multi-disciplinary data must be assessed, with different BIM analyses and software [60]. BIM provides an effective platform for attaining compliance with sustainability rating criteria

[9], allowing for easier and faster data assessment, resource-use reduction, improved process efficiency, automatic calculations, and modification updates [16,25,159].

Different BIM-based approaches have been used for several BSA methods, but LEED has commonly been the most addressed worldwide [60,195,196]. Azhar et al. [16] were among the first authors attempting to use BIM in the LEED method. In 2011, they have established a BIM conceptual framework able to assess 2 prerequisites and 17 credits. Among them, they evaluated water-related criteria from LEED by using the BIM tool IESVE. They were able to achieve a 47% reduction in water use with a set of water-reduction measures. Jalaei and Jrade [21,190] have extended BIM application in LEED criteria, developing a practical framework to address 38 credits and 5 prerequisites. Nguyen et al. [197] have also developed and validated a conceptual framework for the automated assessment of a set of LEED criteria with BIM. Li et al. [24] have focused their research on the Location and Transportation criteria, developing a framework based on Dynamo and web map service to assess two criteria from LEED. Ryu and Park [198] have used the BIM authoring platform Autodesk Revit to assess Energy and Atmosphere credits from LEED and have concluded that it could have a significant impact when performing buildings energy simulations. Carvalho et al. [60] have identified that approximately 67% of LEED criteria are currently available to be assessed with BIM, mainly in the categories of Materials and Resources, Energy and Atmosphere, Sustainable Sites, and Indoor Environmental Quality.

BIM has also been integrated into other BSA methods. Edwards et al. [22] have applied different BIM software to evaluate 8 credits from 6 different categories of BREEAM Refurbishment and Fit-out. They have noticed that BIM is more useful when assessing energy-related and indoor comfort-related criteria. Oti et al. [199] have assessed 7 different criteria from 3 categories of BREEAM Offices using Autodesk Revit and a coding framework made in Visual Basic. Ilhan and Yaman [19] have used ArchiCAD and Visual Studio to fully assess the Materials category of BREEAM Europe Commercial. The systematic review from Carvalho et al. [60] have identified that 24% of BREEAM credits have already been assessed with BIM, mainly regarding the Materials and Energy categories.

Carvalho et al. [20] have highlighted the role of BIM in the SBTool method, proposing a novel framework to integrate BIM in the assessment of the Portuguese residential version of SBTool. Moreover, they further validated the framework through a case study, where they were able to verify the theory for 13 criteria [9]. They have also related the development of thermal projects with the sustainability assessment of energy-

related criteria, by using energy performance results both for the sustainability assessment and project submission [126]. The attractiveness of developing a BIM-based application for SBTool was also evaluated and faced with LEED and BREEAM methods [60]. Results show that at least 68% of SBTool criteria can be assessed with BIM, with the potential to reach up to 98%. Consequently, the BIM-based application for SBTool has great attractiveness potential as it can evaluate the same or more criteria than LEED and BREEAM.

Wong and Kuan [25] have explored the use of BIM for the assessment of BEAM Plus using residential case studies. Results have shown BIM applicability to assess 26 out of 56 criteria in a faster and more accurate way when faced with the traditional method. Gandhi and Jupp [200] have addressed the Australian Green Star scheme and have successfully assessed 66% of its credits. Although, they have noticed that BIM potential could be further explored and proper guidelines and standards for building certification are still required. Also, for the Green Star but for the New Zealand version, GhaffarianHoseini et al. [201] suggest that BIM is able to support the assessment of 75% of the BSA criteria, agreeing with other authors on the need for appropriate guidelines. Liu et al. [202] have also explored the Green Mark version for non-residential buildings in Singapore, identifying 31 out of 78 criteria that can be assessed with BIM-based performance simulations.

Solla et al. [203] investigated the application of BIM for the assessment process of the Malaysian Green Building Index (GBI). Through a round of questionnaires, industry experts have validated BIM capability to operate digital GBI criteria. Akhanova et al. [194] have analysed BIM integration on the building sustainability assessment framework for Kazakhstan. They have concluded that BIM is able to fully support the assessment of 24 out of 46 criteria and provide important data for the assessment of 6 other criteria. With no relation to established schemes, Salehabadi and Ruparathna [204] have proposed a set of key performance indicators to evaluate social, environmental, economic, and resiliency dimensions and have integrated them into a BIM-based framework.

When regards software, Autodesk Revit seems to be the preferred one among researchers [60,205]. 81% of BIM-BSA related studies have used it as a BIM authoring platform, both to create/edit BIM models or to host applications to automate BSA. Microsoft Excel appears next, being used in 27% of related studies [60].

BIM integration in BSA can be seen as a rule-checking procedure, where computational rules are defined to translate BSA criteria. Automated rule checking has already been recognised as a proper pathway to evaluate combinatorial features from buildings, in line with the multi-disciplinary data required for BSA [89].

Most of the existing approaches are focused on the project design stage, where BIM potential to enhance building sustainability is higher [53,60]. Designers are able to quickly compare the sustainability performance of different solutions and optimise the sustainability level of the project [20]. Nevertheless, the diversity of BSA methods and BIM approaches has led to different sustainable ratings for the same project, which contributes to increased inconsistency and disparities between the outcomes of different researches. The need to adapt BSA methods to each location conditions is accepted but the diversity of methods and the lack of BIM guidelines are hampering the development and establishment of a common approach to integrating BIM and BSA [194,195]. There is an urgent need for a unified approach, which integrates BIM technologies with all sustainability aspects [90].

In this context, several authors have been arguing about the lack of standards, asking for the development of proper standards and guidelines, which include building sustainability factors [195,200,201]. Moreover, researchers suggest that future BIM standards should include requirements for BSA, and specific BIM coordination and execution plans should be developed [90,200].

2.3.3 Benefits and limitations

BIM benefits can be sorted by the main three dimensions of sustainability [152]. Under the environmental dimension, key benefits regard the reduction of resource consumption, such as energy, water, and materials, which is achieved by optimising building design. It can also support the selection of more eco-friendly materials by performing LCA. For the Social dimension, it is noticed an improvement in communication and collaboration between stakeholders, as well as an improved and healthy built and indoor environment. The BIM trend will also create more innovative job opportunities for the community and act as an instrument of social engagement by involving buildings occupants. By improving process efficiency, fewer resources will be spent during the project and problems can be anticipated, resulting in economic savings. Moreover, by optimising design, capital and lifecycle costs are also reduced. BIM can help in assuring the facility economic viability, increase productivity, and reduce waste. Other common BIM-related benefits, such as the automatic and accurate extraction of the bill of materials and cost estimations, reduction of resource use, automatic update of project modifications, promotion of Lean techniques, enhanced communication, improved design and quality, and cost and time reduction can also be indirectly linked to building sustainability [20,206].

Practical benefits of BIM use for sustainable buildings were noticed by Azhar et al. [16] at the University of South Carolina Campus. BIM was used to improve the sustainability level of the project, resulting in 20% savings of the project total cost over a 10-year period.

BIM has also been used to develop the project and manage the facility of the Shanghai tower in China (Figure 4). Due to the tower complex design and the aim to achieve sustainability targets, BIM was used to optimise shape and design, which lead to a 32% reduction in material use. Additionally, building performance analysis allowed to reduce wind load by 24%, minimising the tower structural requirements. Savings of $12 million were achieved by removing 5% of the structural steel. Overall, the Shanghai tower has 43 different sustainable technologies, including renewable energy sources, rainwater collection, water reuse, extensive landscaping, and optimised shape. Such measures have also allowed reducing the building energy consumption by 21% and CO_2 emissions by 37 000 tons per year [147].



Figure 4 – Shanghai tower [207]

Despite the existing potential, BIM is still not oriented and properly used to support sustainable building design [20,26,193]. The adoption rate is also far from desired, due to limited knowledge, qualification, and awareness by stakeholders [53]. There is a lack of research that considers all dimensions of sustainability [17,53] and interoperability errors are still a common experience. Authors argue that BIM software and exchange file formats are still in need of further developments to embrace more sustainable issues, including proper and clear definitions in BIM standards and guidelines, practical BIM tools for sustainability assessment and compatible and user-friendly BIM software [9,16,17,90,208]. Current applications often struggle with information lost when exchanging their models, requiring extra time for model checking and corrections [20].

Manzoor et al. [150] have developed a research framework to identify the top barriers hindering BIM use for building sustainability. Mixing interviews with a systematic review, the most frequent limitations for BIM were the unavailability of standards and guidelines, the lack of BIM training, the lack of expertise, the high implementation cost and the lack of research and BIM integration.

BIM has also not been comprehensively used in the evaluation process of BSA methods [20]. Dealing with the same mentioned limitations, there is also a lack of software to assess building sustainability and it is necessary to use several BIM platforms and tools to evaluate a single BSA method [60,194]. Besides the increased risk of information lost when exchanging the BIM model, it also requires broader software knowledge, making it too complicated to adopt [16,90,208]. The data complexity of BSA is also a current limitation. Quantitative data is easily assessed within the BIM environment, however, qualitative data can be only observed and not measured, which makes it difficult to be incorporated into BIM [195]. The full potential of BIM is yet to be explored as BIM integration in BSA is a relatively new concept to the industry, which still lacks some maturity for it. Nevertheless, BSA developers are aware of BIM benefits and are already looking for new innovative ways to integrate their products into BIM [147].

2.4 Concluding remarks

Given the current impacts of the building industry and the need to achieve world environmental targets, there is an increasing demand for more sustainable and efficient buildings. A recognised pathway to enhance buildings sustainability is to apply BSA methods, to monitor and evaluate buildings performance, as well as to enhance the integration of sustainability measures. However, existing methods often require multi-disciplinary information and several resources, such as time, money, and man work, making it an inefficient procedure to be applied in the project early stages. Moreover, these stages are when sustainability measures have higher impacts and should be integrated, hindering the full potential of BSA. There is an urgent need for an expedited and common approach to automate and simplify BSA to effetely support and improve building sustainability. With the deployment of BIM, the opportunity for the BSA methods to benefit from its capabilities has emerged, as well as the possibility to effectively integrate BSA into the BIM collaborative process. Beyond the direct benefits for project teams and building occupants, like real-time and early sustainability assessment, significant advantages can be expected to the construction industry, such as more sustainable and ecological buildings and a significant reduction in the sector environmental impacts.

3. A Systematic Review of the Role of BIM in Building Sustainability Assessment Methods

BIM is creating new opportunities for the Architecture, Engineering and Construction industry. One of them is the integration of the BSA during the design process. Currently, an approach for using BIM to foster and optimise the application of BSA methods has not been clearly established yet, creating a knowledge gap on the application of BIM for sustainability assessment purposes. Thus, this paper analyses the current role of BIM to evaluate three BSA methods—LEED, BREEAM and SBTool. The current BIM applicability is assessed by performing a systematic review, where the criteria being assessed and the applied BIM software are identified. A comparison is made to determine which BSA method can currently take more advantage from BIM and to identify the number of assessed criteria from each one. Furthermore, the attractiveness of a BIM-based assessment for SBTool is analysed, facing the actual BIM scenario for LEED and BREEAM. Despite the restrictions, BIM use is increasing for sustainability purposes. Most of the analysed studies and identified software are still focused on the use of LEED for assessing sustainability during the design phase. However, BIM software capabilities can also support the assessment of the other BSA methods so that process replicability can happen. Among the most addressed criteria, the energy and material-related categories are the most eminent. Autodesk Revit is the most-used software. A BIM-based assessment for SBTool will have enough attractiveness. It can assess, at least, the same percentage of criteria as the other schemes, creating new opportunities to enhance building sustainability.

Keywords: building sustainability assessment (BSA); building information modelling (BIM); sustainability

This Chapter is based in the article: Carvalho, J.P.; Bragança, L.; Mateus, R. A Systematic Review of the Role of BIM in Building Sustainability Assessment Methods. Appl. Sci. 2020, 10, 4444. https://doi.org/10.3390/app10134444

3. A SYSTEMATIC REVIEW OF THE ROLE OF BIM IN BUILDING SUSTAINABILITY ASSESSMENT METHODS

3.1 Introduction

The scientific community has already proved the relationship between the built environment and environmental problems [1]. Different actions have been taken to reduce buildings' negative impact and fight against environmental issues. Among them are the BSA methods, which aim at implementing and spreading sustainable principles, evaluating building performance and gathering information to support decision-making [6]. They are usually characterised by assessing several building features and aggregate the results into a sustainability score. Several methods have been developed all over the world by private and public organisations, according to their needs, characteristics and culture [6]. Despite the existence of different BSA methods, the following three are recognised as the basis of all the other approaches [7,8]: Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED) and Sustainable Building Tool (SBTool). These will be used in this research and are presented in the next section.

The application of BSA methods requires the knowledge of a large amount of data, and it is a time-consuming and complicated process. Although they are intended to be used during the project phase to support decision-making, buildings are often assessed during the final construction stages. At these stages, making changes to improve building sustainability has higher costs and most times is unfeasible. This happens due to the lack of time and other resources from design teams during the project phase. Additionally, when a project change is introduced, all the assessment process must be repeated [20]. Thus, the application of BSA methods is usually unbearable given the deadlines of the projects, and this situation does not encourage designers to use it. To overcome this constraint, there is a need to reduce the assessment time and complexity, by automating and simplifying the sustainability assessment procedures. As a result, designers will be encouraged to improve the sustainability of their projects effectively.

With the recent deployment of BIM, emerges the opportunity for BSA methods to benefit from its capabilities. BIM can be described as a working methodology, which makes it possible to manage the project's 3D-model and data in a digital format during the building's lifecycle [15]. All societies will benefit from it, with better and more efficient constructions that require fewer resources [88]. BIM and sustainability look for practical proposals for new architecture and engineering procedures, preserving the natural environment and ecosystems. Both concepts intend to achieve a new lifestyle, a modern environmental education and an

updated perspective of the impact of human development on the planet. The BIM methodology has already been applied in different sustainable fields, as for energy modelling, acoustic analysis, water-use reduction, lifecycle analysis, construction waste management and even in supporting managers during the building's operation [159]. Nevertheless, BIM's main advantage lies in the collaborative process, where stakeholders can work on a central model and continuously share information about their project discipline. As a result, errors, incompatibilities and interferences between project disciplines are often identified in preliminary project stages, facilitating decision-making, as well as optimising costs and time.

By allowing multi-disciplinary information to be overlaid and grouped into a single model, BIM creates an excellent opportunity to incorporate sustainable measures in a project [16]. Furthermore, Azhar et al. [63] have identified that the pre-construction and project phases are the ones where decisions to improve building sustainability are supposed to be made. As this is also when projects can most benefit from BIM, the influence that it can have on building sustainability becomes clear. Wong and Zhou [53] argued that BSA methods should be used from the preliminary design stages, creating an integrated process and a more significant impact on the project. Designers are provided with detailed information to select the best sustainable solutions, allowing for the efficient development of high-performance buildings [158]. When BIM is used to improve the sustainability of a project, savings can reach up to 20% of the total project cost in 10 years [63].

In recent years, the attention of researchers about the application of BIM to facilitate the practical implementation of BSA methods has increased [17–19,159]. BSA method developers were driven to find new ways to integrate their products in this new paradigm [209,210]. To date, several criteria from different BSA methods have already been assessed with BIM. However, BIM it is still not used comprehensively in the implementation of the BSA methods [20]. The assessment of BSA methods exploits the full potential of BIM for building sustainability, as multi-disciplinary data must be assessed, with different BIM analyses and software. Among the most common advantages of using BIM to evaluate BSA methods, are the easier and faster data assessment, the resource-use reduction (time, money and human), improved process efficiency, automatic calculations and modifications updates [16,25,159,211]. With BIM, designers can quickly compare the sustainability performance of different solutions and select the ones that optimise the sustainability level of the project. Facing the potential capabilities of BIM for BSA methods, a review study from Chong [90] proposes that future BIM standards should include the requirements for a building

sustainability assessment. Despite all the benefits, the scientific community have identified a set of existing limitations. Some issues are the lack of platforms and tools to assess building sustainability, the need to use several BIM tools to evaluate a single BSA method, the stakeholder awareness of sustainable issues or the interoperability restrictions between software [16,90,208]. A recent review from Santos et al. [17] has also identified a lack of research that considers all dimensions of sustainability, reinforcing Wong and Zhou's [53] position. These authors have also affirmed that the full potential of BIM to sustainable construction is yet to be explored. Researchers suggest that future platforms and tools should be further developed to embrace more sustainable issues, and exchange format files should be improved to reduce errors when transferring BIM models (reducing the need for model checking and remodelling) [16,19,208].

Up to date, a set of generic reviews have been made about the application of BIM in sustainability issues [18,90,159]. Most of them are focused on the project phases, where BIM can enhance building sustainability. Therefore, there is still a lack of research about the practical implementation of BIM to assess specific BSA criteria with case studies. In a review from Ansah et al. [196], some frameworks and practical assessments were identified, but few insights were given about the most effective software and topic trend. However, they still have identified that most researchers tend to use BIM to assess LEED criteria (both for frameworks and practical assessments), with few BIM-based assessments on other BSA schemes. Azhar et al. [16] were one of the first researchers to approach the topic in 2011, by proposing a BIM framework that was able to assess 17 credits and two prerequisites from LEED. In practice, they have only assessed six credits and one prerequisite from LEED v2.2, which was significant progress at the time. More recently, Jalaei and Jrade [21,190] were able to assess a total of five prerequisites and 33 credits from LEED v3 (that belong to six different sustainability categories) with a BIM-based procedure.

Despite the greater focus on LEED, some approaches to other assessment schemes have been made. Edwards et al. [22] have used several different BIM software to assess eight credits from six categories belonging to the BREEAM UK Refurbishment and Fit-out 2014 scheme. Wong and Kuan [25] have gathered the necessary data for evaluating 26 out of 56 criteria from BEAM Plus (with Autodesk Revit, developed by Autodesk, Inc, San Rafael, CA, USA). They achieved a faster assessment with fewer resources when compared with the traditional method. For the Australian Green Star Building certification, Gandhi and Jupp [200] have assessed 66% of its credits. They argue that the capabilities of BIM were not used to their full potential. It is essential to develop BIM execution and coordination plans, which addresses the requirements

of green building certification. GhaffarianHoseini et al. [201] have suggested a conceptual framework, where 75% of the criteria from the New Zeeland Green Star certification can be supported by BIM, highlighting the importance of creating proper guidelines for BIM integration. By carrying out a Delphi analysis using 24 experts, Liu et al. [202] have identified that 31 out of 78 items from the Singapore Green Mark Non-Residential Buildings 2015 can be assessed with BIM and building performance analysis tools. Concerning the SBTool, Carvalho et al. [20] have presented a 3-stage framework for a BIM-based Application Programming Interface (API) to automate the assessment of 24 of the 25 criteria from the Portuguese residential version of this BSA scheme. They are currently developing a practical assessment of the identified criteria.

As it was possible to understand, different approaches and software are being used to integrate BIM in BSA methods. Additionally, several BSA methods and versions are also being applied, making it challenging to create a common understanding of the actual level of BIM integration. Facing the existing knowledge gaps, the present research aims at establishing a common understanding regarding which BSA criteria (from the most recognised schemes) were already practically assessed with a BIM-based procedure. To archive this goal, a systematic review will be carried out. Relevant publications from the past 10 years will be identified, to analyse the topic trend in terms of interest, applied software, preferred journals and addressed BSA method/version. Furthermore, it is also intended to investigate the applicability and attractiveness of a BIM-based process to assess SBTool, facing the existing procedures available for LEED and BREEAM.

The outcomes of this research will provide a basis and guidance for future researchers on the topic of the actual and prospective state of BIM integration in BSA methods. As BSA methods usually have similar criteria (applied procedures/software can be adapted to other sustainability schemes) [196], insights will also be gathered for process replicability.

3.2 Building Sustainability Assessment Methods

3.2.1 BREEAM

The BREEAM method was created in 1990 by the Building Research Establishment (BRE) in the UK. BREEAM was launched as a credit award system for new office buildings but quickly developed systems for other

buildings, such as homes, supermarkets or industrial buildings. BREEAM credits are divided over ten categories: Energy, Health and Wellbeing, Innovation, Land Use, Materials, Management, Pollution, Transport, Waste and Water [212]. Each category is subdivided into a set of assessment issues, each with its own aim and benchmarks. Every benchmark needs to be determined by a BREEAM expert assessor before credits can be assigned to the project. Once the assessment is entirely performed, the final score is determined by the sum of the weighted category scores [213]. BREEAM encompasses both mandatory and optional credits and allows to "trade" compulsory credits in different categories, while always setting minimum standards in essential areas.

Nowadays, the BRE has different BREEAM Standards available for Communities, Infrastructures, New Construction, In-use and Refurbishment and Fit-out, and it is recognised in more than 60 countries.

BRE has already started research about the capabilities of BIM. Currently, they have available different BIM-related services, such as certification, consultants, training and some research projects [214]. BRE has also released a BREEAM API to explore and integrate its rating data on thousands of certified building assessments across 50 countries, available for different tools, websites or software [209].

3.2.2 LEED

The first version of LEED, developed by the United States Green Building Council (USGBC), dates from 1998. The aim was to provide building owners and operators with a concise framework to identify and implement green building solutions. It is mostly used in the USA, and it is recognised in more than 30 countries [16].

LEED is a point-based system, with a balance between known effective practices and emerging concepts, following six major categories: Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality and Innovation in Design. Using existing validated technologies, LEED assesses the environmental performance of buildings from an overall point of view during their lifecycle. The number of points that the project earns determines the certification level. In addition to credits, some sections of LEED include prerequisites that also must be satisfied, even though they do not count towards the building's total points [213].

Nowadays, LEED has several rating systems, in four main areas: Building Design and Construction, Operations and Maintenance, Interior Design and Construction and Neighborhood Development. These

systems cover different types of buildings, from residential, hospitals, retail, schools and warehouses, among others [215].

BIM applications on LEED are usually initiatives from researchers, private organisations or designers. Several authors have developed their specific applications for LEED, according to their needs. In 2014, the USGBC released some applications for LEED automation: Autodesk apps for LEED, COMNET Energy Modeling Portal, Greengrade LEED Management Software, Green Wizard, IES Tap for LEED, Tracker Plus LEED and Trane [210].

3.2.3 SBTool

The iiSBE developed the SBTool. This method is considered one of the most comprehensive of all the BSA methods and has the flexibility to be adjusted to the local conditions of each region [6,8]. This feature allows to compare the sustainability level of buildings from different countries.

SBTool has influenced the national rating systems of Austria, Spain, Japan and South Korea. Custom versions have been introduced in Italy, Czech Republic and Portugal [73]. It can be adapted to assess the sustainability level of different type of buildings, such as houses, offices, schools or medical facilities, and already has versions for urban neighbourhoods.

SBTool has a set of parameters with different weights according to the national standards and practices. Each parameter is classified with a qualitative "score" that results from the comparison between two benchmarks: best and conventional practice. After weighing all the parameters, a final sustainable classification is given to the building. The parameter weights and the benchmarks must reflect a country's characteristics and specific factors [6]. The system covers a wide range of sustainable building issues. The scope can be modified to be as narrow or as broad as desired, from more than 100 criteria to half a dozen. Parameter weights can also be adjusted to region-specific and site-specific factors.

3.3 Methodology

Facing the existing literature gap about the application of BIM to evaluate BSA methods criteria, the main objective of this study is to understand the actual practical implementation of BIM to evaluate BSA criteria. The goal is to identify which BSA criteria are available (and proved) to be assessed with BIM, as well as the

most effective BIM software for such kind of analysis. It is also intended to analyse the topic trend in the past 10 years and the attractiveness level of BIM integration in the SBTool method, facing the two most known BSA schemes—LEED and BREEAM. Therefore, the following main research questions were established:

- What is the actual practical implementation of BIM to assess BSA criteria?
- Which percentage of BSA criteria can be assessed with BIM?
- What is the BIM software commonly used to assess BSA criteria?
- Which are the most preferred journals by researchers on the topic?
- Facing the current integration of BIM in LEED and BREEAM, will a BIM-automated assessment for SBTool be attractive enough?

To accurately answer the formulated research questions, a systematic review will be carried out, adapted from Tawfik et al.'s [216] guide. Figure 5 summarises all the procedure sequences for this study. After the research question(s) definition, a preliminary search will be performed to identify similar review studies and establish the contribution of this study. Then, the search strategy will be defined in terms of scope and keyword combinations. This review will only focus on publications that directly address the practical assessment of, at least, one criterion from the selected BSA methods—LEED, BREEAM and SBTool. These BSA methods were selected as they provide the basis for all the other existing frameworks [7,8].

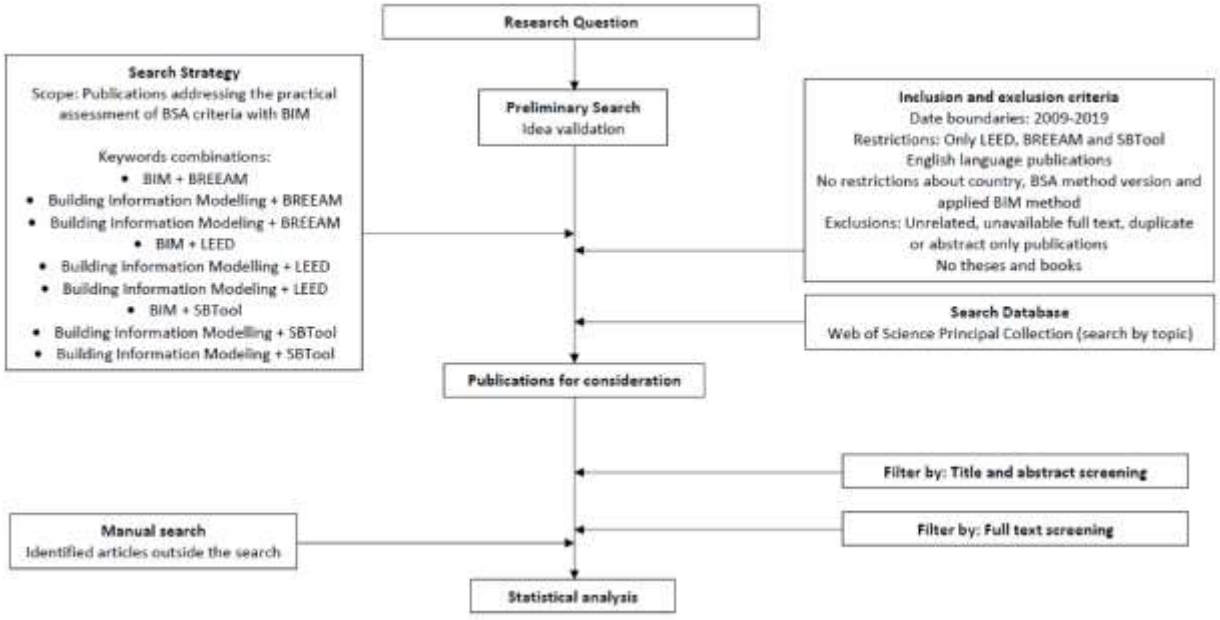


Figure 5 – Systematic review procedure

The research boundaries were defined by identifying the inclusion and exclusion criteria. The considered period is between 2009 and 2019. There were no restrictions regarding country of origin, BSA method version and applied BIM software, but only English language publications were considered. Publications for which the full text is unavailable and abstract only publications were excluded from the analysis.

Regarding the database, Web of Science was chosen as a research engine, due to its broader citations database. It encompasses registers from most of the existing high-impact journals.

By applying all the criteria, publications for consideration will be gathered and exported to a reference citation manager to remove duplications and for filtering. First by title and abstract reading and, then, by full-text reading. Finally, after identifying all the key publications for the research, a manual search will be performed to add a couple of publications about the topic that did not appear when using the selected keywords.

To analyse all the results, the key publications will be organised through tables, covering the following information:

- year of publication;
- title;

- journal;
- addressed BSA method;
- assessed criteria;
- adopted software.

This data will be used to carry out a statistical analysis, where the following aspects will be identified: percentage of assessed credits from each BSA method, the most assessed categories, the most common applied software, the topic trend in the past 10 years and the journals with most publications on the topic. Based on the current state of implementation of BIM in LEED and BREEAM, the attractiveness of a BIM-based assessment for SBTool will be investigated, as well as the replicability level of the applied procedures in those schemes (when applicable).

3.4 Results

3.4.1 Related Review Studies – Idea Validation

A quick search about the application of BIM in BSA methods shows that different proposals are being used to include BIM in several BSA methods and versions. The results also show an increased interest in the topic, creating a need to identify which criteria were already assessed with BIM. Up to date, some systematic reviews have been done on the use of BIM in building sustainability, as presented in Table 2. The most common journal to publish BIM-based reviews is Automation in Construction with three publications, followed by the Sustainable Cities and Society journal with two publications. Understandably, most of the reviews are focused on the use of BIM in generic sustainability applications, as well as in different project lifecycle stages to improve building sustainability [18,90,159]. A trend was also verified, which concerns the review of BIM-based Life Cycle Assessments [14,205] and BIM. Common journals and top authors/citations were also already identified [17].

Table 2 – Related review studies

Year	Journal	Title	Scope and Aim	Research Sample	Main Conclusions
2015	*Automation in Construction*	Enhancing environmental sustainability over building lifecycles through green BIM: A review [53]	Green-BIM related publications and their research focus in building lifecycle—planning and design, construction, operation, repair and maintenance, demolition and others	84 academic publications	BIM has emerged as a popular energy performance analysis tool during a building's conceptual design stage. It has also been applied to on-site emissions estimation and to visualisation. Green BIM development has only started to scratch the surface, and its full potential is yet to be explored by practitioners.
2017	*Journal of Cleaner Production*	A mixed review of the adoption of Building Information Modelling (BIM) for sustainability [90]	Current state-of-the-art BIM development for sustainability by construction phase—planning, design, construction, operation and maintenance, refurbishment and demolition, use of products and materials and energy consumption	36 standards and guidelines and 91 academic publications	Standards and guidelines are mainly focused on planning, design, construction, energy consumption, operation and maintenance; Academic publications are focus on design and energy consumption.
	Energy and Buildings	Critical review of BIM-based LCA method to buildings [14]	Review of academic publications centred on BIM-based LCA	11 academic publications	The integration of BIM–LCA has mainly been developed in new buildings or projects; its utility from early stages of design has been mostly recognised. Furthermore, this paper concluded that almost half of the case studies developed an environmental impact assessment based on LCA but focused on the energy lifecycle.
	Automation in Construction	Building Information Modeling (BIM) for green buildings: A critical review and future directions [159]	Applications of BIM in supporting the design, construction, operation, and retrofitting processes of green buildings; the various functions of BIM for green building analyses such as energy, emissions, and ventilation analysis and; the applications of BIM in supporting green building assessments (GBA)	Over 400 academic publications	BIM is an essential tool for the design stage of green buildings and has potential value for the construction, facility and operation management phases. Primary BIM functions to assess the sustainability level of a building include the following analysis: energy performance, carbon emissions, natural ventilation, solar radiation, natural and artificial lighting, water usage, acoustics performance and evaluation of thermal comfort. Green BIM applications could bring several benefits for GBA, such as estimating scores, managing application documents, and improving the process efficiency

2017	*Renewable and Sustainable Energy Reviews*	Lifecycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities [205]	Sustainability and energy-efficient methodologies in BIM, including LCA, energy analysis and sustainable rating systems. Focus on BIM-based LCA—lifecycle stage and applied software	34 academic publications	Evaluation frameworks that quantify the performance criteria of sustainable and energy-efficient structural systems could emerge, while intuitive decision workflows in the future engineering practices could also be consolidated. The benefits of such approaches are higher during the earlier design stages of buildings where decisions have fewer cost, are more effective and are easier to be implemented.
2019	*Sustainable Cities and Society*	Analysis of the scientific evolution of sustainable building assessment Methods [18]	Study about the evolution of the research field employing a systematic literature review of bibliographic records for sustainable building assessment methods, and a review based on the bibliometric analysis	565 academic publications	Sustainable building assessment methods and sustainable building are significant themes, especially over the last five years, with a gradual increase in the number of studies. Instruments have evolved from tools that only looked at environmental aspects towards more complete instruments that include economic and social aspects in the evaluation of sustainable building.
		A review and outlook for integrated BIM application in green building assessment [196]	Review on the breadth of green building evaluation matrixes achievable with BIM	19 academic publications	LEED criteria were identified as the most frequently addressed. Assessments concerning the categories of energy and atmosphere, materials and resources have been extensively demonstrated through Revit scheduling and API. The development density, community connectivity and alternative transportation, although seldom addressed, have been well demonstrated in the literature.
	Automation in Construction	Informetric analysis and review of literature on the role of BIM in sustainable construction [17]	Current state of the literature on sustainable construction and BIM, including environmental, economic, and social dimensions and their search combinations	317 academic publications	The number of published scientific works on BIM and sustainable construction registered exponential growth in previous years. There is a higher synergy between environmental and economic dimensions, and between environmental and social dimensions. There is a lack of research that considers all dimensions of sustainability. Top 10 researchers and journals on the subject were identified.

3.4.2 Publications for consideration

By applying the keyword combinations of the systematic review (Figure 5), the research on the Principal Collection of Web of Science returned a total of 245 peer-reviewed publications. By applying the reference manager citation filter for duplicated publications, only 83 publications were left for consideration. However, when reading the title and abstract from all the remaining publications, only 41 were left over regarding the assessment of BSA criteria from the selected schemes. The final filtration stage was performed by reading the 41 full-text publication (whenever available), resulting in 23 publications concerning the research question(s): 19 for LEED, two for BREEAM, one for both and one for SBTool. Finally, by performing a quick manual research, three additional publications were found outside the keyword combinations. One for LEED, one for BREEAM and another one for both schemes, achieving the final number of 26 publications for consideration. Figure 6 presents the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram with the search phases and number of records. The first exclusion phase represents the title and abstract filtering. Full-text publications that were excluded did not address the practical assessment of one or more BSA criteria.

Initial insights are in line with other review studies, pointing out the trend in research in assessing LEED criteria with BIM [200]. LEED has more than 400% of the studies compared with BREEAM. Concerning the SBTool, only one publication was found regarding a framework for a BIM-based assessment, which will be further explored later. All 26 publications will be used to conduct the statistical analysis.

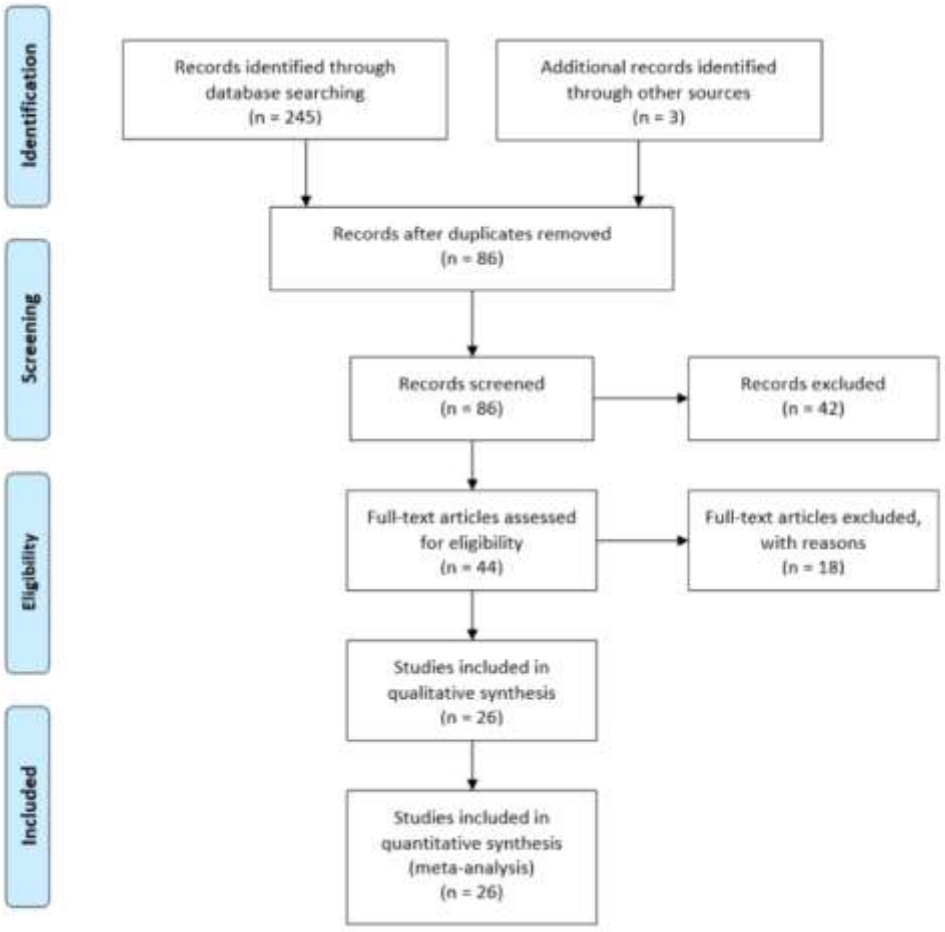


Figure 6 – PRISMA flow diagram [217]

3.4.3 BIM Application in BREEAM

From the performed analysis, five papers regarding the practical application of BIM in the BREEAM method are identified in Table 3. Between 2013 and 2019, different BREEAM versions have been addressed in all five publications. With the data from Table 3, Figure 7 was organised to present the BREEAM categories that were assessed using BIM. A commonly assessed category is Energy, attended in 4 out of 5 studies, followed by the Materials category, addressed in three studies. In total, the identified studies have assessed 20 different BREEAM criteria, in the categories of Materials, Energy, Land Use and Ecology, Management, Water, Waste, Health and Wellbeing and Pollution (8 categories out of 10). The Innovation and Transport categories have no assessed criteria. A common BREEAM version was used to understand the percentage of credits available to assess with BIM. As all the addressed versions are different, it is hard to define a common

percentage for all. Thus, this analysis was only made for BREEAM UK Refurbishment and Fit-out 2014, as it is the publication with most assessed criteria (eight credits). For this case, a BIM-based procedure was possible to apply for the assessment of 24% of the scheme version credits (8 out of 34). Nevertheless, identified authors usually were able to assess approximately seven credits from each BREEAM version.

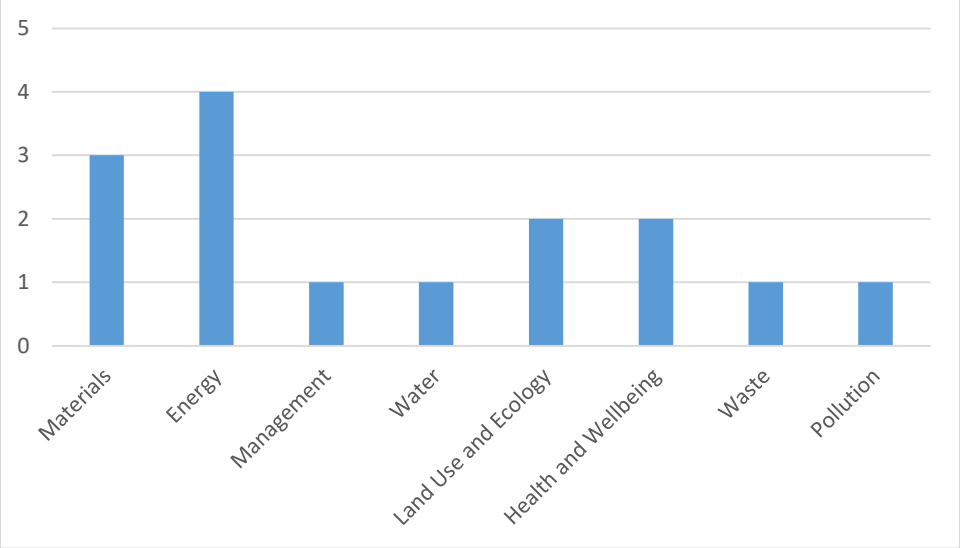


Figure 7 – BREEAM categories assessed with BIM

With regard to the software use (Figure 8), Autodesk Revit, IESVE (IES, Glasgow, United Kingdom) and Visual Studio (Microsoft Corporation, Redmond, CA, USA) were identified as commonly applied to assess BREAM criteria (all used in 2 out of 5 studies). In total, 16 different software were used to assess 20 BREEAM criteria.

Concerning the preferred journal by researchers, Automation in Construction has been chosen for the publication of 2 out of 5 studies. Only one publication was found for the remaining three journals.

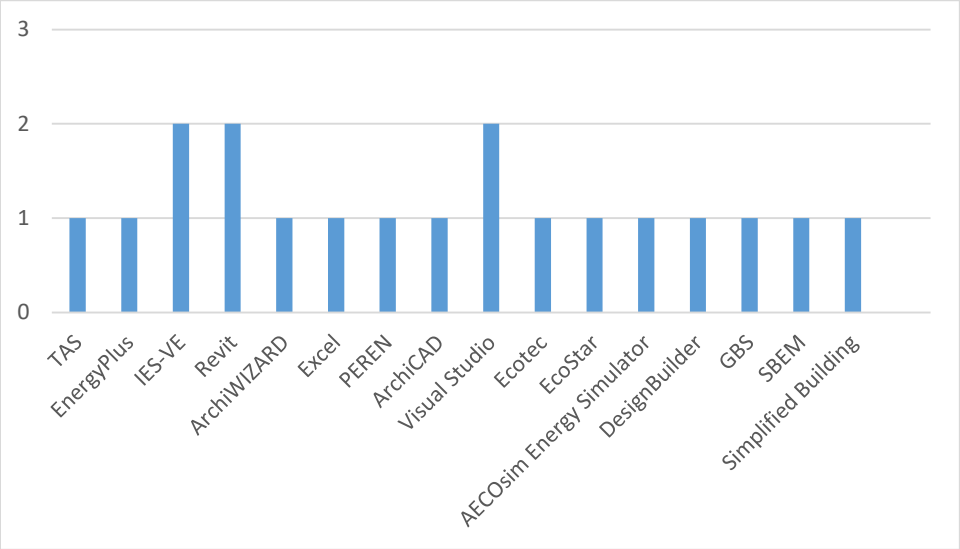


Figure 8 – Applied software to assess BREEAM criteria

3.4.4 BIM Application in LEED

According to the analysis, LEED is the most-used BSA method by researchers regarding the use of BIM. As presented in Table 4, 22 from the 26 identified studies have addressed, at least, one LEED credit, between 2011 and 2019. The most used LEED version by researchers is BD+C: New Construction v3 (2009) is addressed in nine publications, followed by BD+C: New Construction v4 addressed in five papers. Figure 9 presents the different versions applied in the identified publications. Note also for the application of different LEED versions in school buildings, which have happened in three publications.

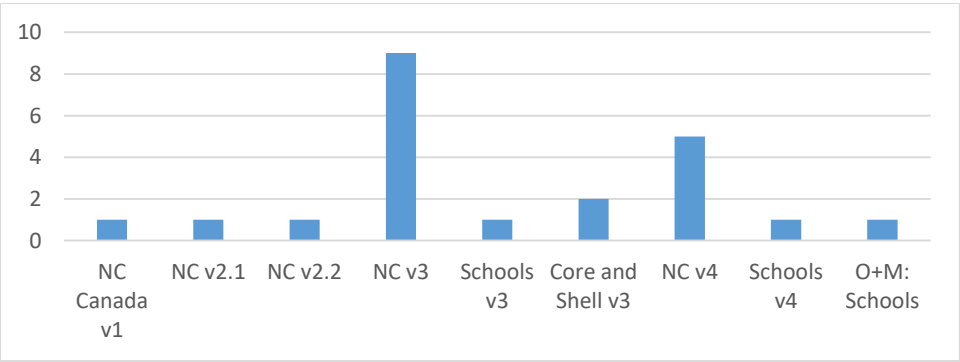


Figure 9 – Addressed LEED versions

All LEED categories have been assessed somehow in the identified studies, as presented in Figure 10. The most common assessed credits are from the Materials and Resources category, addressed in 9 out of 22 publications. The following categories are Energy and Atmosphere (8), Sustainable Sites (7) and Indoor Environmental Quality (6). All the other categories have only been assessed in one publication. In total, the selected articles have assessed 84 different credits and 11 prerequisites from the categories of Sustainable Sites, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation in Design Process, Regional Priority, Water Efficiency and Pilot-Credits in different LEED versions. Regarding LEED v3—the most addressed version—a total of five prerequisites and 33 credits have been assessed, representing 67% of all the scheme items (excluding Pilot Credits).

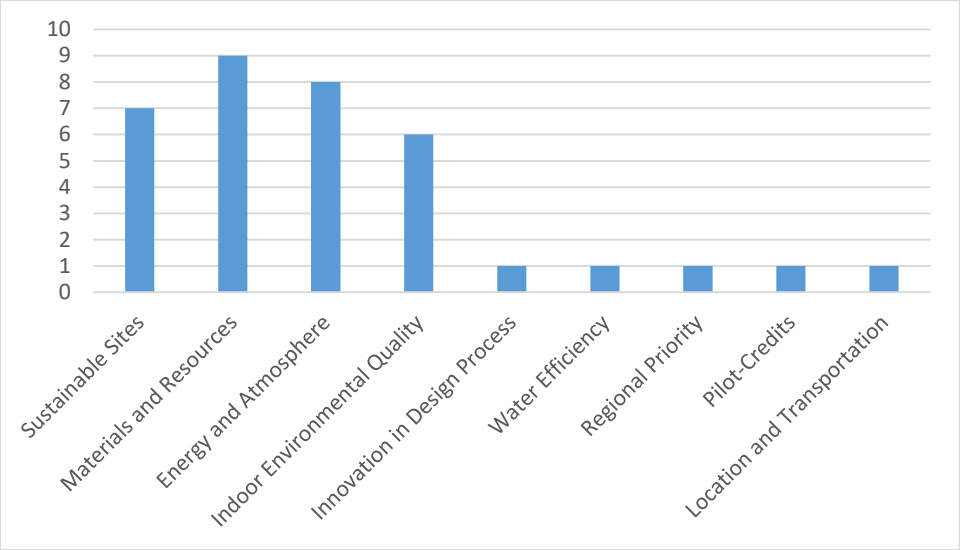


Figure 10 – Addressed LEED categories

The most commonly used software is Autodesk Revit (19 out of 22) for 3D modulations and API's development, applied in 76% of LEED identified publications. Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) is the second most recorded software with 24% (used in 6 out of 22), followed by Dynamo (Autodesk, Inc, San Rafael, CA, USA) with 16% (4 out of 22). IESVE, LEED Sustainable Sites and Google Maps (Google LCC, Mountain View, CA, USA) are the following, all with 12% (used in 4 out of 22). A total of 25 different software was used. Figure 11 presents the mentioned statistics.

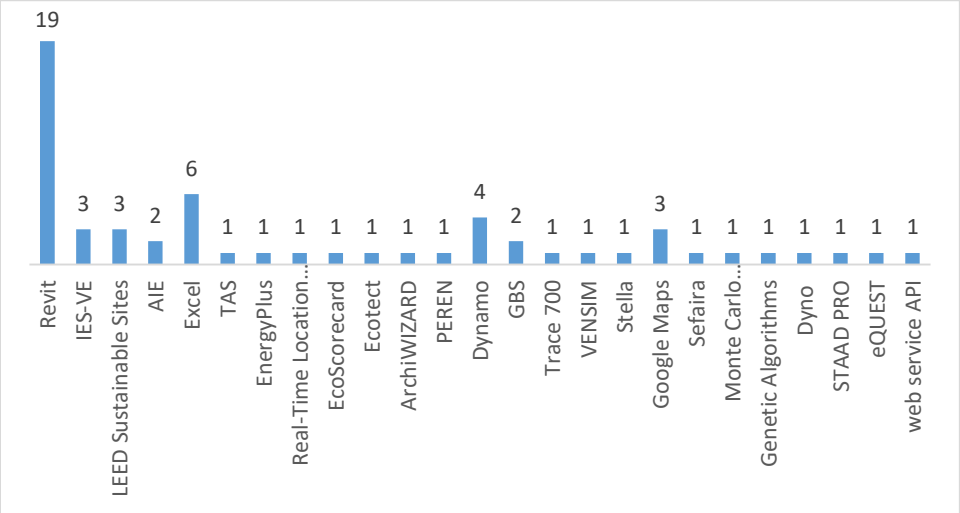


Figure 11 – Applied software to assess LEED criteria

With regard to the most preferred journals for LEED-related publications, 4 out of 22 papers were published in *Conference Proceedings*. *Automation in Construction* followed with three publications, followed by the *Journal of Architectural Computing* and *Journal of Cleaner Production*, both with 2 articles.

3.4.5 BIM Application in SBTool

The application of BIM in SBTool is still in an initial stage, with the proposal of conceptual approaches. The only identified study regarding SBTool and BIM dates from 2019 and has identified a BIM-based framework to assess the SBTool^{PT}-H —Portuguese method—to assess the sustainability of residential buildings [20]. This study proposed the creation of an Autodesk Revit API, which can directly and/or indirectly support the evaluation of 24 out of the 25 sustainability criteria. Autodesk Revit was identified as the most useful BIM software in the SBTool^{PT}-H case. It has the capability to support the assessment of more than a dozen criteria. This is due to the criteria characteristics, which are mainly quantitative data from the building model. Authors have also identified several common software that can be used to assess the remaining criteria, such as Autodesk Green Building Studio (GBS), developed by Autodesk, Inc, San Rafael, USA), Google Maps or Microsoft Excel [20].

A practical application of the proposed framework was already preformed for 17 criteria on the categories of Land Use and Biodiversity (5 out of 5), Energy Efficiency (2 out of 2), Materials and Waste Management (5 out of 5) and Occupant's Health and Comfort (5 out of 5). From all, 12 of these criteria were assessed by

creating shared parameters and using the schedule function of Autodesk Revit (and Microsoft Excel as an interface). The two criteria from the Energy Efficiency category (and one from the Occupant's Health and Comfort category) were assessed by exporting a 3D-model for Cypetherm REH (Cype Ingenieros, Alicante, Spain) and GBS, to perform the energy analysis. The two remaining criteria from the Occupant's Health and Comfort category were evaluated by exporting the Autodesk Revit model to Cypetherm EPlus and Cypesound RRAE (both from Cype Ingenieros, Alicante, Spain). Currently, seven criteria are still requiring practical validation, namely on the water efficiency category (2), accessibility category (2), lifecycle environmental impact (1) and the economic dimension (2). With a BIM-based API, authors aim at optimising and automating the assessment procedure of SBTool^{PT}-H and support designers during the project phase. This study was published in the *Automation in Construction* journal.

Table 3 – BIM integration on BREEAM

Year	Journal	Title	BREEAM Version	Assessed Criteria	Software
2013	*Energy and Buildings*	Variations in results of building energy simulation tools, and their impact on BREEAM and LEED ratings: A case study [218]	New Construction Non-Domestic Buildings 2011	Ene 01	TAS, EnergyPlus, IESVE
2015	*International Journal of Architectural Computing*	An "Environmental BIM" Approach for the Architectural Schematic Design Stage [219]	International 2013	Ene 01, Ene 04 Man 05 Le 06 Wat 01 Hea 01, Hea 02	Revit, ArchiWIZARD, Excel, PEREN
2016	*Automation in Construction*	Green building assessment tool (GBAT) for integrated BIM-based design decisions [19]	Europe Commercial 2009	Mat 01, Mat 02, Mat 03, Mat 04, Mat 05, Mat 06 and Mat 07	ArchiCAD, Visual Studio
		Structural sustainability appraisal in BIM [199]	Offices 2008	Ene 01 Mat 01, Mat 03, Mat 04 Le 03, Le 04, Le 05	Revit, Visual Basic
2019	*Journal of Building Engineering*	Sustainability-led design: Feasibility of incorporating whole-lifecycle energy assessment into BIM for refurbishment projects [22]	UK Refurbishment and Fit-out 2014	Ene 03 Hea 01, Hea 02, Hea 04, Wst 05 Mat 03, Mat 05 Pol 04	Ecotec, EcoStar, AECOsim Energy Simulator, DesignBuilder, GBS, SBEM, Simplified Building, IESVE

Mat–Materials; Ene–Energy; Man–Management; Wat–Water, Le–Land Use and Ecology; Hea–Health and Wellbeing; Wst–Waste; Pol–Pollution.

Table 4 – BIM integration on LEED

Year	Journal	Title	LEED Version	Assessed Criteria	Software
2011	*Automation in Construction*	Building information modelling for sustainable design and LEED rating analysis [16]	NC v2.2	WEc2, WEc3.1, WEc3.2, EAp2, EAc1, EQc7.1, EQc8.1	Revit, IESVE
2012	*Journal of Architectural Computing*	Data Sharing for Sustainable Building Assessment [220]	NC v2.1	SSp1, SSc2	Revit, LEED Sustainable Sites
2013	*Building Simulation*	Integrating building information modelling with sustainability to design building projects at the conceptual stage [190]	NC v3	SSc5.2, SSc6.1, SSc6.2, SSc7.1, SSc7.2 SSc8; EAc1, EAc3, EAc5, EAc6; MRc2, MRc3, MRc4, MRc5, MRc6; EQp1, EQc2, EQc4.1, EQc4.2, EQc4.3, EQc4.4, EQc5, EQc6, EQc7, EQc8.1, EQc8.2; IDc1, IDc2; RPc1, RPc2	Revit, Athena Impact Estimator (AEI), Excel
	Energy and Buildings	Variations in results of building energy simulation tools, and their impact on BREEAM and LEED ratings: A case study [218]	NC v3	EAc1	TAS, EnergyPlus, IESVE
2014	*Proceedings of the 2014 Winter Simulation Conference*	Lifecycle evaluation of building sustainability using BIM and RTLS [221]	Schools v3	SSp1, SSp2, SSc1, SSc2, SSc3, SSc4.1, SSc4.2, SSc4.3, SSc4.4, SSc5.1, SSc5.2, SSc6.1, SSc6.2, SSc7.1, SSc7.2, SSc8, SSc9, SSc10	Revit, Real-Time Location System, LEED Sustainable Sites
	Journal of Information Technology in Construction	Integrating Building Information Modeling (BIM) and Energy Analysis Tools with Green Building Certification System to Conceptually Design Sustainable Buildings [222]	NC Canada v1	EAp2, EAc2, MRc3, MRc4, MRc5, MRc7, EQc4.1, EQc4.3, EQc8.1	EcoScorecard, Revit, Ecotect, IESVE, Excel, AEI

SS—Sustainable Sites; MR—Materials and Resources; EA—Energy and Atmosphere; EQ—Indoor Environmental Quality; ID—Innovation in Design Process; WE—Water Efficiency; RP—Regional Priority; LT—Location and Transportation.

Year	Journal	Title	LEED Version	Assessed Criteria	Software
2015	*Journal of Architectural Computing*	An "Environmental BIM" Approach for the Architectural Schematic Design Stage [219]	Core and Shell v3	SSc5.2 SSc6.1 EAp2, EAc1, EAc2 MRc1.1 EQc7.1 EQc8.1	Revit, ArchiWIZARD, Excel, PEREN
	Sustainable Cities and Society	Integrating building information modelling (BIM) and LEED system at the conceptual design stage of sustainable buildings [21]	NC v3	EAp1, EAp2, EAp3, EAc1, EAc2, EAc3, EAc4, EAc5, EAc6 MRp1, MRc1, MRc2, MRc3, MRc4, MRc5, MRc6, MRc7	Revit
2016	*11th European Conference on Product and Process Modelling*	Building Information Modeling (BIM) for LEED IEQ category prerequisites and credits calculations [223]	NC v3	EQp1, EQc2	Revit and Dynamo
	22nd International Conference on Virtual System and Multimedia	Utilisation of building information modelling (BIM) in planning an adaptive reuse project of a Traditional Malay House (TMH) [224]	NC v3	EQc8.1	Revit, GBS
	Sustainability	A Study on the LEED Energy Simulation Process Using BIM [198]	NC v3	EAc1	Revit, Trace 700
	Journal of Environmental Informatics	Framework for Sustainable Low-Income Housing Projects using Building Information Modeling [225]	NC v3	MRc3, MRc4, MRc5, MRc6, MRc7	Revit, Excel, VENSIM, Stella
	5th Creative Construction Conference	Integrating BIM and Web Map Service (WMS) for Green Building Certification [226]	NC v3	SSc2, SSc4	Revit, Google Maps
	Journal of Green Building	Green Building and Biodiversity: Facilitating Bird Friendly Design With Building Information Models [137]	Core and Shell v3	Pilot-Credits SSpc55	Revit, Dynamo

SS—Sustainable Sites; MR—Materials and Resources; EA—Energy and Atmosphere; EQ—Indoor Environmental Quality; ID—Innovation in Design Process; WE—Water Efficiency; RP—Regional Priority; LT—Location and Transportation.

2017	*Journal of Civil Engineering and Management*	Desired points at minimum cost in the "optimise energy performance" credit of leed certification [227]	NC v4	EAc2	Revit, Sefaira, Excel
	Automation in Construction	Integrating web map service and building information modelling for location and transportation analysis in green building certification process [228]	NC v4	SSc2, SSc4.1	Revit, Google Maps, LEED Sustainable Sites
2018	*Journal of Cleaner Production*	BIM-based approach for optimising lifecycle costs of sustainable buildings [23]	NC v3	MRc3, MRc4, MRc5, MRc6, MRc7	Revit, Monte Carlo simulation tool, Genetic Algorithms
	Civil Engineering and Environmental Systems	Building information modelling for an automated building sustainability assessment [7]	O+M: Schools	SSc2	Revit, Dyno and Dynamo
	Journal of Technology for Architecture and Environment	MSOT: materials selection optimisation in the LEED v4 protocol—a case study with BIM [229]	NC v4	MRc2, MRC3, MRc4	Revit, Excel
2019	*Journal of Cleaner Production*	Framework for construction system selection based on lifecycle cost and sustainability assessment [230]	Schools v4	MRc1, MRc5	STAAD PRO and eQUEST
	Automation in Construction	A BIM-WMS integrated decision support tool for supply chain management in construction [231]	NC v3	MRc5	Revit, Google Maps
	Building & Environment	Integration of Building Information Modeling and Web Service Application Programming Interface for assessing building surroundings in early design stages [24]	NC v4	LTc4, LTc5	Dynamo, web service API

SS—Sustainable Sites; MR—Materials and Resources; EA—Energy and Atmosphere; EQ—Indoor Environmental Quality; ID—Innovation in Design Process; WE—Water Efficiency; RP—Regional Priority; LT—Location and Transportation.

3.5 Discussion

From the performed analysis, it is possible to validate previous conclusions [196] about the most addressed BSA method. Between 2011 and 2019, 22 papers were published about the practical evaluation of LEED criteria, making it the most-preferred scheme for authors. Only five publications were found regarding BREEAM and one about a BIM-based framework for SBTool. Despite the research period that was set between 2009 and 2019 (the past 10 years), no publications about the topic were found in 2009 and 2010, including review articles.

A clear publication trend is noticed in the past years (Figure 12). Until 2015, the subject of BIM integration in BSA methods was still with low general interest, with a couple of publications per year. However, in 2016 the interest peak was witnessed with the publication of eight related papers. Despite the publication decrease in the following years, since 2018 an increased interest was again noticed, with a positive forecast for the next years. As BIM platforms and tools are continuously being developed, new approaches and processes are created to support building sustainability assessment.

Furthermore, the global concerns about environmental impacts will also promote research about building sustainability, supporting the positive prediction for the subsequent years. According to the Web of Science database, in 2019, five articles were published about the practical assessment of BSA methods with BIM. From those five articles, three were regarding LEED, one about BREEAM and one concerning SBTool.

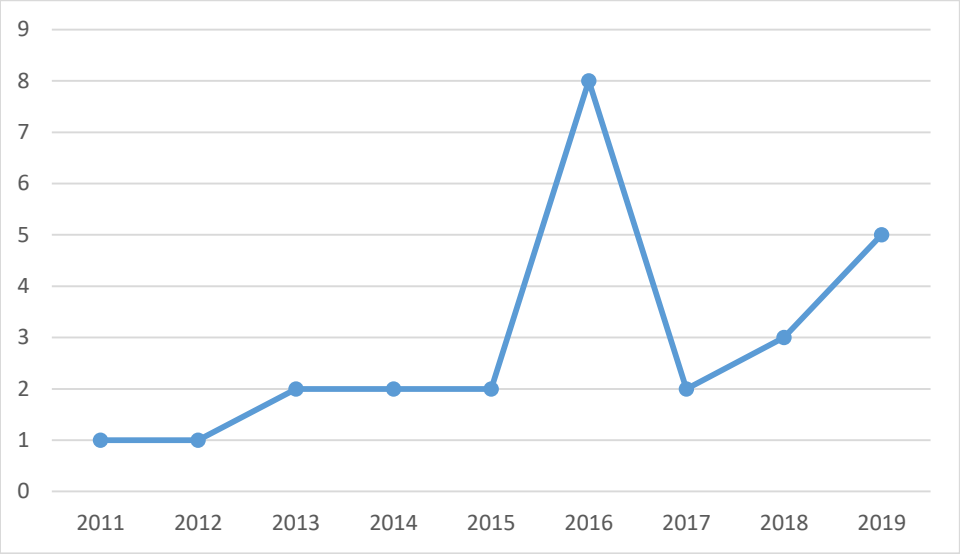


Figure 12 – Total articles published per year (LEED, BREEAM and SBTool)

Regarding the preferred journals, Automation in Construction stands out with six publications (Figure 13)—three on LEED, two on BREEAM and one on SBTool—representing 23,1% of the authors' choices. As some of the most recognised and cited BIM-related articles (such as [16,19,25]) belongs to this journal, new researchers tend to try publications within this journal. Papers in conference proceedings have provided four related articles, representing 15,4%. A significant increase in these types of publications is expected in the following years. Papers that address only one or two criteria are usually insufficient for journal publication. Journal of Cleaner Production and Journal of Architectural Computing are the following ones, both with two publications each (7,7% each). All the other 12 identified journals had one related publication within the research period (3,8% each).

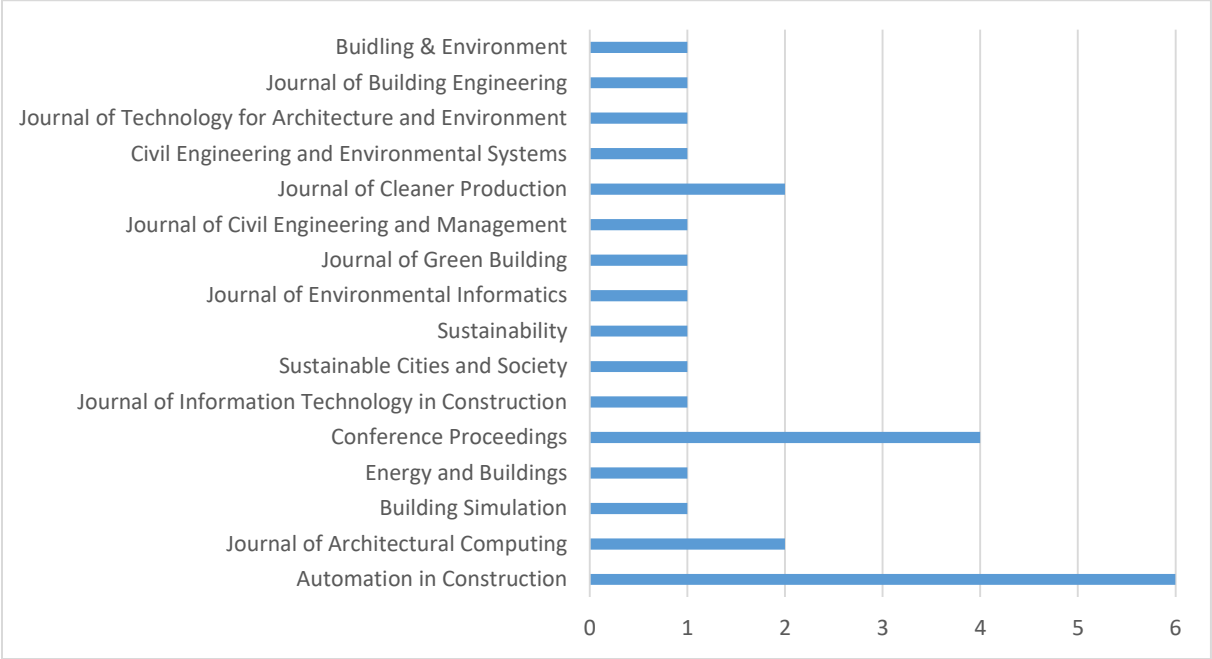


Figure 13 – Preferred journals (BRREAM, LEED and SBTool)

The most commonly assessed categories are materials and energy-related ones, both covered by the BREEAM and LEED versions, as presented in Figure 14. Twelve of the selected articles have addressed, at least, one criterion from those categories. Site-related and indoor environment-related categories are the following ones, approached in 10 and 8 papers, respectively. Overall, these are the most commonly assessed categories with BIM for both schemes. The identified articles have also evaluated the design, water and region-related criteria for LEED and BREEAM. Operation-related criteria were only assessed for the BREEAM method. This type of results was expectable since the existence and development of several BIM energy analysis tools adapted to region-specific contexts (data for energy and indoor environment-related categories). Material-related categories (quantitative data) are usually assessed through schedules, with the support of Microsoft Excel both for LEED and BREEAM. Site-related categories (majority assessed for LEED in eight publications) can benefit from the use of the LEED Sustainable Sites software. It allows designers to perform a full and concise assessment of the Sustainable Sites category from LEED.

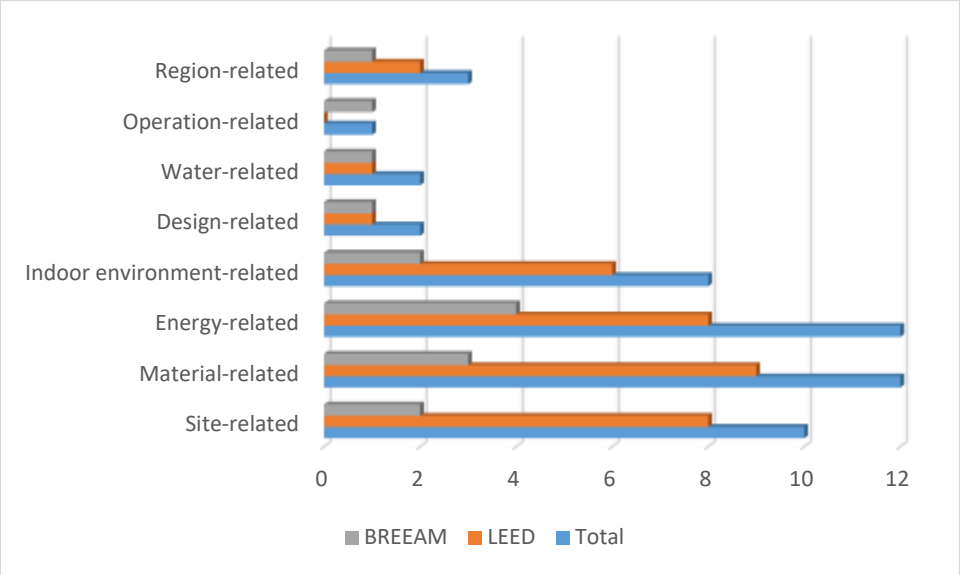


Figure 14 – Commonly assessed categories (BREEAM and LEED)

In total, 33 different software types have been used in LEED and BREEAM publications (25). Figure 15 presents all the software that have been used, at least, in two different studies. A clear trend on the use of Autodesk Revit is noticed, which has been selected in 20 out of 25 publications. Autodesk Revit is mostly used to create and edit BIM models (and then export to specific BIM analysis tools). Still, its capabilities are also used to assess quantitative criteria with the schedule function. Similar conclusions about the trend use were also reached by [205]. Microsoft Excel was the second most used, which was applied in six publications. Twenty-four other software types were also used in the identified publications. On average, 2,8 software types are used in each publication, with a minimum of 1 and a maximum of 8.

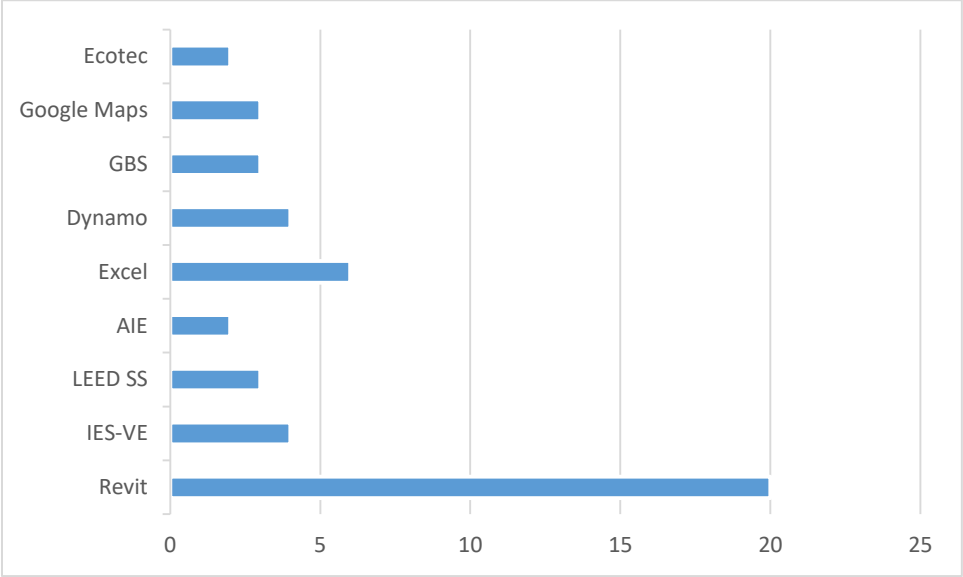


Figure 15 – Commonly used software (BREEAM and LEED)

In what concerns the development of a BIM-based assessment for SBTool, only one publication was identified. In this study, a BIM framework is proposed for the assessment of the Portuguese residential version— SBTool^{PT}-H. This can be related to the need to adapt the international SBTool to region-specific factors. LEED and BREEAM have developed international versions, which can be almost directly applied worldwide.

Nevertheless, based on Carvalho et al. [20] and in the current work, in the SBTool^{PT}-H framework, 24 out of 25 criteria were theoretically identified as possible to be evaluated with the support of BIM. Only one criterion regarding the building user guide (which is a sort of checklist) cannot benefit at all from the BIM methodology.

By practical implementation the theoretical framework, 17 criteria were already validated with the support of different BIM tools. Autodesk Revit and Microsoft Excel themselves can support the evaluation of 12 out of 25 criteria (site, material and indoor environment-related). These are mainly related to quantitative data from the site and building but also about specific building conditions. Five other criteria (energy and indoor environment-related) were also assessed by exporting an Autodesk Revit model for Cype and GBS software.

From the seven criteria that were not validated yet, two region-related criteria can be assessed with similar procedures (Google Maps API) as the ones applied by Chen et al. [226,228] for LEED. The water-related category (two criteria) can be assessed by using Autodesk Revit and GBS to forecast water consumption and

water-saving measures. Three other criteria (LCA-related and economy-related) require the use of Autodesk Revit and Cype Arquimedes (Cype Ingenieros, Alicante, Spain) in combination with other software, such as GBS, Microsoft Excel or Cypetherm REH.

Overall, to assess 24 out of 25 criteria from SBTool^{PT}-H with a BIM-based process, a total of eight different software types are required. However, half of the criteria can be evaluated only by Autodesk Revit and Microsoft Excel. The current practical integration of BIM in SBTool^{PT}-H allows the evaluation of site-related, energy-related, material-related and indoor environment-related categories. These are the same sustainability assessment categories that is possible to assess in LEED and BREEAM.

Figure 16 presents a comparison between the criteria that can be currently assessed with BIM for LEED, BREEAM and SBTool. LEED NC v3 and BREEAM UK Refurbishment and Fit-out 2014 were used as they are the versions with more assessed criteria. For SBTool, both the theoretical proposal and the practical assessment were used to understand the actual and future expected BIM integration. When comparing all the schemes, it is possible to realise that BREEAM UK 2014 has the lowest BIM integration, with only 24% of the criteria being possible to be assessed with BIM. On the other hand, 67% of LEED v3 criteria (excluding Pilot Credits) and 68% of SBTool^{PT}-H criteria can already be evaluated with BIM. According to the theoretical proposal, SBTool^{PT}-H has the potential to be 96% assessed with the support of BIM (seven more criteria than the actual integration). However, these criteria are still requiring further practical validation. These features give enough attractiveness to a BIM-based assessment for SBTool^{PT}-H. The use of BIM will enable the evaluation of, at least, the same percentage of criteria as the most assessed scheme, in identical categories and with fewer resources. However, it must be noticed that SBTool^{PT}-H is the adaptation to a national context of the international scheme. Some adjustments should be made when replicating the BIM framework for other countries and/or building types.

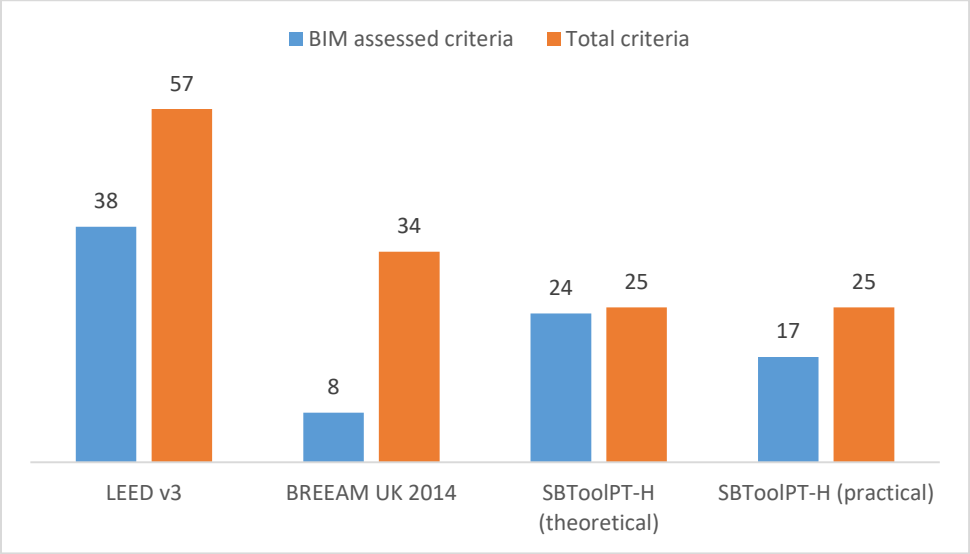


Figure 16 – Number of LEED, BREEAM and SBTool criteria that is possible to assess with BIM

3.6 Conclusions

The construction industry is more and more embracing BIM as societies' and authorities' concerns about the negative impacts of buildings are increasing, with new approaches to improve their sustainability being sought. The application of BIM for sustainability purposes can reduce the number of required resources, as well as improve the overall quality of a building. Therefore, less energy will be required, and fewer emissions will be produced.

BSA methods are also taking advantage of BIM to foster and automate their assessment procedures. The potential of BIM lies in information share among the involved stakeholders and on process efficiency, significantly reducing the necessary time to perform a sustainability assessment. BIM also provides designers with detailed information to compare the impacts of different sustainable solutions and to assess the sustainability of their buildings since the project early stages.

The analysis made in this study has identified that, currently, the BIM method is mostly used to assess LEED sustainability criteria (22 out of 26 studies). With regard to the BSA categories, globally, energy-related and material-related categories have been attended to in 50% of the studies. Site-related categories have been addressed in 42% and indoor environment-related categories in 35%. Concerning the software, overall, Autodesk Revit was commonly used by researchers, adopted in 81% of the identified articles, followed by

Microsoft Excel (27%). This happens due to the Autodesk Revit capacity to create, edit and export/import BIM models. Autodesk Revit is also frequently used when specific API is required or to gather quantitative data from the model. Regarding journals, a pattern was not completely identified. Nevertheless, Automation in Construction has provided 23% of the papers for this research. Conference Proceedings have provided 15% of the publications, and the Journal of Architectural Computing and Journal of Cleaner Production have both provided 7,8%. The remaining publications came from several different journals.

Overall, at least 67% of the LEED criteria and 24% of BREEAM criteria can currently be assessed with BIM. According to the analysis, a theoretical proposal aims to reach a 98% assessment of the SBTool criteria using BIM. At the moment, only 68% is already practically validated. Nevertheless, facing the current BIM integration on the three schemes, SBTool has a great attractiveness potential. It can evaluate the same (or more) criteria than LEED and BREEAM, on identical related categories (energy, materials, site and indoor environment).

Additionally, only by using Autodesk Revit and Microsoft Excel, it is possible to support the assessment of 48% of the SBTool criteria. It constitutes a comprehensive basis for the designer's decision-making since the earlier design stages. Currently, despite the increased use of BIM to assess BSA methods, there is still a knowledge gap between them. BIM is not yet properly oriented towards sustainable building. As BSA methods are based on multi-disciplinary information, there is still a need to use several different BIM tools. Interoperability problems are also commonly found, requiring time for model checking. Moreover, there is a need to create common procedures and standards to support designers in performing a BSA with BIM. Procedures must be established and validated, so designers could achieve reliable and comparable results.

BSA developers are also aware of this paradigm and are continually developing new strategies to integrate BIM into their systems. All the studied methods already have conceptual or developed frameworks, which can be embedded in the BIM workflow, to improve and speed up the assessment procedures. Thus, BSA can be easier articulated with all the other project disciplines, improving information-sharing. From the analysis of the current and future applications of BIM in BSA methods, it is expected that the relation between both will be more reliable, smoother and faster. It will enable the total integration of BSA in the collaborative process and promote the efficient development of high-performance buildings.

This study outcomes reinforce the actual knowledge on the topic and establish a basis for future research. It identified which BSA criteria/categories can already be assessed using BIM and which software is commonly used to implement this process. The attractiveness of a new BIM-automated assessment for SBTool and the replicability of the new approach to the BREEAM and LEED methods was also analysed.

For future research (and based on the limitations of the actual study), more databases as well as more keyword combinations should be included in a more comprehensive review. Furthermore, other BSA methods, such as Green Star, DGNB or BEAM, should be included to create a broader basis and knowledge on the topic.

4. OPTIMISING BUILDING SUSTAINABILITY ASSESSMENT USING BIM

The construction industry is responsible for various negative impacts on the environment leading to an increasing demand for sustainable buildings. There are several BSA methods that allow designers to assess and optimise the building sustainability level. Due to the potential of BIM, the opportunity for BSA methods to adopt and benefit from BIM arises. Despite the benefits in the approach simplification for assessing building sustainability, so far the method has not been used comprehensively in the evaluation process. This paper analyses how using BIM can contribute to optimising BSA methods, focusing on the SBTool^{PT}-H. BIM applicability is assessed and a framework for a BIM-based application – SBTool^{BIM} – is proposed. BIM is still not oriented to sustainable building, but it has great potential. For the SBTool^{PT}-H, results show that it is possible to directly and indirectly assess 24 out of 25 criteria using BIM.

Keywords: Building information modelling (BIM); Building sustainability assessment (BSA); Sustainability; SBTool

This Chapter is based in the article: J.P. Carvalho, L. Bragança, R. Mateus, Optimising building sustainability assessment using BIM, Automation in Construction. 102 (2019) 170–182. https://doi.org/10.1016/J.AUTCON.2019.02.021

4.1 Introduction

4.1.1 Sustainability and building sustainability assessment (BSA) methods

Over recent decades, there has been increasing concern about the impact of buildings on the environment [25,232]. The relation between environmental problems and the construction industry has already been proven and accepted by the scientific community [1,32,33]. Nowadays, the AEC industry is responsible for 40% of the total energy use, 32% of CO_2 emissions and 25% of the generated waste in Europe on an annual basis. In this context, public authorities and the society, in general, have shown particular interest for more sustainable, efficient and ecological buildings and building technologies [39].

The definition of the concept of sustainable development has been widely discussed and updated over the last years [233]. In 1987, the Brundtland report (Our Common Future) established sustainable development as "...the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [37]. This goal was also defined as a priority in the AEC industry since the conventional way to design, build, operate and demolish a building is normally responsible for using large amounts of non-renewable materials, energy and for producing huge amounts of waste [234,235].

Following the two first United Nations main conferences about the Environment and Sustainable Development (Rio de Janeiro, 1992 and Johannesburg, 2002), three main dimensions for sustainable development and construction were established: Environmental dimension, Economic dimension and Social-cultural dimension [233,235].

The first definition of sustainable construction was provided by Charles Kibert in 1994 during the First World Conference on Sustainable Construction (Florida). He defined it as the "responsible creation and management of a healthy building environment, considering the ecological principles and the efficient use of resources". The following 6 principles were established for a sustainable construction [41]:

- Minimise resource consumption;
- Maximise resource reuse;
- Use renewable or recyclable resources;

- Protect the natural environment;
- Create a healthy and non-toxic environment;
- Pursue quality in creating the built environment.

Due to the identified concerns, there was a need to evaluate the impact of buildings on the environment. Therefore, several organisations developed BSA methods in order to implement and spread sustainable measures in construction projects, evaluate and monitor buildings performance and gather information to support designer's decision making in the different stages of a project [6,45]. The use of BSA methods provides an opportunity for design teams to demonstrate the environmental, economic and social benefits of the buildings they design to the local community [53].

During the past two decades, several BSA methods have been developed all over the world by private companies and public organisations or authorities [6]. Some methods were developed with the purpose of being used all over the world and, others were developed or adapted to suit the specific environmental, economic and socio-cultural characteristics of a certain region [8,45]. These methods are usually characterised by assessing a number of partial building features and aggregating the results into an environmental rating or sustainability score [6].

The first known BSA method, BREEAM, dates back to 1990 and it was established by the BRE in the UK. This BSA method together with the SBTool, developed by the iiSBE and LEED, developed by the USGBC, provide the basis for all the other approaches used throughout the world [6,8].

This study aims to evaluate how the BIM methodology can contribute to optimising, simplifying and automating Building Sustainability Assessment methods. The above evaluation will consider a Portuguese BSA method – SBTool^{PT}-H – and a framework for a BIM-based end-user application to optimise the assessment process.

4.1.2 SBTool^{PT}-H

This paper focuses on the analysis of the SBTool^{PT}-H method that resulted from adapting the international Sustainable Building Tool (SBTool) to the context of Portuguese residential buildings. The SBTool is

considered the most comprehensive of all the BSA methods [8] and has the flexibility to be adjusted to the local conditions of each region [6,8]. This feature allows this method to be used to compare the sustainability of buildings from different countries.

The SBTool^{PT}-H has been developed with the purpose of creating a generic methodology to assess the sustainability of existing, new and renovated Portuguese buildings. Besides the sustainability assessment, the method is also targeted to support design teams since the early stages of a project and to raise awareness of construction market's stakeholders about the individual and global benefits of adopting more sustainable solutions [6].

In the SBTool^{PT}-H the three dimensions of sustainable development are considered – Environment, Society and Economy. Each dimension is defined by categories, which in turn is defined by sets of sustainability criteria, as presented in Table 5.

Table 5 – SBTool^{PT}-H list of categories

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

The SBTool^{PT}-H has a total of twenty-five sustainability criteria, which can be found in Table 6. The number and nature of the criteria vary from one category to another according to the priority of sustainable development that is expressed by the category and its importance to the Portuguese context. Each sustainability criterion has a different weight according to the national standards and practices. Each criterion is classified with a quantitative "score" that results from the comparison between two benchmarks: best and conventional sustainability practice. After weighing all the criteria, a final sustainable classification is given to the building [6].

Nowadays, assessing a building using the SBTool^{PT}-H method is a time-consuming and inefficient process, as it requires several data and calculations and is mostly based on an interactive process that seeks to find the design approach that results in the targeted sustainability level. The use of SBTool^{PT}-H is usually incompatible with tight deadlines of the design phase, making it difficult to use. Furthermore, project teams are discouraged from improving the sustainability level of their projects, since any project modification will result in repeating the entire assessment process.

Using BIM can streamline and reduce the time needed to perform an assessment using SBTool^{PT}-H. The faster data assessment and the whole-building analysis allowed by BIM can support designers in decision making when different sustainable measures are introduced. By reducing the time needed to perform the assessment and the integration in a BIM workflow an opportunity will be created to introduce the SBTool^{PT}-H in Portuguese AEC companies. This will promote the development of buildings with higher performance than the conventional practice, thus contributing to a more sustainable built environment.

4.1.3 Building information modelling (BIM)

Construction projects are becoming more difficult and complex [77]. In order to optimise, automate and modernise the traditional processes of the AEC industry, BIM has emerged and it is already changing the current scenario of construction projects. Due to its advantages compared to the traditional design approaches, there are several design teams, in different countries, using this method. Furthermore, some countries are promoting its use as a conventional design practice. For example, in the UK, since the beginning of 2016, it is mandatory to use BIM in all public projects [77].

The BIM concept can be defined as a set of policies, processes, and technologies which conceive a working methodology, making it possible to manage 3D drawings and other project data in a digital format, during the entire building life cycle. It is an integrated process where the functional and physical characteristics of a project are managed, digitally simulating the real construction of the project [15]. This paradigm change will have impacts and benefits not only for the construction sector but also for the society in general, such as better constructions which consume fewer materials, require less human and financial resources and operate more efficiently [88].

4. OPTIMISING BUILDING SUSTAINABILITY ASSESSMENT USING BIM

The essence of BIM lies in the project stakeholders sharing information during the whole building lifecycle. When compared to the traditional approach (Figure 17), which is sequential, disorganised and lacks information sharing, BIM allows each stakeholder to work individually but always connected to a central model, that contains all building related information, namely the architectural and technical/engineering projects. This allows designers to quickly identify errors and incompatibilities, facilitating decision making, as well as optimising costs and time [77].

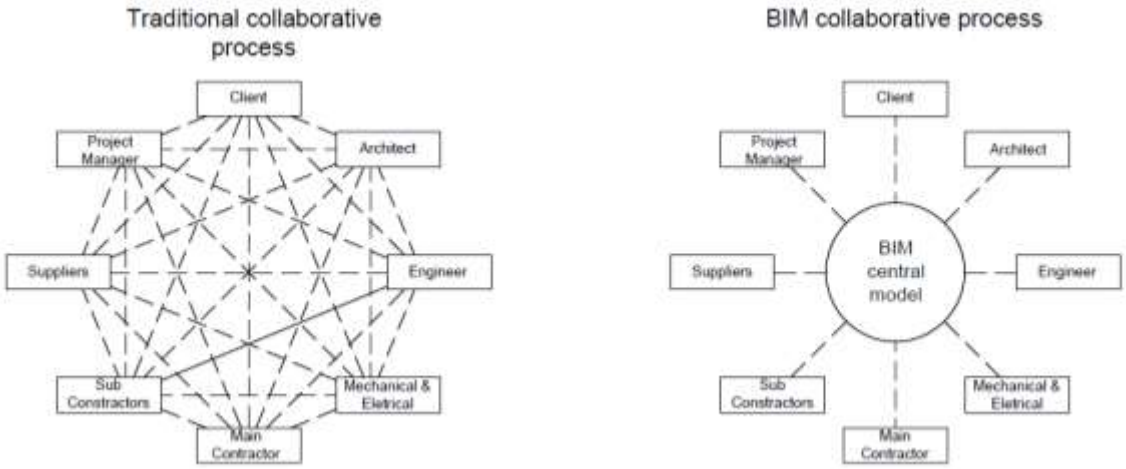


Figure 17 – Traditional approach vs a BIM approach, adapted from [236].

When applied to a construction project, this methodology results in a virtual model (BIM model) that contains all the project characteristics. This model is developed by an object-oriented parametric modulation which means that parameters are defined to characterise the relation between objects (such as beams, columns, ducts, pipes, etc.). Depending on the purpose of the model, objects must have a certain LOD in order to carry out the required operations. The LOD describes the amount and type of information contained in a BIM model. It ranges from LOD 100, the conceptual project model, to LOD 500, the as-built model. To create the virtual model, it is recommended using a BIM platform – software that generates multiple uses information and creates and edits BIM models.

After the modulation, the BIM model can be used throughout the entire building life cycle: visualisation, documentation, management, cost planning, maintenance, operation, detailed analysis, logistics, demolition, etc. [77,94]. Most of these uses require additional BIM tools – different types of software that perform a specific type of analysis. Exchanging information between these tools and the BIM platform can be done in

different ways. Depending on the analysis objective, different exchange file formats such as IFC and gbXML can be used. For some BIM platforms and tools, direct links to connect them already exist.

Despite all the BIM benefits, only 36% of construction companies in Western Europe are using it [157]. This fact can be explained by the difficulty of adopting new methodologies inside companies, mainly due to the change resistance from traditional methods empowered by the lack of knowledge on the subject [237]. Other possible reasons may be the high investment needed in software and professional qualification, which also leads to a productivity loss during the adaptation phase. Interoperability matters between software and the lack of normalisation also contribute negatively to the BIM implementation [94,237,238].

4.1.4 Sustainability of the construction sector and BIM

Due to the need of providing adequate answers to the increasing demand for sustainable buildings, several processes and technologies have been developed with the purpose of reducing energy needs, project costs, construction period, CO_2 emissions, waste, etc. [158,203]. Among those, BIM is a method that is emerging. By allowing multi-disciplinary information to be overlaid and grouped into a single model, BIM creates an excellent opportunity to incorporate sustainable measures throughout the different stages of a project [16].

In 2008, Krygiel and Nies [156] listed the main aspects where BIM can be applied with the purpose of improving the sustainability level of a project:

- Building orientation;
- Building massing;
- Daylight analysis;
- Water harvesting;
- Renewable energy;
- Energy modelling;
- Sustainable materials.

BIM methodology can also offer other capabilities, which can be directly or indirectly linked to sustainability as [206]:

- Automatic and accurate bill of materials and cost estimations;
- Reduction of resource use;
- Construction/deconstruction/rehabilitation waste management;
- Automatic update of project modifications;
- Facilitates the implementation of lean construction techniques.

Based on the capabilities presented before, when using BIM, designers are provided with detailed information in order to select the best sustainable solutions for the building. The use of BIM technologies has the potential to change the AEC traditional practices, allowing for the efficient development of high-performance buildings and, therefore, more sustainable ones. Additionally, a study conducted by Azhar et al [16] on the University of South Carolina Campus, used BIM to improve the sustainability level of the project. The results showed savings of 20% on the total cost of the project (900,000 USD) over a 10-year period.

According to Azhar et al [63], the pre-construction and project phases are the critical ones, where decisions regarding building sustainability are supposed to be made. Since this is also the phase when projects can most benefit from BIM, the influence that it can have on the sustainability of buildings becomes clear.

A study carried out by Wong and Zhou [53] concluded that BSA methods should be used from the preliminary design stages, so that the process of sustainable design will become more efficient and cost-effective, creating a greater impact on the construction project. The same study also proposed that BIM should be used together with a BSA method in order to obtain more reliable and concise results. Despite BIM being extremely useful during the design stages, several authors argue that the BIM method should also be used during the following lifecycle stages of a building, including operation, repair, maintenance, and demolition in order to take full advantage of using it to promote efficient and high-performance buildings [53,238].

Despite all the benefits, the application of BIM in BSA methods has not been clearly defined yet. Some authors point out the following as possible reasons: the lack of data obtained from BIM platforms and tools to be used in the sustainability assessments, as well as the lack of embodied tools to assess the sustainability level, based on the methodology of most common BSA methods [8,16,208]. Therefore, they suggest that future platforms and/or tools should be further developed to cover more parameters and aspects related to sustainable issues.

Nevertheless, some steps have already been implemented by Azhar et al [16], which have developed and validated a conceptual structure to establish the connection between the data gathered by the BIM method and the necessary data for the LEED certification process. The results showed that some of the parameters needed for the sustainability assessment could be directly or indirectly gathered using the results from Autodesk Revit and IESVE software. They also concluded that this process has the capacity to simplify the LEED certification while saving time, costs and resources. However, this study was only applied to 17 out of 29 LEED criteria and 2 out of 3 pre-requisites, and therefore, more comprehensive studies regarding the remaining LEED credits should be carried out. Another study, developed by Wong and Kuan [25], tested the usefulness of the BIM method to obtain the necessary parameters to assess the sustainability level of buildings using the BSA method BEAM Plus. The results showed that 26 out of 56 criteria can be obtained much faster and with fewer resources with the support of BIM when compared to the traditional methods. Based on this context, a review study from Chong et al [90] concluded that future BIM standards should include a set of requirements for a building sustainability assessment.

According to the capabilities mentioned and existing proposals, it is consistent to affirm that BIM can become an essential tool for developing more sustainable buildings, by effectively acting on the main dimensions of sustainable construction: environment, society and economy.

4.1.5 Autodesk Revit's application programming Interface (API)

The API works as an intermediary to different software or applications in order to allow the exchange of information. It defines the procedure to request services or information from a software or application [239,240].

"*APIs are made up of two related elements. The first is a specification that describes how information is exchanged between programs, done in the form of a request for processing and a return of the necessary data. The second is a software interface written to that specification and published in some way for use*" [239]. There are three types of APIs: Local API, the original form, which offers operating systems or middleware services to application programs; Web API, which represents widely used resources such as HTML pages and is assessed using simple HTTP protocol. These APIs are often called REST or RESTful; and Program API, based on Remote Procedure Call technology that makes a remote program component appear to be local to the rest of the software.

Autodesk Revit API is designed to reflect the same user interaction paradigms as the program's Graphical User Interface. It allows the user to program with any NET compliant language including Visual Basic.NET, C# and C++/CLI. Autodesk Revit API is suitable to be used in the following areas [241]:

- Creating add-ins and macros to automate repetitive tasks in the Autodesk Revit user interface;
- Enforcing project design standards by checking for errors automatically;
- Extracting project data for analysis and to generate reports;
- Importing external data to create new elements or parameter values;
- Integrating other applications, including analysis applications, into Autodesk Revit products;
- Creating Autodesk Revit project documentation automatically.

Autodesk Revit API has been generally used in the AEC industry to perform and improve several types of analysis. Oti, Tizani et al [199,242] used Autodesk Revit API to appraise alternative steel-framed building design solutions using multi-criteria performance analysis. The intention was to support structural engineers in assessing the sustainability measures of alternative design solutions at the early design stages. The life cycle approach was used to explore costs, as well as the carbon and ecological footprint.

Pereira and Amorim [243] have created VeR_Arq to improve project quality, information exchange and control. The aim was to automate and systemise a validation procedure to check project biosecurity and legal standards in laboratory animal facility projects.

Kim et al [166] and Kota et al [170] have created two prototypes – Revit2Modelica and Revit2Radiance – for thermal and daylight simulations. The goal was to optimise the flow of information between Revit-Modelica and Revit-Radiance/DAYSIM. Despite the good results achieved, the authors recognised slight differences between Revit2Modelica and the validation engine: The Lawrence Berkeley National Laboratory Modelica Buildings Library, which was validated using the ANSI/ASHRAE Standard 140–2007. Further validation is also needed for Revit2Radiance API prototype as only geometry and materials were checked. The research has identified that BIM does not have all the necessary information for Radiance and DAYSIM. However, it provides options to incorporate the required information.

Jalaei and Jrade [21] have developed a methodology to integrate BIM with LEED-NC to automatically calculate Energy and Atmosphere and Material and Resources credits. Autodesk Revit API was needed to calculate the soft cost that includes the fees required to register and to obtain the LEED certification for the proposed sustainable building. The authors proposed using the Google Maps API to calculate the distance between the location (origin) of the materials suppliers and the location of the project (destination). These authors demonstrated that BIM and LEED integration was feasible but with considerable constraints, as it does not analyse the costs associated with different materials or systems that can be used to attain each credit or point.

Cheng and Ma [180] have created a BIM-based system for estimating and planning CDW in the context of Hong Kong. Autodesk Revit API was used to extract material and volume information and to integrate the information for detailed waste estimation. Automated, fast and accurate waste estimation can be achieved using this system. The system also considered waste recycling and reuse.

Some recognised simulation software, such as DesignBuilder, IESVE or Dynamo also have their own Autodesk Revit API to improve information exchange with Autodesk Revit and saves users' time.

4.2 Methodology

As mentioned before, the aim of this work is to assess how the data provided by BIM platforms and tools can contribute to optimising, simplifying and automating BSA methods. A problem-oriented approach will be used, since the goal is to find a practical solution for a practical problem – developing a method that simplifies and optimises the BSA using the BIM approach. For this purpose, a Portuguese BSA method – SBTool^{PT}-H – will be considered as the case study and will be studied in order to evaluate the potential of BIM in assessing the sustainability criteria. Therefore, a theoretical analysis covering each criterion of the mentioned BSA method will be implemented, focusing on how each one can be directly or indirectly evaluated using one BIM process and how much the assessment process could be optimised and simplified. To achieve this goal, as a first stage, each sustainability criterion will be studied to identify the necessary data for the assessment and the BIM process that could be used to gather the required information. The study will consider Autodesk Revit as a BIM modelling platform since it is one of the most used in the AEC industry. The existing Autodesk Revit APIs (such as DesignBuilder or Dynamo) and the possibility to import and export several format types,

which include IFC and gbXML, will optimise information exchange and software interoperability. Several online tutorials also helped in selecting Autodesk Revit [167,244].

In the following stage, based on the results of the previous analysis, the applicability of BIM to optimise the SBTool^{PT}-H assessment process will be assessed. At the end, an application framework for developing a BIM-based end-user application – SBTool^{BIM} – will be proposed, according to the capabilities and restrictions of BIM and SBTool^{PT}-H. The suggested framework will define the BIM model details for each stage of the evaluation, identify the need to collect external information, the sequence of tasks and processes, the interoperability between platforms/tools, the predicted limitations, and indications on how to obtain and aggregate the results from the BIM platforms and tools. The aim is to match the framework with BIM platform Autodesk Revit, as it is one of the most used BIM platforms, as well as with the API functions, which serve as intermediary links to allow communication between different software. The research procedure is summarised in Figure 18.

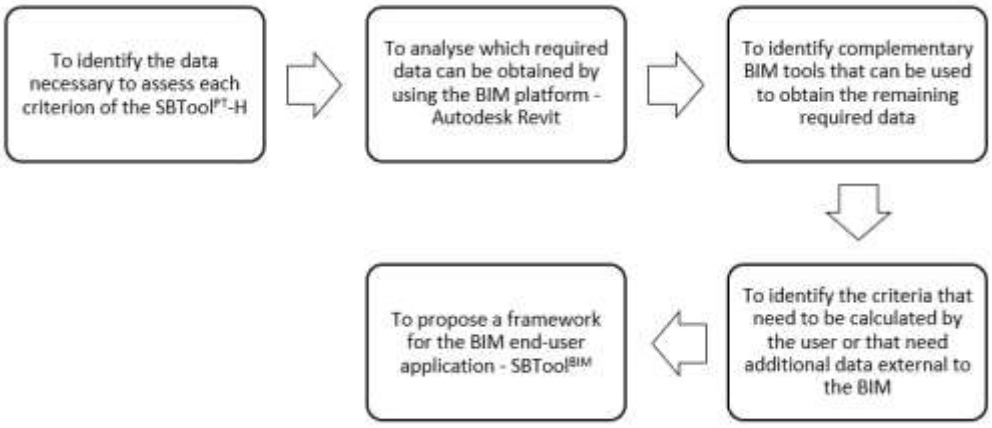


Figure 18 – Research Procedure

4.3 Results and discussion

The BSA method SBTool^{PT}-H is based on assessing 25 sustainability criteria, covering the three dimensions of sustainable development: Environment; Society; and Economy. Table 6 presents an overview of the potential of Autodesk Revit and additional BIM tools to fully (F) or partially (P) evaluate each SBTool^{PT}-H criterion. All the additional BIM tools mentioned can perform specific analysis for the assessment by importing Autodesk Revit models with IFC, gbXML or direct links. Additionally, the necessary model details

and the User Interference (UI) need to collect external information, as regulatory or legislative data are also discussed. Whenever it is not possible to use a BIM methodology/process to aid the criterion evaluation, a way to support designers to access the information that they need is suggested.

Table 6 – SBTool^{PT}-H criteria evaluation

	Criteria	Data needed for SBTool^{PT}-H	Potential BIM use	Analysis Software			UI
				Revit		Additional software	
				F	P		
Environment	P1 – Construction materials embodied environmental impact	Quantity of materials; Life Cycle Assessment (LCA) Database; Environmental Impact quantification.	There is LCA software that can import materials schedules from BIM platforms, such as Autodesk Revit. Job duplication is avoided, and the existence of errors is minimised. Although the use of LCA software within BIM workflow is able to analyse of all the life cycle stages, there are still some restrictions such as interoperability problems or the lack of consideration of the materials transportation-related impacts.		X	SimaPro ATHENA Impact Estimator GABI	
	P2 – Urban density	Total construction area; Site area; Maximum Land Use Index.	Autodesk Revit uses quantity schedules to obtain the necessary areas to calculate the building's land use index rate. Identifying the Maximum Land Use Index allowed by the local Municipal Urban Plan requires the user interference.		X		✓
	P3 – Soil sealing index of the development	Sealed and non-sealed soil area; Site area.	For this criterion, it is necessary to define the sub-regions of the building and external surface areas inside the BIM model. Following this, the property "sealed soil" or "non-sealed soil" must be attributed to each defined sub-region. At the end, a quantity schedule with the previous information can be obtained and exported to an Excel spreadsheet.	X			
	P4 – Use of pre-contaminated land	Pre-contaminated land area; Site area.	This criterion could be assessed using a similar approach to the one presented for P3. Inside the BIM model, a property identifying if it is "pre-contaminated land" or not is attributed to each sub-region of the building plot. At the end, it is very straightforward to obtain the discriminated pre-contaminated and natural areas of the development.	X			
	P5 – Use of native plants	Green area; Native plants area.	To evaluate this criterion, there are 2 different steps: first, using a similar process to the previous criteria, sub-regions are defined with the property "green area" to obtain all the model green area; secondly, the class/family "native plants" need to be created and attributed to each defined sub-region. At the end, a quantity schedule can be produced filtered by class/family.	X			
	P6 – Heat-island effect	Site area; Green area; Reflectance ≥ 60% area.	A similar process to the one presented for the previous criteria can be adopted, defining sub-regions with the properties "green area" and "reflectance ≥ 60% area". At the end, the areas in horizontal projection of the development can be obtained, discriminated by area property.	X			
	P7 – Non-renewable primary energy consumption	Building primary energy needs; Maximum primary energy needs according to the regulation.	The assessment of this criterion uses the method of the Portuguese regulation on the residential buildings energy efficiency (REH). Therefore, BIM platforms or tools must be used that allow designers to consider the Portuguese regulation.			CYPETHERM REH	

UI – User Interference – External information and data to the BIM model must be collected, such as regulatory or legislative data, resource cost, among others.

	Criteria	Data needed for SBTool^{PT}-H	Potential BIM use	Analysis Software				UI
				Revit		Additional software		
				F	P			
Environment	P8 – In-situ energy production from renewables	Building energy performance; Number of occupants; Quantity of energy produced in-situ from renewables.	The quantity of energy produced by local renewable sources in some BIM tools can be estimated. Nevertheless, these tools are limited to certain sources of renewable energy production, namely solar energy, such as photovoltaic and solar thermal energy.			CYPETHERM REH Green Building Studio		
	P9 – Materials and products reused	Total material cost; Total reused material cost.	The cost estimation BIM tools allow designers to gather all the needed information for this criterion. Cost, material bill and a specific schedule regarding the percentage of reused materials in the building can be obtained from the BIM model.		X	Vico		
	P10 – Use of materials with recycled content	Quantity of materials; Percentage of recycled content per material.	The data to calculate the total weight of material can be assessed by quantity schedules with the materials characteristics (density and dimensions). The percentage of recycled content can be discriminated by material in the BIM model. This information can be exported to an Excel spreadsheet to calculate the total weight of material and the total percentage of recycled content. The creation of a database of products with this information is recommended.		X			
	P11 – Use of certified organic materials	Total certified organic material cost; Total organic material cost.	All timber and organic based products (objects in the BIM model) and their certification must be identified. By obtaining quantity schedules filtered by material type, the total quantity of these products can be assessed. The creation of a database of products with this information is recommended.	X				
	P12 – Use of cement substitutes in concrete	Total weight of cement substitutes; Total binder weight used in concrete.	This criterion can be obtained by a similar process from the previous one. The ratio of cement substitutes of the concrete used in the construction must be identified. The information needed can be assessed by extracting a filtered quantity schedule. It is recommended to create a database of different concretes using this information.	X				
	P13 – Waste management during operation	Interior bin type, number and volume; Exterior bin type and distance.	Information regarding the building interior conditions can be assessed by the architectural BIM model. If the neighbourhood is modelled, some external conditions can also be assessed. Nevertheless, the user will always need to collect data about the local waste collection system.		X			✓
	P14 – Water consumption	Number and type of equipment where water is consumed; Equipment water efficiency/consumption.	To assess this criterion, the Mechanical, Electrical, and Plumbing (MEP) model must have performance data related to the equipment where water is used. With a quantity schedule, it is possible to obtain the number of pieces of equipment that consume water. Having the information, the necessary data can be obtained to assess the criterion.		X	Green Building Studio		
	P15 – Reuse of grey and rainwater	Total reused water (grey, rain); Total water consumption.	The water and cost savings can be estimated by adopting rain harvesting and grey water recovery technologies using existing BIM tools.			Green Building Studio		

UI – User Interference – External information and data to the BIM model must be collected, such as regulatory or legislative data, resource cost, among others.

	Criteria	Data needed for SBTool^{PT}-H	Potential BIM use	Analysis Software			UI
				Revit		Additional software	
				F	P		
Social	P16 – Natural ventilation efficiency	Natural ventilated areas (cross flow and single side ventilated area; Total floor and opening areas; Type of window frames.	BIM can only support the evaluation of this criterion by providing information regarding the floor and exterior opening areas. All the other information must be collected and processed by the user.		X		✓
	P17 – Indoor air quality	Quantity of finishing materials containing low VOC; Total quantity of finishing materials with VOC.	To obtain this information from the BIM model, information about the toxicity (e.g. content of Volatile Organic Compounds – VOC) of the finishing materials needs to be input. The necessary data can be obtained to assess this criterion by extracting the material schedule filtered by material type (finishing material) and toxicity level. The creation of a database of products with this information is recommended.	X			
	P18 – Thermal comfort	Local climatic file; The hourly dynamic operational temperature of each indoor area.	BIM tools can perform dynamic energy performance simulations to assess the building operational temperature. However, the user must collect data about the average cumulative exterior temperature in local climatic files and compare it with the temperature profiles of each indoor area to allow the classification of the thermal comfort level.			Green Building Studio IES Virtual Environment DesignBuilder	✓
	P19 – Natural lighting performance	Total glass area; Indoor areas (windows, floor, walls and ceiling) of each room and respective reflectance; Glass characteristics; Visible sky angle.	Several BIM tools allow designers to perform the necessary artificial light and daylight analysis to evaluate this criterion. However, for a correct evaluation, it is fundamental to model the vicinity building shapes and obstructions as well as the glass characteristic. All the necessary data can be assessed using BIM.		X	DAYSIM RADIANCE	
	P20 – Acoustic comfort	Air born sound insulation index of walls; Impact sound insulation from floors; Sound insulation from building integrated system (e.g. lift, air conditioning systems, etc.).	BIM tools allow designers to evaluate the acoustic insulation indexes. Nevertheless, the quantification of the noise annoyance caused by the collective equipment may be difficult to obtain. At the end, the user must collect data regarding the acoustic requirements established by the Portuguese legislation to calculate the acoustic comfort level (RRAE).			EASE CYPESOUND RRAE	✓

UI – User Interference – External information and data to the BIM model must be collected, such as regulatory or legislative data, resource cost, among others.

	Criteria	Data for SBTool^{PT}-H	Potential BIM use	Analysis Software			UI
				Revit		Additional software	
				F	P		
Social	P21 – Accessibility to public transport	Distance to public transportation stations; Types of public transportation that building occupants can use; Schedule of public transportation.	BIM cannot fully support the assessment of this criterion. The only benefit is the connection between the modulation platform and Google Maps to assess the travel distances from the building to the public transportation stops nearby. The neighbourhood modulation can help identify the nearby stops.			Geographic Information Systems (GIS) Google Maps	✓
	P22 – Accessibility to urban amenities	Nearby amenities; Distance of amenities.	As the last criterion, BIM can only aid by measuring the distance between the building and the urban amenities. If the neighbourhood is modelled, the identification of amenities can be simplified. The possible existence of a plug-in that exports the travel distances would permit an automatic evaluation.			Geographic Information Systems (GIS) Google Maps	✓
	P23 – Occupants awareness and education regarding sustainability issues	Having a building user guide available; User guide content.	For now, BIM cannot support the assessment of this criterion. However, it may be possible to include the information needed in future Autodesk Revit Plug-in, where the user defines the content of the building user guide before the model simulation.				✓
Economic	P24 – Capital costs	Building/dwelling selling price; Selling price of ten similar buildings/dwellings located nearby.	BIM is able to estimate the total building costs, supporting the estimation of its selling price. At the end, the user must collect the necessary data to establish the conventional and best practices regarding the market price of similar buildings/dwellings located nearby.		X	Vico Office	✓
	P25 – Operation costs	Energy, water and solid waste unitary costs; Energy and water consumption; Volume of solid waste production.	The BIM model can have information regarding the energy and water consumptions during operation. These data depend on the number of occupants. The user must collect the local unitary energy, water and waste costs.			Green Building Studio CYPETHERM REH DesignBuilder	✓

UI – User Interference – External information and data to the BIM model must be collected, such as regulatory or legislative data, resource cost, among others.

From the analysis in Table 6, it can be concluded that BIM can fully support the evaluation of 15 out of the 25 criteria from the SBTool^{PT}-H. It has also been found that BIM can potentially help to some extent in gathering part of the required information to assess the other 9 remaining criteria. Despite that, for some criteria, it is still necessary to use the user knowledge and efforts to collect some of the required information. It has also been found that the assessment of the sustainability criteria related to amenities and accessibility will not benefit much from BIM if the neighbourhood is not modelled. Concerning Autodesk Revit as a BIM platform, it can provide the necessary information to fully assess 8 criteria and partially assess 3 criteria. As Autodesk Revit allows to create and edit the BIM model, 13 criteria can be partially or fully assessed when the model is exported to the additional software (at least 6).

Based on the previous analysis, Figure 19 presents a possible organisation for the SBTool^{BIM} framework. Figure 19 presents the different stages of the assessment process for the SBTool^{PT}-H, the information flow, as well as the additional software needed when a BIM-based end-user application is used.

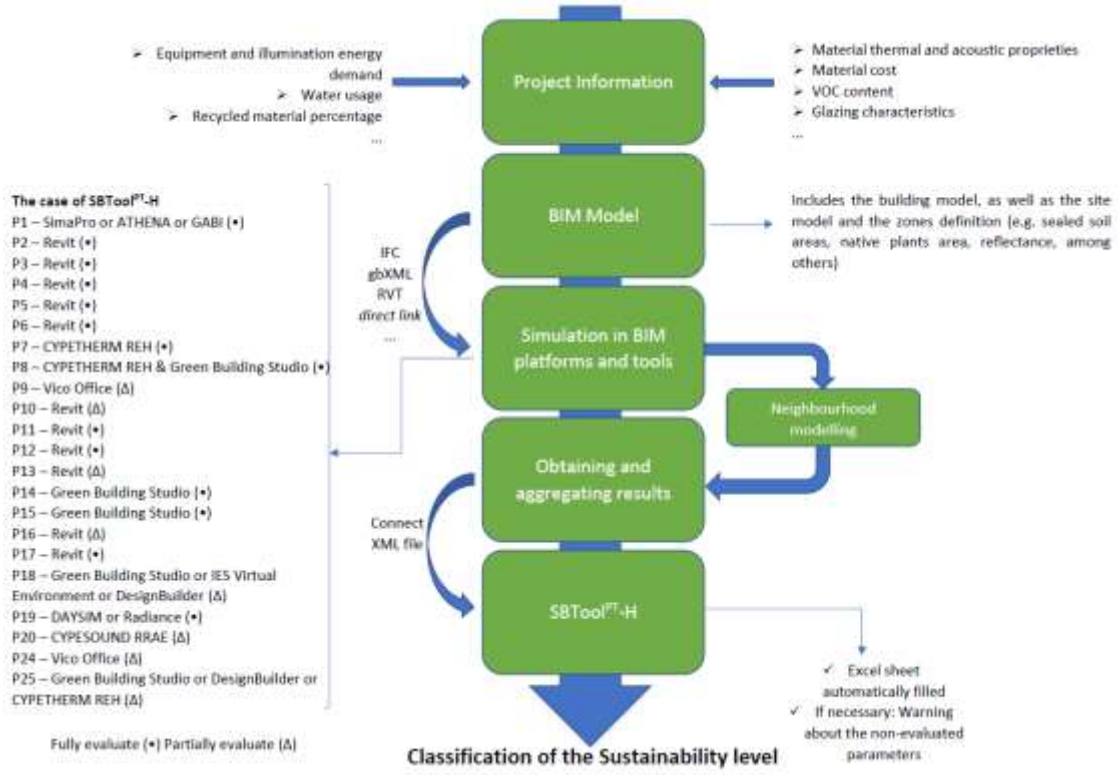


Figure 19 – Basis for SBTool^{BIM} organisation framework

First, it is necessary to collect all the data for the BIM model. Thus, the model will have the necessary information which enables stakeholders to compare the performance and sustainability level of different

design scenarios. It is recommended that stakeholders collect and define all the needed information and guidelines for the project before the modulation stage. By doing so, this phase will be developed smoothly and faster since they will only focus on performing the building assessment.

The second phase is the model creation in a BIM platform, e.g., Autodesk Revit. It includes all the models (Site, Architectural, Structural, and MEP) together with the attributes of the different areas, materials and building elements used.

The third phase is the sustainability criteria assessment (except for the ones that require the neighbourhood modulation). The interoperability between these platforms and tools can be performed using the following data exchange formats: IFC, gbXML and Autodesk Revit direct links. Since these data exchange formats are not fully developed yet, some interoperability problems may occur, and information may not be completely transmitted from one model to another.

To assess the remaining criteria, the fourth phase is the neighbourhood modulation. Using a BIM/GIS software will allow designers to create building shapes and typologies with some specific attributes and details.

When all the data needed to perform the building sustainability assessment is collected, it is necessary to define a method to aggregate the results from different software. This will be the main challenge in this phase. Since it is necessary to use several different software, aggregating and making the results compatible may be a time-consuming process.

Finally, it is necessary to adapt the SBTool^{PT}-H spreadsheet to be connected with a specific spreadsheet that contains the data from the BIM platforms and tools in order to automatically fill the required information to assess the SBTool^{PT}-H criteria. With the conceptual framework for the BIM-based end-user application and with all the necessary software identified, it is possible to start streamlining the core of the BIM-based end-user application – SBTool^{BIM}.

This BIM-based end-user application aims to simplify and speed up the SBTool^{PT}-H assessment process by automating the assessment procedure. At the same time, it will promote the introduction of sustainable measures, as well as support designer's decision making during the project stage. Thus, the typical time-

consuming process of SBTool^{PT}-H assessment will be reduced, encouraging designers to optimise the sustainability of their projects.

The SBTool^{BIM} will be connected to Autodesk Revit and will be developed using the Autodesk Revit API. The SBTool^{BIM} application will be able to extract specific data from the BIM model to assess, whenever possible, the SBTool^{PT}-H criteria. Based on the research, the SBTool^{BIM} will be divided into three different phases, according to the required assessment procedure for the different sustainability criteria, as presented in Table 7. These phases were based on the analysis made in Table 6, where the type of information and the necessary software to assess each sustainability criteria were identified. Phase one gathers all criteria that can be assessed directly from the data that is possible to extract from the virtual model in the BIM platform. Those criteria that need additional and specific external BIM tools to access certain qualitative and quantitative parameters to be used in the BSA method SBTool^{PT}-H are included in the second phase. Finally, those criteria which need information from outside the building boundaries are organised in phase three.

Table 7 – Assessment phases for the SBTool[BIM] framework according to the assessment procedure

Phase	Description	Criteria assessed	Fully or Partially assessed	UI
1	The SBTool[BIM] will only gather information from the Autodesk Revit BIM model, as dimensions and quantities. The user must endow the BIM model with some specific information, such as VOC content, green area, recycled content, etc. The data will be produced, directly and only in Autodesk Revit, by quantity schedules. In this assessment phase, the user does not need to export or import any type of file or perform any kind of analysis. The BIM model must have information regarding architecture, structural and Mechanical-Electrical-Pluming (MEP) disciplines. Criterion P23 cannot be directly supported by BIM. However, SBTool[BIM] will be prepared to ask the user to introduce some information regarding the existence and content of the building user manual.	P2	Fully	✓
		P3	Fully	
		P4	Fully	
		P5	Fully	
		P6	Fully	
		P10	Partially	
		P11	Fully	
		P12	Fully	
		P16	Partially	✓
		P17	Fully	
		P23	-	✓
2	This assessment phase consists of gathering specific information produced by external BIM analysis tools (such as thermal analysis, daylight analysis, LCA, water consumption, costs...). The way that data will be gathered depends on the analysis procedure: if Autodesk Revit direct link is used, SBTool[BIM] will automatically filter the necessary data for the assessment when the analysis is made. If Autodesk Revit direct links are not available, SBTool[BIM] will gather the data when the IFC or gbXML file (with the analysis data) is uploaded to Autodesk Revit.	P1	Fully	
		P7	Fully	
		P8	Fully	
		P9	Partially	
		P14	Fully	
		P15	Fully	
		P18	Partially	✓
		P20	Partially	✓
		P24	Partially	✓
		P25	Partially	✓
3	The last assessment phase can be better applied when the neighbourhood is modelled. If the user has the necessary information, by using BIM-GIS software and Google Maps, some data for the assessment can be collected. Despite that, BIM cannot fully evaluate all these criteria, but the provided information can save the designer's time compared with the manual assessment procedures.	P13	Partially	✓
		P19	Fully	
		P21	Partially	✓
		P22	Fully	✓

SBTool[BIM] can be applied individually in each of the three assessment phases. By doing this the project sustainability level from the beginning of the design will be improved. Before the assessment, the SBTool[BIM] will also ask the user for some input data, namely, the "external information", such as regulatory data or energy and water fares.

After the SBTool[BIM] has all the information for each assessment phase, it will perform the calculations needed or simply extract data for a new Excel Spreadsheet that will be linked to the original SBTool[PT]-H Excel spreadsheet, following the flow presented in Figure 20, Figure 21, Figure 22, for each assessment phase respectively. Thus, whenever the information is available, the SBTool[PT]-H spreadsheet will be automatically

filled and a sustainability score will be calculated. Besides the result being presented in the SBTool^{PT}-H worksheet, the aim is that the sustainability score can also be displayed in Autodesk Revit, so that the user can rapidly assess and improve the sustainability level of the project. When a possible error occurs, or missing information is required, SBTool^{BIM} will display a warning with the error report.

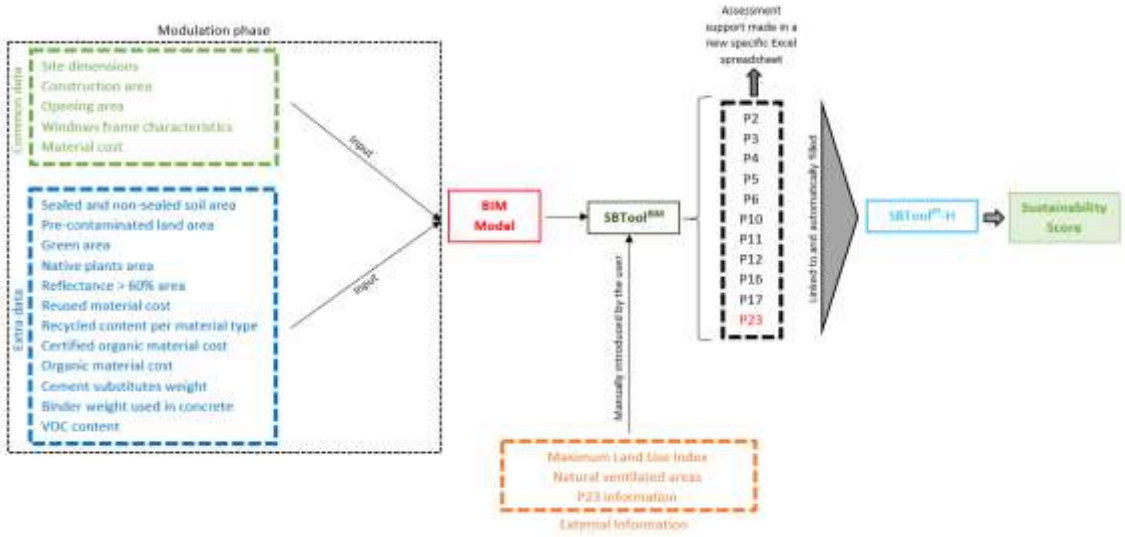


Figure 20 – Information flow – SBTool^{BIM} – Phase 1

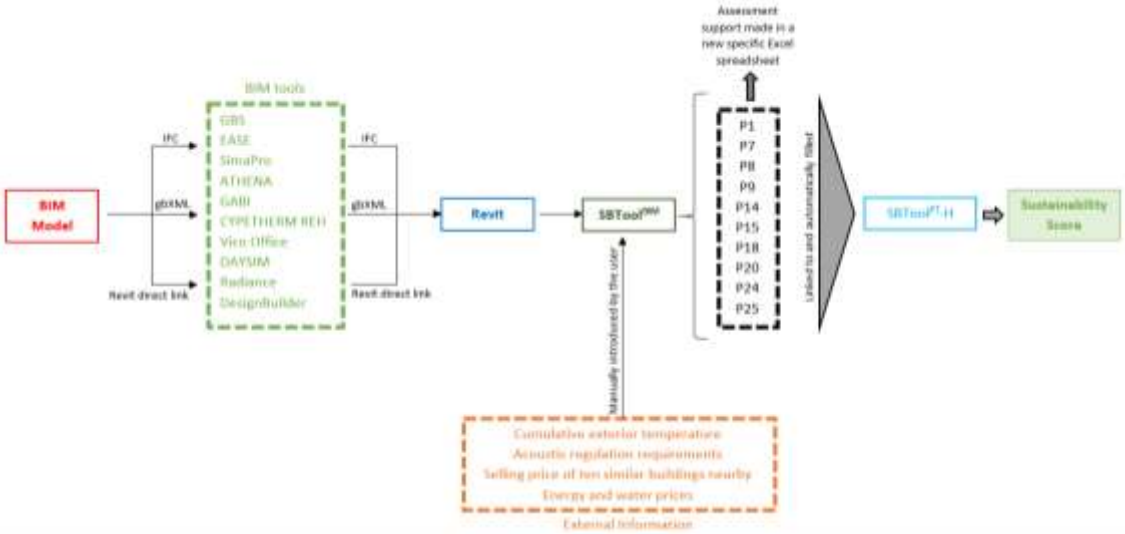


Figure 21 – Information flow – SBTool^{BIM} – Phase 2

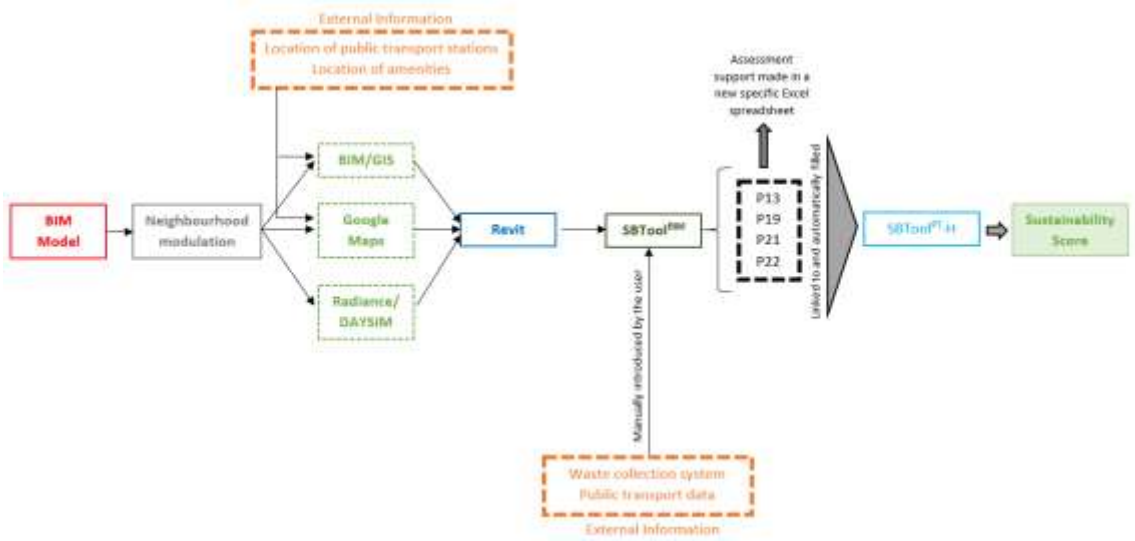


Figure 22 – Information flow – SBTool[BIM] – Phase 3

In the first assessment phase (Figure 20), the Autodesk Revit scheduling function will be used to extract quantitative information from the virtual model. The Autodesk Revit scheduling function provides an overview of different sources of information and quantifies the building materials and elements [25]. By detailing the information of building materials and components, all the dimensional and quantities data for the evaluation of the SBTool[PT]-H criteria P2, P3, P4, P5, P6, P10, P11, P12, P16, and P17 can be assessed. The importance of providing the model and its objects with a certain level of information should be highlighted – such as material and site area characteristics (as listed in the "Extra data" in Figure 20) – in order to extract and perform a correct quantity filtration, both for areas and materials. Otherwise, most of the data, such as native plants area, sealed soil area or the VOC content will be impossible to assess.

As a general example for this phase, Figure 23 presents the assessment procedure for criterion P5 – Use of native plants from category C2 – Land use and biodiversity. As stated, it is essential to detail the virtual model, in Autodesk Revit, with the required information to evaluate the performance at criterion P5, which is related to the percentage of the building site green area occupied by native plants. Then, by using the Autodesk Revit schedule function, a quantity schedule filter by region and native plants can be obtained with the building's total green area and number/area of native plants. Objects representing native plants should be created, detailed and stored in the Autodesk Revit library or the native plant regions should be defined. This schedule is then extracted to a new spreadsheet, which in turn is linked to the SBTool[PT]-H spreadsheet and an assessment for criterion P5 can be reached. As the virtual model objects can have different types of

information, several criteria can be easily and simultaneously assessed by selecting proper filters in the schedule function. Other criterion such as P2 – Urban density (Figure 23) can easily be assessed, as it only requires extracting an area schedule filtered by level. In the case of P2, the user must also manually insert the Maximum Land Use Index defined by the local municipal regulation into the SBTool^{PT}-H spreadsheet.

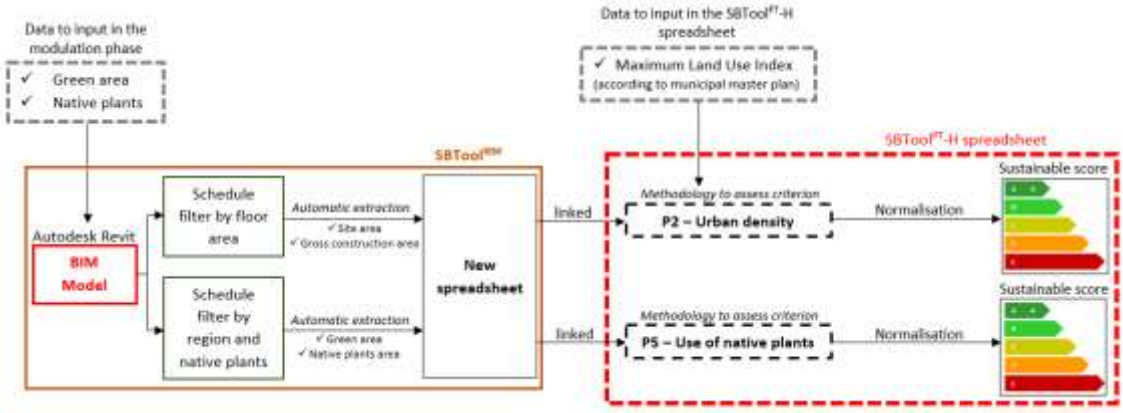


Figure 23 – Assessment of SBTool^{PT}-H criteria P2 and P5

The second assessment phase (Figure 21) consists of gathering qualitative and quantitative information from IFC and gbXML sources and Autodesk Revit direct links, which have been used in specific BIM tools (for sustainability analysis purposes, such as energy performance simulation or acoustic analysis). The SBTool^{BIM} will automatically gather information from Autodesk Revit direct links or when the IFC or gbXML source files are uploaded again in Autodesk Revit. In this phase, the following SBTool^{PT}-H criteria: P1, P7, P8, P9, P14, P15, P18, P20, P24, and P25 can be assessed directly or indirectly.

Concerning the use of BIM tools in this assessment phase, the user will need to input some information directly into those BIM tools (e.g. utility prices or photovoltaic (PV) panel characteristics), as well as prepare the BIM model (in Autodesk Revit) to perform the intended analysis. For instance, to perform thermal analysis, the user must define the energy settings in Autodesk Revit before exporting the file. The criteria assessment in this phase is expected to be a time-consuming process, as different analysis from several BIM tools are required. Besides the fact that the user needs to prepare the BIM model for the BIM tool simulation, the analysis must be performed individually and sequentially, tool by tool. These needs reinforce the fact that BIM software should include more sustainability issues, in order to reduce the number of BIM tools that are necessary to assess a few sustainability criteria from just one BSA method. Further developments are still necessary to reduce the necessary time and tasks for this assessment phase procedure.

4. OPTIMISING BUILDING SUSTAINABILITY ASSESSMENT USING BIM

As an assessment example, the evaluation procedure for category C3 – Energy Efficiency (which includes criteria P7 – Non-renewable primary energy consumption and P8 – In-situ energy production from renewables) is presented in Figure 24. By exporting the virtual model IFC file from Autodesk Revit to an additional BIM tool for energy analysis – CYPETHERM REH – the heating, cooling, domestic hot water (DHW) and primary energy needs can be assessed, according to the Portuguese regulation (as well as the regulation limit values). In this case, before the model simulation in CYPETHERM REH, the renewable energy production needs to be known, which must be done in GBS. Having obtained this data, together with the building area and the number of occupants (extracted from the virtual model), all the required information to assess the criteria P7 and P8 is available.

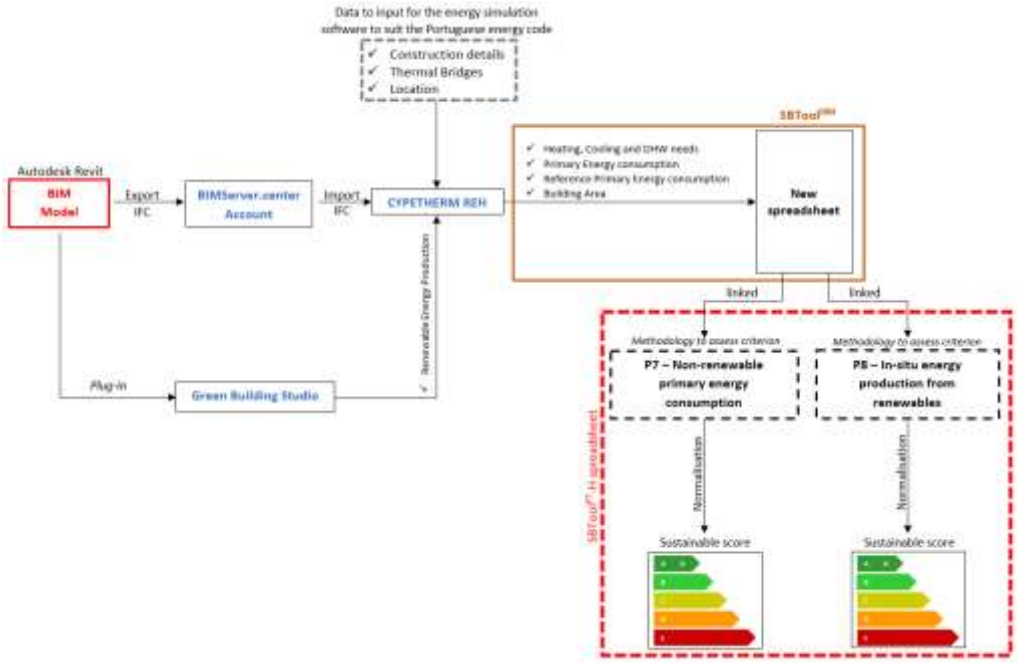


Figure 24 – Assessment of SBTool[PT]-H criteria P7 and P8

The third assessment phase (Figure 22) focuses on the evaluation of the building surrounding environment and neighbourhood quality, to support the assessment of criteria P13, P19, P21, and P22. Most of these criteria will require the knowledge of some necessary information, for example, the distance to the recycling bins, the distances between the building and nearby amenities and public transport stations or the public transport frequency. Google Maps Revit plug-in is expected to be used to evaluate distances (in meters and in time). To do that, the user will need to define the building location and introduce the location of public transport stations and urban amenities.

Figure 25 presents an assessment example for this phase, focusing on criteria P21 – Accessibility to public transport and P22 – Accessibility to urban amenities from category C7 – Accessibilities. To find out the distances and travel times between the building and nearby transport stations and amenities, a similar process to the one developed by Jalaei and Jrade [245] will be used. The SBTool^{BIM} will be linked to Google Maps and by introducing the destination addresses (e.g. postal codes), the application will connect with Google Maps and present the distance (in meters) and travel time (in minutes) from the building. This data will support the assessment of the selected criteria.

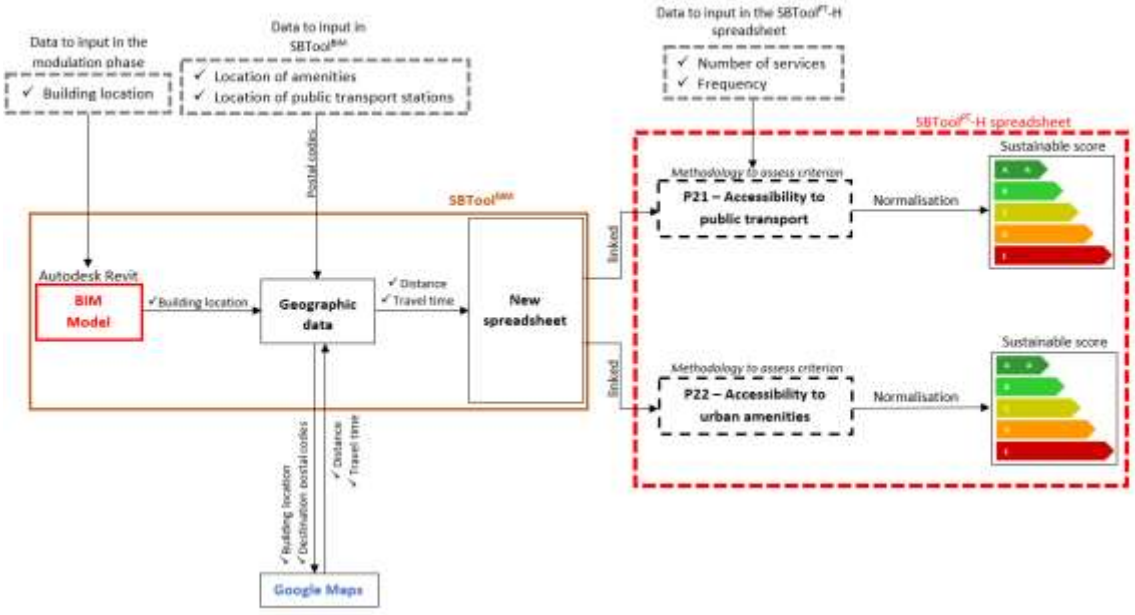


Figure 25 – Assessment of SBTool^{PT}-H criteria P21 and P22

As presented earlier, some of the criteria cannot be fully assessed by using BIM. Whenever this happens, the SBTool^{BIM} will fill in the SBTool^{PT}-H worksheet with the available data and alert the user, indicating which criteria were not assessed and what information is still missing. Then, the user must collect the missing data and make the necessary calculations to finalise the criteria assessment. Nevertheless, it is expected that the assessment of all the sustainability criteria will be improved somehow, in terms of time, by using SBTool^{BIM}.

Regarding the stage at which to perform the sustainability assessment, it should be done as soon as possible during the project design phases, so designers can start making changes to optimise the building performance from the first choices. However, as different criteria must be evaluated in different project

phases with different procedures, a comprehensive sustainability assessment will only be possible to obtain at a later stage of the process.

4.4 Conclusions

The use of the BIM method in the AEC industry may be an essential path to optimise building performance and reduce the environmental impacts of the industry in the future. Given the demand for better and sustainable buildings, it is important to create ways to integrate and automate the BSA methods within the BIM context. Therefore, project teams will be able to identify and compare different sustainable design scenarios at an early stage of the project, without spending too much time, money and other resources.

Despite the existing studies in some BSA methods, a technique to use BIM in BSA has not yet been established. According to the results presented in this paper, BIM documentation can be used to directly or indirectly evaluate most of the SBTool^{PT}-H sustainability criteria in an automatic and faster way when compared to the traditional processes. The results have shown that 8 SBTool^{PT}-H criteria can be fully assessed and 3 partially assessed only by using Autodesk Revit. These are mainly concerning dimensional and quantity criteria and are obtained by using the scheduling function that is one of the main advantages of the BIM to simplify the assessment by using this BSA method. It has also been found that for 13 criteria additional software is still necessary to provide all or part of the required data for the assessment.

As BSA methods are based on a set of different sustainability criteria, different BIM tools are still needed to assess the required information, which can be a barrier to using BIM to assess the different sustainability criteria. Actual BIM software is not adapted to assess many sustainability criteria. Thus, the need for a plug-in that includes the necessary software and aggregates all the results from BIM software arises. However, as different BSA methods have different sustainability criteria, a specific plug-in oriented to each BSA method is necessary to optimise and automate the assessment process.

Overall, it was found that even though BIM is still not oriented to building sustainability, it has great potential. Both BIM software and plug-ins still need improvements and further developments in this field in order to be suitable to use for BSA purposes. The use of fewer BIM software to evaluate one BSA method and an easier way to assess many sustainability criteria at once are still necessary to improve time-efficiency. These conclusions are in line with similar studies for other BSA methods, presented in the state-of-art analysis,

which pointed out the lack of data provided by the BIM platforms and tools to be used in the sustainability assessments.

With the development of SBTool^{BIM}, major contributions are expected to improve the sustainability level of the buildings. As this is a BIM-based method, both BIM integration benefits and the benefits of using BSA methods will be achievable for projects and companies. As BSA is typically made in later stages and apart from the conventional design phases, project changes to improve buildings sustainability are expensive and usually unfeasible. By integrating BSA into this kind of approach, the sustainability assessment will be articulated with all the other project disciplines, improving information-sharing among stakeholders. Designers will be able to assess their buildings sustainability from the early stages of the project. By supporting designer's decision-making, sustainable measures can be introduced and compared with lower costs and resources consumption in a shorter period of time.

Nevertheless, some restrictions can be observed in the proposed framework for the SBTool^{BIM} that need to be overcome in order to automate the full evaluation process. Some of these restrictions are the neighbourhood modulation and the technique to aggregate the results from several different software, which may not be compatible among them.

It must be noted that maximum benefits can only be achieved when the construction companies have the knowledge or have integrated BIM in their processes. Otherwise, there will be an adaptation period, where the benefits will not be so noticeable.

5. SUSTAINABLE BUILDING DESIGN: ANALYSING THE FEASIBILITY OF BIM PLATFORMS TO SUPPORT PRACTICAL BUILDING SUSTAINABILITY ASSESSMENT

Due to the time-consuming and complicated process of performing BSA, this is usually incompatible with construction companies' deadlines. With the emergence of BIM in the construction industry, the opportunity for BSA methods to adopt and benefit from BIM arises. Following a previous study, this paper aims to put in practice a proposed theoretical approach to facilitate the implementation of the BSA since the preliminary design stages using, as an example, the Portuguese SBTool^{PT}-H method. Therefore, this paper analyses how BIM platforms can contribute to optimising the BSA evaluation. To achieve this goal, a case study was modelled and characterised in Autodesk Revit and, tailored parameters were created to support the assessment. The results show that Autodesk Revit can support the evaluation of 13 SBTool^{PT}-H sustainability criteria, in a faster and automated way when faced with the traditional assessment process. The capabilities of BIM platforms and its wider use by designers can significantly contribute to the integration of BSA methods in the BIM collaborative process, thus contributing to a more sustainable built environment.

Keywords: Building information modelling (BIM); Building sustainability assessment (BSA); Sustainability; SBTool

This Chapter is based in the article: J.P. Carvalho, L. Bragança, R. Mateus, Sustainable building design: Analysing the feasibility of BIM platforms to support practical building sustainability assessment. *Computers in Industry* 127 (2021) 103400. https://doi.org/10.1016/j.compind.2021.103400

5. SUSTAINABLE BUILDING DESIGN: ANALYSING THE FEASIBILITY OF BIM PLATFORMS TO SUPPORT PRACTICAL BUILDING SUSTAINABILITY ASSESSMENT

5.1 Introduction

Facing the need to achieve more efficient and sustainable buildings, designers are increasingly looking for ways to minimise the environmental impact and the energy consumption of buildings [53,202]. To evaluate and monitor the environmental performance of buildings and to gather information to support designer's decision making, BSA methods have been developed [6,10,45]. BSA methods are usually characterised by assessing several partial building features and aggregating the results into an environmental rating or sustainability score. Among the most known methods are BREEAM from the BRE, LEED developed by the USGBC and the SBTool, developed by the iiSBE. These are the most recognised BSA methods and, together, they provide the basis for all the other approaches used throughout the world [6,7], which were developed to meet specific local aspects and conditions [55].

With the increasing demand for better and efficient construction projects, BIM has emerged to support designers in managing all the projects data [77]. By allowing multi-disciplinary information to be overlaid into a single model, BIM creates the opportunity to include and analyse sustainable measures in different project stages [16]. Designers are supported with detailed information to compare and select the best sustainable solutions to their projects, allowing for the efficient development of sustainable and high-performance buildings [14,19,26].

According to several authors [63,64,80], sustainable measures should be analysed and integrated during the pre-construction and, preferably, during the preliminary design phases. These are also the phases when BIM can have more impact, enhancing the influence that it can have on building sustainability [60]. The possibility to automate and optimise the BSA process with BIM, could stimulate designers to increase the use of these methods and improve buildings sustainability. BSA methods exploit the full potential of BIM, since multi-disciplinary data must be assessed, with different procedures and software [60,189].

Up to date, preparing all the documentation and perform a BSA is considered a complicated and time-consuming process. This situation is usually unbearable with the project companies' deadlines, and often inaccurate data is used, or there is a loss of essential data during the assessment process [10,25,246]. Additionally, when a modification is done in the project to improve building sustainability, all the assessment process must be repeated, discouraging designers from implementing it.

5. SUSTAINABLE BUILDING DESIGN: ANALYSING THE FEASIBILITY OF BIM PLATFORMS TO SUPPORT PRACTICAL BUILDING SUSTAINABILITY ASSESSMENT

Based on the actual opportunity to integrate BSA methods in BIM, this paper analysis the capability of the BIM platform Autodesk Revit to support the assessment of a set of sustainability criteria from the BSA method SBTool^{PT}-H. A previous study developed by the same authors [8] disclosed, in a theoretical approach, a set of criteria that were possible to be assisted by the use of Autodesk Revit. In this research, the identified process to assess those criteria will be practically tested to verify and adapt the theoretical analysis. A case study was selected, modelled and characterised in Autodesk Revit to achieve this objective. After, the quantity schedules with the required data were extracted and linked to the SBTool^{PT}-H calculation process to allow an automatic assessment of the criteria that was previously identified.

5.1.1 SBTool^{PT}-H

This study will focus the analysis on the BSA method SBTool^{PT}-H, which has resulted from the adaptation of the international SBTool method to the context of Portuguese residential buildings. The SBTool is considered one of the most comprehensive BSA methods due to its flexibility to be adjusted to the local conditions of each region [6,8]. Thus, sustainability scores of buildings from different countries can be compared. This approach also meets with Mahmoud et al. [57] suggestion to develop a common global method to allow such comparisons between buildings form different locations. Nowadays, SBTool has already influenced several national and other rating systems, which have been introduced in countries as Spain, Italy, Japan, Czech Republic, Germany or South Korea. In Portugal, SBTool has custom versions for residential, hospital, hotels and service buildings, as well as for urban areas [6,69,70].

The main aim of the Portuguese residential version – SBTool^{PT}-H – was to create a generic methodology to assess the sustainability of existing, new and renovated buildings and, to raise awareness of construction market stakeholders about the benefits of adopting more sustainable solutions [6]. SBTool^{PT}-H is divided into three dimensions – Environment, Society and Economy – which in turn are divided into sustainability categories that cover twenty-five sustainability criteria, as presented in Table 8. The SBTool^{PT}-H under-study criteria are also presented.

Table 8 – SBTool^{PT}-H list of categories

Dimension	Category	Number of criteria	Number of criteria in study	Dimension weight (%)
Environment	C1 – Climate change and outdoor air quality	1	1	40
	C2 – Land use and biodiversity	5	5	
	C3 – Energy Efficiency	2	0	
	C4 – Materials and waste management	5	5	
	C5 – Water efficiency	2	0	
Social	C6 – Occupant's health and comfort	5	2	30
	C7 – Accessibilities	2	0	
	C8 – Education and awareness of sustainability	1	0	
Economic	C9 – Life-cycle costs	2	0	30

Each sustainability criterion 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 two benchmarks: best and conventional national practice. Then, the "score" is normalised and converted into a qualitative assessment scale by using equation (1). This conversion is made to establish a dimensionless value and to avoid scale aggregation effects, and problems such as "bigger is better" or "bigger is worse" related to the comprehensive list of sustainability issues considered. In the normalised "score", 0 corresponds to the conventional national practice and 1 to the national best practice. This normalised classification is still converted into a qualitative scale, from E to A+, where D corresponds to the conventional practice and A to the best practice, according to Table 9.

Table 9 – SBTool^{PT}-H qualitative scale

Level	Conditions
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	$\overline{P} < 0{,}00$

After weighing all the sustainability criteria, a final sustainable classification is given to the building [6].

$$\overline{P_i} = \frac{P_i - P_{*i}}{P_i^* - P_{*i}} \ \forall_i \qquad (1)$$

In equation 1, $\overline{P_i}$ is the result of the normalisation of the parameter i, P_i is the value resulting from the quantification and P_i^* and P_{*i} are the benchmarks of the parameter i, representing the best and conventional practice levels, respectively.

To date, assessing manually the sustainability level of building using the SBTool^{PT}-H method is a tedious and inefficient process, as it requires a lot of data and calculations, and it is usually based on an interactive process that pursues to find the best building design to optimise the building sustainability level. The use of SBTool^{PT}-H is also generally incompatible with the short deadlines of a project, making it difficult to implement. As result, project teams are discouraged to improve the sustainability level of their projects, as any project modification will lead to the repetition of the assessment process.

5.1.2 Building Information Modelling (BIM)

BIM can be described as a set of policies, processes, and technologies that conceive a working methodology to manage the project data and the 3D model during the building life cycle [15]. BIM will overcome some incompatibilities between different project disciplines and benefit the general society, with better and efficient constructions [88]. BIM will create the opportunity to virtually construct the whole building model through simulations and analysis before the construction itself onsite [81,90,91]. By improving information share

and collaboration between stakeholders, BIM allows designers to quickly identify errors and incompatibilities, facilitating decision-making, optimising costs and time [77,247]. BIM can impact throughout all the building life cycle as in visualisation, documentation, management, cost planning, maintenance, operation, detailed analysis, logistics or demolition [77,94,111].

The application of BIM results in a data-rich 3D virtual model [103,180]. The model is developed by an object-oriented parametric modelling, where parameters are defined to characterise the relation between the objects. Depending on the model purpose, objects must have a certain set of characteristics and data to carry out the intended analysis [248]. Those characteristics are usually categorised by the model LOD, which "*specify and articulate with a high level of clarity the content and reliability*" of a BIM model at different phases of the project [106]. This classification identifies the specific minimum content requirements, and it is defined based on the objects graphic and data information [14]. The LOD ranges from 100, the conceptual project model, to 500, the as-built model.

It is necessary to use a BIM platform to create the virtual model, which generate multiple uses information and allow to create and edit BIM models. On the other hand, to use most of the BIM approach capabilities, it is necessary to export the model to additional BIM tools to perform a specific type of analysis, as energy performance or life cycle analysis. The information exchange between software can be made in different ways, and the most common is using the IFC model. The IFC model specification is a "platform-neutral, object-based structured file format" that describes building and construction industry data, registered by ISO as an official International Standard [26]. Other file formats, as the gbXML, are also emerging, mostly to exchange data for green and sustainable analysis, due to its capacity to incorporate thermal descriptive data [81].

When applied to improve buildings sustainability, BIM can act in several fields, as building orientation and massing, daylight analysis, water harvesting, energy analysis and sustainable materials selection [156]. Additionally, other BIM features as rigorous quantities take-offs, automatic modification updates and information share can contribute to reducing resources use and construction cost, leading to significant savings.

5.1.3 BIM and BSA methods

BIM provides an effective platform for attaining compliance with sustainability rating criteria. Recently, the application of BIM-based technologies in sustainability certification has increased researcher's attention [17,19,25]. Carvalho et al. [60] have identified LEED method as the most common used on BIM-related research. Azhar et al. [16], have validated a conceptual structure which establishes the connection between the BIM method and the LEED certification process. Results show that part of the required parameters for the sustainability assessment can be directly or indirectly gathered from Autodesk Revit and IESVE software. The conceptual structure has simplified the LEED certification process and, simultaneous has saved different resources. However, the study was only applied to 17 out of 29 LEED criteria and 2 out of 3 pre-requisites. More recently, Jalaei and Jrade [21] have assessed Energy and Atmosphere and Material and Resources credits from LEED v3 using only the Autodesk Revit. Li et al. [24] have used Autodesk Revit, Dynamo and a Web map service to assess two Location and Transportation credits from LEED v4. In other BSA methods, Wong and Kuan [25] have used BIM to gather the required data to assess the sustainability level of buildings with BEAM Plus method (also considering Autodesk Revit as the BIM platform). The results proved that 26 out of 56 criteria could be rapidly assessed with fewer resources when supported by BIM. Due to the model data automatic update, BIM enhances the accuracy of BEAM Plus submissions with the latest information. Gandhi and Jupp [200] have applied BIM information technology to support the Australian Green Star Building Certification assessment of a commercial office. Results show that it is theoretically possible to support the evaluation of 88 % of the BSA credits. However, when applied to a project, only 66 % of the credits were addressed using BIM, pointed out that the capabilities of BIM technologies were not used to their full potential. They conclude that it is essential to develop BIM execution and coordination plans which address the requirements of green building certification. A conceptual framework developed by GhaffarianHoseini et al. [201] for BIM integration in the New Zeeland Green Star certification, suggests that 75 % of the criteria can be supported by BIM, highlighting the importance of creating proper guidelines for successful integration. A study from Edwards et al. [22] have identified eight BIM-based energy tools that can be used to assess credits from BREEAM and LEED on different categories. A theoretical analysis of Liu et al. [202] have identified that almost 40 % of the Singapore Green Mark Non-Residential Buildings 2015 can be easily assessed with BIM and building performance analysis tools. With this basis, a review study

from Chong et al. [90], concluded that future BIM standards should embrace a set of requirements for a building sustainability assessment.

Overall, the authors agree that BIM is still not oriented and properly used to support sustainable building design, but it has great potential [20,26]. Despite all the benefits in the approach simplification, so far, BIM has not been used comprehensively in the evaluation process of BSA methods. Santos et al. [17] argue that there is a lack of research that considers all dimensions of sustainability. Together with several authors, they suggest that BIM software and exchange file formats (as IFC and gbXML) still needs further developments to include more sustainable issues [16,17,90,208]. Furthermore, there is an interoperability gap between BIM platforms and tools, with some information lost during the model exportation, requiring time for model checking and corrections. Design teams also need to be more qualified and owners aware of this matter. Nevertheless, BIM is considered an essential tool for sustainable construction and is expected to be in extensive use in the near future [19].

5.1.4 Autodesk Revit

Several studies have already stated Autodesk Revit as one of the most popular BIM platforms used in the construction industry [60,81,167]. On a review study from Eleftheriadis et al. [205], Autodesk Revit was chosen as BIM platform in 24 out of the 34 articles about life cycle analysis, energy analysis and sustainable certification. Autodesk Revit interoperability capabilities allow stakeholders to use several other BIM specific simulation tools, without modelling the building geometry and information twice. In face-to-face interviews from Wong and Kuan [25] with BIM and sustainable design experts, Autodesk Revit was pointed out as the most appropriate BIM software for assisting BEAM Plus submission. The scheduling function in Revit provides an overview of different sources of information, quantifies the building materials and elements, and support the assessment process of different sustainable rating systems Wong and Kuan [25]. A systematic review from Carvalho et al. [60] have identified that Autodesk Revit has been used in 80 % of the studies relating BIM with BSA. Autodesk Revit contains relevant parameters to sustainable design which can be automatically activated during the design process. Personalised parameters, as green building properties, can also be created and stored as project parameters [246]. Autodesk Revit also provides an API that allow users to extend the capabilities of an existing application and reflects the same user interaction paradigms as the

program Graphical User Interface [180,239,241]. Until 2008, more than 150 specialised API were made for Autodesk Revit in different construction fields, including add-ons for regulation validation, energy and daylight analysis, waste estimation or even applications to improve information exchange between recognised software as IESVE or Dynamo with Autodesk Revit [81,166,170,180,243,249].

5.2 Material and methods

On a previous study [20], the theoretical possibility to use Autodesk Revit to assess several sustainability criteria from the SBTool^{PT}-H method was verified. The theoretical proposal has disclosed that it is possible to fully assess 7 sustainability criteria and indirectly assess 5 sustainability criteria only by using Autodesk Revit. Furthermore, with additional BIM tools, it is possible to fully or partially assess other 5 sustainability criteria. Thus, the aim of this paper is to verify, in practice, the theoretical applicability of Autodesk Revit to assess those criteria that only require this software, as well as the UI. Table 10 presents the selected criteria for the study and the required data for the assessment. A case study was modelled and characterised to perform the evaluation. The case study has specific data to assess the selected sustainability criteria in Autodesk Revit 2018. The model contains both the site, the architectural and the structural models, which will have information regarding the characteristics presented in Table 10. This data will be assigned to the model objects and elements using the “Shared Parameters”, which allow personalising the type of data contained in each model object and element.

Table 10 – Sustainability criteria of SBTool^{PT}-H under analysis

	Criteria	Data needed for SBTool^{PT}-H	Revit		UI
			F	P	
Environment	P1 – Construction materials embodied environmental impacts	Materials quantities; LCIA impacts.		X	
	P2 – Urban density	Total construction area; Site area; Maximum Land Use Regulation index.		X	✓
	P3 – Soil sealing index of the development	Sealed and non-sealed soil area; Site area.	X		
	P4 – Use of pre-contaminated land	Pre-contaminated land area; Site area.	X		
	P5 – Use of native plants	Green area; Native plants area.	X		
	P6 – Heat-island effect	Site area; Green area; Area with reflectance ≥ 60%.	X		
	P9 – Materials and products reused	Total material cost; Total reused material cost.	X		
	P10 – Use of materials with recycled content	Materials quantities; Percentage of recycled content per material.		X	
	P11 – Use of certified organic materials	Total certified organic material cost; Total organic material cost.	X		
	P12 – Use of cement substitutes in concrete	Total weight of cement substitutes; Total binder weight used in concrete.	X		
	P13 – Waste management during operation	Interior bins type, number and volume; Exterior bins type and distance.		X	✓
Social	P16 – Natural ventilation efficiency	Natural ventilated areas (crossflow and single side ventilated area); Total floor and openings areas; Type of window frames.		X	✓
	P17 – Indoor air quality	Quantity of finishing materials containing low VOC; Total quantity of finishing materials with VOC.	X		

All the model objects will need to be correctly and identically characterised to enable the aggregation of all data in quantity schedules. After modelling, Autodesk Revit quantity schedules will be used to filter and extract the necessary information for the assessment. Then, schedules will be linked to the SBTool^{PT}-H excel spreadsheet to automate and reach an assessment for the sustainability criteria under study. The research methodology and all the necessary data to characterise the model is summarised in Figure 26.

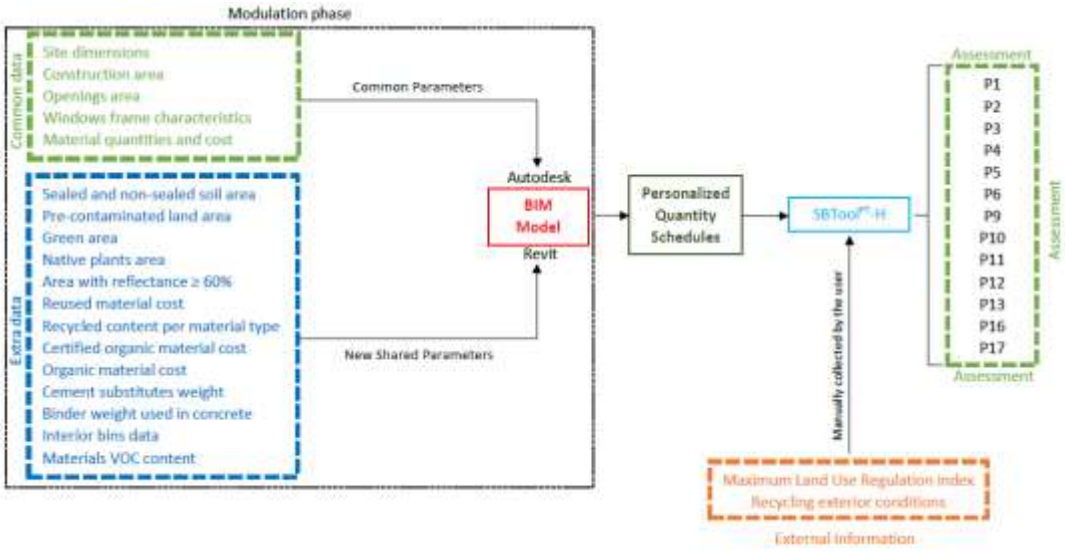


Figure 26 – Research procedure

It is pretended that the chosen case study building is small and simple enough since the objective is to prove the practical application of the theoretical analysis developed in the previous research. Thus, a 3-bedroom single-family dwelling, located in Braga, Portugal, with a net floor area of 72,14 m² and 9,84 m² of openings was selected as a case study (Figure 27).

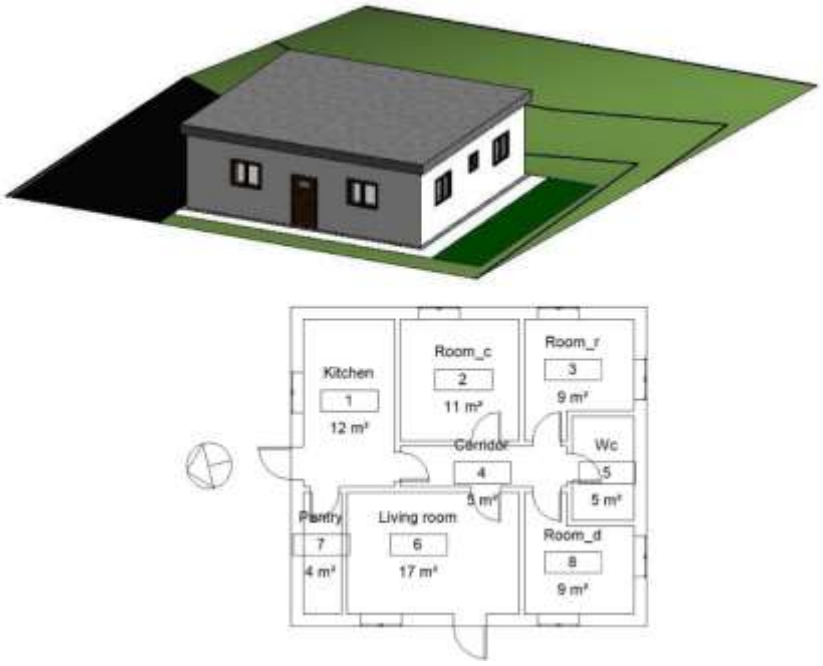


Figure 27 – Case study

To assess the proposed SBTool^{PT}-H criteria, BIM model materials and project information must be assigned. Table 11 presents all the adopted materials and characteristics for the BIM model. These materials and characteristics were mainly defined according to the current Portuguese practices (based on ITE 40 [250]). The aim was to detail the model with the required data for the BSA as, for example, the presence of certified wood or the materials recycled content.

Table 11 – Case study characteristics

Element	Description
Exterior Walls	Cavity double brick wall with rigid thermal insulation in the air cavity. Cement plaster in both sides, interior plastic paint and exterior plastic paint (with low VOC) finishing. Bricks have 50% of recycled content. Rigid thermal insulation (XPS) has 25% of recycled content.
Interior Walls	Single pane brick wall with cement plaster and interior plastic paint finishing in both sides. Bricks have 50% of recycled content
Roof	Concrete slab with asphaltic waterproofing membrane, exterior rigid thermal insulation and prefabricated concrete tile. Concrete (C20/25) with 400 kg/m^3 of binder (300kg of cement and 100 kg of fly ashes) and 35% of recycled content (recycled aggregates).
Floor	Concrete slab with interior rigid thermal insulation and oak floor finishing. Concrete (C20/25) with 400 kg/m^3 of binder (300kg of cement and 100 kg of flying ashes) and 35% of recycled content. Oak floor produced with certified wood and with low VOC. Rigid thermal insulation has 25% of recycled content.
Windows	Produced with reused pine wood from a nearby location. Double glass has 10% of recycled content.
Doors	Exterior and interior doors in pine wood. Door frames were produced with reused pine wood from a nearby location.
Site	Surface mostly covered by lawn, with some area for native plants. It also has sidewalks (with high reflectance) surrounding the building, as well as an access road/car parking.

5.3 Results

Different processes were required before the extraction of the schedule to evaluate the proposed SBTool^{PT}-H criteria. First, the BIM model site surface was introduced and detailed in Autodesk Revit, by splitting the site surface into several other surfaces. These surfaces area, name and characteristics correspond to the different adopted site zones for the case study: Building surface, Sidewalks surface, Entrance surface, Green surface and Native plants surface. The main surface material was also defined. This information composes the base data for the assessment of the site related parameters.

Then, it was necessary to create personalised parameters for the building materials, topography model and project information. These parameters were created according to the required data for the assessment to automate the data appraisal process. A total of 14 personalised parameters ware created in Autodesk Revit by using the Shared Parameter function. By choosing this option, created parameters can appear in schedules, as well as be imported to other Autodesk Revit projects. Furthermore, they can also be exported to other BIM software if aligned with the IFC property sets [111]. The personalised parameters list and characteristics are presented in Table 12. All of them were defined as part of the Green Building Properties.

Table 12 – Created Shared Parameters in Autodesk Revit

Created for criterion	Parameter name	Applied to (category)	Appears on (schedule)	Parameter type
P4	Pre-contaminated land area	Project Information	Project Information	Number/Area
P5	Reflectance over 60%?	Topography surfaces	Topography	Yes/No
P9	Reused Material	Materials	Material Take-off	Yes/No
P10	Recycled content	Materials	Material Take-off	Number/percentage
P11	Certified Wood	Materials	Material Take-off	Yes/No
P12	Total binder weight (kg)	Materials	Material Take-off	Number/Mass
	Total cement substitutes (kg)	Materials	Material Take-off	Number/Mass
P13	Recycling conditions – availability of recycling bins	Project Information	Project Information	Yes/No
	Does the recycling bins have a volume over 15l?	Project Information	Project Information	Yes/No
	Does the recycling system include the collection of used batteries?	Project Information	Project Information	Yes/No
	Does the recycling system include the collection of used cooking oil?	Project Information	Project Information	Yes/No
P16	Mechanical Ventilation	Project Information	Project Information	Yes/No
	Cross Ventilation?	Rooms	Room	Yes/No
P17	Low VOC content	Materials	Material Take-off	Yes/No

To exemplify the created parameters, Figure 28 presents some of them in the Green Building characteristics for the Topography model, Materials and Project Information.

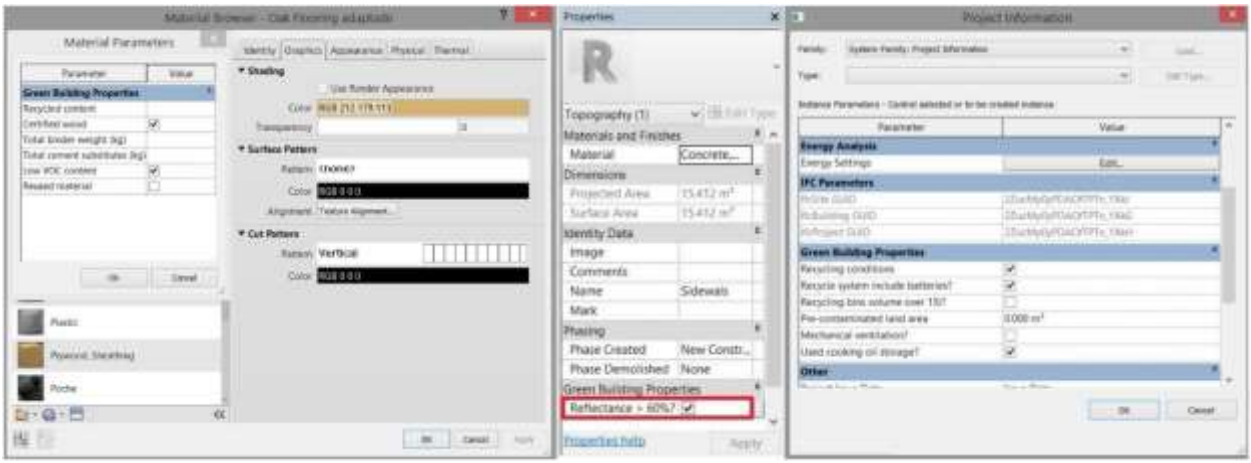


Figure 28 – Created Shared Parameters in Autodesk Revit

After detailing every parameter, it is possible to start the schedule extraction process. At this point, it is necessary to highlight that schedules must also be personalised to perform some extra calculations, as the total materials cost and mass. For this study, four different schedules were developed: Topography Schedule (Figure 29), Room Schedule (Figure 29), Project Information Schedule (Figure 30) and Material Take-off Schedule (Figure 30). All these schedules were required, as they present a different type of information that is necessary for the assessment and cannot be combined in one single schedule. For the Material Take-off Schedule, new variables were created to automatically perform some calculations required for SBTool^{PT}-H, as the percentage of cement substitutes.

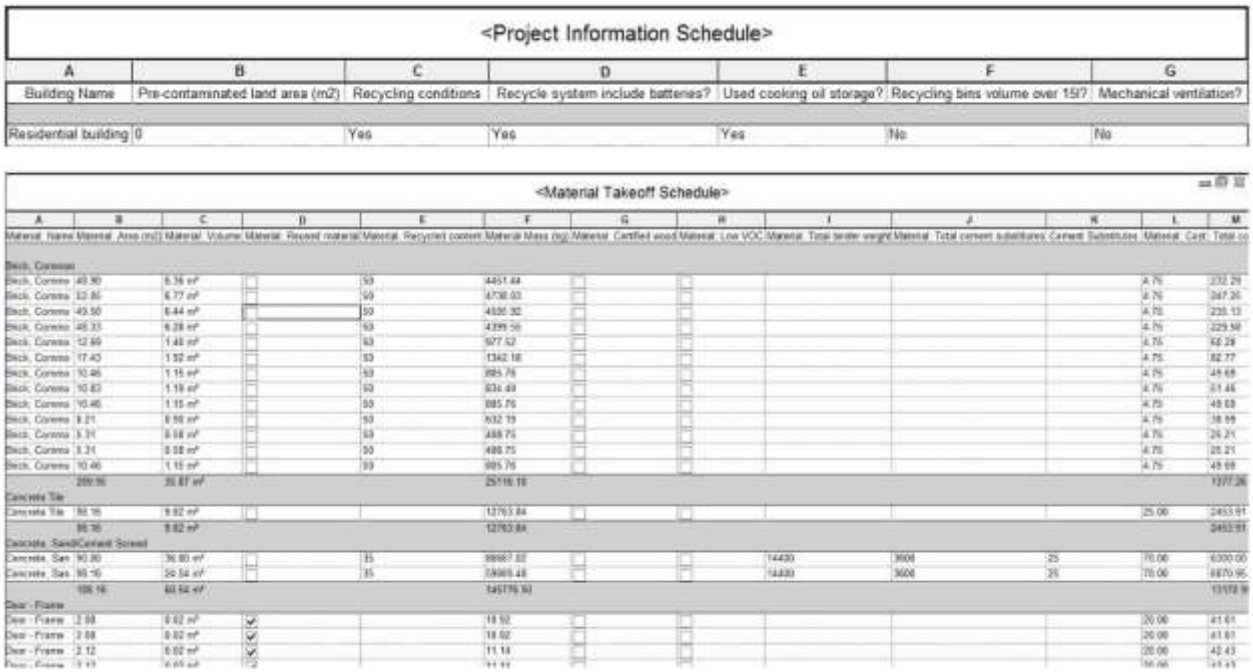
<Topography Schedule>

A	B	C
Surface Area (m2)	Name	Reflectance > 60%?
416.78	Grass	☐
97.76	Building	☐
84.13	Access road	☐
21.35	Native plants	☐
620.01		
15.41	Sidewals	☑
15.41		

<Room Schedule>

A	B	C	D
Area (m2)	Volume (m3)	Name	Cross ventilation?
12.16	37.08	Kitchen	☐
11.46	34.94	Room_c	☐
8.98	27.39	Room_r	☑
5.35	16.31	Corridor	☐
5.12	15.60	Wc	☐
16.60	50.63	Living room	☐
3.67	11.19	Pantry	☐
8.80	26.83	Room_d	☑

Figure 29 – Topography and Room Schedules



<Project Information Schedule>

A	B	C	D	E	F	G
Building Name	Pre-contaminated land area (m2)	Recycling conditions	Recycle system include batteries?	Used cooking oil storage?	Recycling bins volume over 15l?	Mechanical ventilation?
Residential building	0	Yes	Yes	Yes	No	No

<Material Takeoff Schedule>

A	B	C	D	E	F	G	H	I	J	K	L	M
Material: Name	Material: Area (m2)	Material: Volume	Material: Reused material	Material: Recycled content	Material: Mass (kg)	Material: Certified wood	Material: Low VOC	Material: Total binder weight	Material: Total cement substitutes	Cement Substitutes	Material: Cost	Total co
Brick, Common												
Brick, Comma	48.90	6.36 m²		50	4451.44						4.75	232.29
Brick, Comma	53.85	6.77 m²		50	4738.03						4.75	247.20
Brick, Comma	45.50	6.44 m²		50	4535.32						4.75	235.13
Brick, Comma	46.33	6.28 m²		50	4399.56						4.75	229.58
Brick, Comma	12.69	1.48 m²		50	977.57						4.75	68.28
Brick, Comma	17.43	1.52 m²		50	1342.18						4.75	82.77
Brick, Comma	10.46	1.15 m²		50	885.76						4.75	49.68
Brick, Comma	10.83	1.19 m²		50	834.49						4.75	51.46
Brick, Comma	10.46	1.15 m²		50	885.76						4.75	49.68
Brick, Comma	8.21	0.56 m²		50	632.19						4.75	38.99
Brick, Comma	5.31	0.58 m²		50	488.75						4.75	25.21
Brick, Comma	5.31	0.58 m²		50	488.75						4.75	25.21
Brick, Comma	10.46	1.15 m²		50	885.76						4.75	49.68
	269.56	35.87 m²			25116.19							1377.26
Concrete Tile												
Concrete Tile	80.16	9.82 m²			12763.84						25.00	2453.91
	80.16	9.82 m²			12763.84							2453.91
Concrete, Sand/Cement Screed												
Concrete, San	90.80	36.80 m²		35	88887.02			14400	3600	25	70.00	6300.00
Concrete, San	85.16	28.54 m²		35	69665.48			14400	3600	25	70.00	6870.95
	188.16	65.54 m²			145776.50							13170.9
Door - Frame												
Door - Frame	2.68	0.52 m²	☑		18.52						20.00	41.61
Door - Frame	2.68	0.52 m²	☑		18.52						20.00	41.61
Door - Frame	2.12	0.52 m²	☑		11.14						20.00	42.43
Door - Frame	3.49	0.65 m²	☑		11.14						20.00	45.45

Figure 30 – Project Information and Material Take-off Schedules

All these schedules were exported as txt files and then uploaded in the Microsoft Excel – Conversion spreadsheet. This conversion spreadsheet was prepared to be connected with the SBTool^{PT}-H spreadsheet, so it can be automatically filled. With the data provided by Autodesk Revit schedules, it is possible to directly support and speed up the assessment of 13 SBTool^{PT}-H criteria. Those sustainability assessment criteria are presented below. Note that the SBTool^{PT}-H spreadsheet automatically performed all the presented calculations. The information is presented to illustrate how the extracted data from schedules are used in the SBTool^{PT}-H spreadsheet.

5.3.1 Category C1

5.3.1.1 P1 – construction materials embodied environmental impacts

To assess criterion P 1, SBTool^{PT}-H compares the building materials embodied impacts with the national conventional (pre-defined in SBTool^{PT}-H and adapted for the Portuguese region) and best practices (25 % of the conventional practice). Table 13 presents the environmental impacts of the building elements, which are achieved by multiplying the construction elements areas with the impact factors from the SBTool^{PT}-H Life Cycle Impact Assessment (LCIA) database [251]. The building element areas are based on the BIM model

and were taken from the Material Take-off schedule, which describe all building elements. In SBTool^{PT}-H, the user must manually assign all LCIA factors to each building element of the project.

Table 13 – Case study materials environmental impacts

				Environmental impact categories quantification (per m²)						Environmental impact categories quantification					
			Area (m²)	GWP ($kgCO_2$)	ODP (kgCFC-11)	AP ($kgSO_2$)	POCP (kgC_2H_4)	EP ($kgPO_4$)	FFDP (MJ)	GWP ($kgCO_2$)	ODP (kgCFC-11)	AP ($kgSO_2$)	POCP (kgC_2H_4)	EP ($kgPO_4$)	FFDP (MJ)
Exterior walls		Common brick 15 cm + 11 cm	198,78	2,20E-01	1,58E-08	5,48E-04	4,00E-05	6,71E-05	2,58E+00	4,37E+01	3,14E-06	1,09E-01	7,95E-03	1,33E-02	5,13E+02
		XPS 4 cm	99,40	4,14E+00	1,10E-07	1,49E-02	6,75E-03	1,24E-03	1,05E+02	4,12E+02	1,09E-05	1,48E+00	6,71E-01	1,23E-01	1,04E+04
		Cement plaster in both sides (1,5 cm each)	198,78	1,95E-01	8,00E-09	3,15E-04	1,29E-05	4,87E-05	1,31E+00	3,88E+01	1,59E-06	6,26E-02	2,56E-03	9,68E-03	2,60E+02
	Finishing	Painting both sides	198,79	2,46E+00	3,69E-07	1,69E-02	7,72E-04	4,23E-03	4,78E+01	4,89E+02	7,34E-05	3,36E+00	1,53E-01	8,41E-01	9,50E+03
Interior walls		Common brick 11 cm	91,16	2,20E-01	1,58E-08	5,48E-04	4,00E-05	6,71E-05	2,58E+00	2,01E+01	1,44E-06	5,00E-02	3,65E-03	6,12E-03	2,35E+02
		Cement plaster in both sides (1,5 cm each)	182,30	1,95E-01	8,00E-09	3,15E-04	1,29E-05	4,87E-05	1,31E+00	3,55E+01	1,46E-06	5,74E-02	2,35E-03	8,88E-03	2,39E+02
	Finishing	Painting	182,32	2,46E+00	3,69E-07	1,69E-02	7,72E-04	4,23E-03	4,78E+01	4,49E+02	6,73E-05	3,08E+00	1,41E-01	7,71E-01	8,71E+03
Floor slab	Finishing	Oak floor	90,00	-1,20E+00	1,28E-08	8,05E-04	7,29E-05	1,29E-04	1,98E+00	-1,08E+02	1,15E-06	7,25E-02	6,56E-03	1,16E-02	1,78E+02
		Plaster 2 cm	90,00	1,95E-01	8,00E-09	3,15E-04	1,29E-05	4,87E-05	1,31E+00	1,76E+01	7,20E-07	2,84E-02	1,16E-03	4,38E-03	1,18E+02
		XPS 4 cm	90,00	4,14E+00	1,10E-07	1,49E-02	6,75E-03	1,24E-03	1,05E+02	3,73E+02	9,90E-06	1,34E+00	6,08E-01	1,12E-01	9,45E+03
		Reinforced concrete 40 cm	90,00	1,48E-01	3,55E-09	5,56E-04	5,28E-05	5,76E-05	1,24E+00	1,33E+01	3,20E-07	5,00E-02	4,75E-03	5,18E-03	1,12E+02
Openings		Glass	13,15	9,73E-01	8,01E-08	8,51E-03	2,86E-04	6,53E-04	1,15E+01	1,28E+01	1,05E-06	1,12E-01	3,76E-03	8,59E-03	1,51E+02
		Sash/wood	48,52	-1,20E+00	1,28E-08	8,05E-04	7,29E-05	1,29E-04	1,98E+00	-5,82E+01	6,21E-07	3,91E-02	3,54E-03	6,26E-03	9,61E+01
Roof	Finishing	Concrete tile	98,16	2,12E-01	1,11E-08	4,47E-04	2,34E-05	7,64E-05	1,73E+00	2,08E+01	1,09E-06	4,39E-02	2,30E-03	7,50E-03	1,70E+02
		XPS 5 cm	98,16	4,14E+00	1,10E-07	1,49E-02	6,75E-03	1,24E-03	1,05E+02	4,06E+02	1,08E-05	1,46E+00	6,63E-01	1,22E-01	1,03E+04
		Flexible membrane with bitumen	98,16	5,81E-01	7,27E-07	7,27E-03	1,94E-03	3,02E-04	5,33E+01	5,70E+01	7,14E-05	7,14E-01	1,90E-01	2,96E-02	5,23E+03
		Steam PVC barrier	98,16	1,97E+00	2,84E-09	5,35E-03	3,12E-04	7,59E-04	4,69E+01	1,93E+02	2,79E-07	5,25E-01	3,06E-02	7,45E-02	4,60E+03
		Reinforced concrete 20 cm	98,16	1,48E-01	3,55E-09	5,56E-04	5,28E-05	5,76E-05	1,24E+00	1,45E+01	3,48E-07	5,46E-02	5,18E-03	5,65E-03	1,22E+02
								Total life-cycle environmental impacts		**2,43E+03**	**2,57E-04**	**1,26E+01**	**2,50E+00**	**2,16E+00**	**6,04E+04**

The next step is to calculate the benchmarks for the conventional and best practices, which are based on the conventional elements of Portuguese buildings. Best practice benchmarks mean a factor 4 improvement compared to the conventional ones. Benchmarks are presents in Table 14.

Table 14 – Conventional and best practice benchmarks

Solution type	Area (m^2)	Environmental impact categories quantification (per m^2)						Environmental impact categories quantification					
		GWP (kg$CO_{2)}$	ODP (kgCFC-11)	AP (kg$SO_{2)}$	POCP (kg$C_2H_{4)}$	EP (kg$PO_{4)}$	FFDP (MJ)	GWP (kg$CO_{2)}$	ODP (kgCFC-11)	AP (kg$SO_{2)}$	POCP (kg$C_2H_{4)}$	EP (kg$PO_{4)}$	FFDP (MJ)
Exterior walls	99,40	5,64E+01	3,54E-06	1,52E-01	1,64E-02	1,95E-02	5,84E+02	5,61E+03	3,52E-04	1,51E+01	1,63E+00	1,94E+00	5,80E+04
Exterior walls - Finishes	198,78	2,47E+00	3,71E-07	1,70E-02	7,73E-03	4,24E-03	4,79E+01	4,91E+02	7,37E-05	3,38E+00	1,54E+00	8,43E-01	9,52E+03
Interior walls	91,16	2,89E+01	1,80E-06	6,52E-02	3,77E-03	9,24E-03	2,34E+02	2,63E+03	1,64E-04	5,94E+00	3,44E-01	8,42E-01	2,13E+04
Interior walls - Finishes	182,32	2,47E+00	3,71E-07	1,70E-02	7,73E-03	4,24E-03	4,79E+01	2,25E+02	3,38E-05	1,55E+00	7,05E-01	3,87E-01	4,37E+03
Floor slab	90,00	7,05E+01	3,51E-06	1,73E-01	6,21E-03	2,75E-02	4,65E+02	6,35E+03	3,16E-04	1,56E+01	5,59E-01	2,48E+00	4,19E+04
Floor slab - Finishes	90,00	9,73E+00	8,19E-07	2,97E-02	1,32E-03	3,30E-03	1,12E+02	8,76E+02	7,37E-05	2,67E+00	1,19E-01	2,97E-01	1,01E+04
Envelope openings	13,15	8,31E+00	1,17E-06	1,16E-01	2,29E-03	8,18E-03	1,04E+03	1,09E+02	1,54E-05	1,53E+00	3,01E-02	1,08E-01	1,37E+04
Roof	98,18	7,13E+01	3,60E-06	1,43E-01	6,73E-03	2,46E-02	4,51E+02	7,00E+03	3,53E-04	1,40E+01	6,61E-01	2,42E+00	4,43E+04
Roof - Finishes	98,18	1,67E+01	1,15E-06	4,06E-02	2,93E-03	4,82E-03	1,64E+02	1,64E+03	1,13E-04	3,99E+00	2,88E-01	4,73E-01	1,61E+04
Total life-cycle environmental - Conventional practice								**2,49E+04**	**1,49E-03**	**6,38E+01**	**5,87E+00**	**9,78E+00**	**2,19E+05**
Total life-cycle environmental - Best practice								**6,23E+03**	**3,74E-04**	**1,59E+01**	**1,47E+00**	**2,44E+00**	**5,48E+04**

Finally, the building performance is faced with the benchmarks, and a normalised score is reached for each impact category using equation (1). The normalised scores are then aggregated using a weighting system (pre-defined by SBTool^{PT}-H, according to the Portuguese context), and a final quantitative score for P1 is reached (Environmental Performance – P_{LCA}). The different steps of the process are presented in Table 15.

Table 15 – Environmental impacts normalisation

Environmental impact categories	Life cycle impacts (per m² and per year)				Environmental impact category weight (%) [B]	Weighted value =[A]x[B]
	Best practice	Conventional practice	Case study performance	Normalised value [A]		
GWP (Kg CO2)	6,23E+03	2,49E+04	2,43E+03	1,20	40,7	0,490
ODP (kgCFC-11)	3,74E-04	1,49E-03	2,57E-04	1,10	8,4	0,093
AP (KgSO2)	1,59E+01	6,38E+01	1,26E+01	1,07	13,6	0,145
POCP (kg.C2H4)	1,47E+00	5,87E+00	2,50E+00	0,77	10,1	0,077
EP (kg PO4)	2,44E+00	9,78E+00	2,16E+00	1,04	13,6	0,141
FFDP (MJ)	5,48E+04	2,19E+05	6,04E+04	0,97	13,6	0,131
				$\sum$ = Environmental performance (P_{LCA})		1,078

Using the conversion factors presented in Table 9, which allow to convert the quantitative score into a qualitative score, an A + mark was reached for criterion P1, as presented in Table 16.

Table 16 – Result of the Category C1

Category C1 – Climate change and outdoor air quality
P1 - Construction materials embodied environmental impacts
A+

Takin into consideration the achieved results, the theoretical proposal made in [20] for criterion P1 must be slightly adapted. In the mentioned theoretical proposal, authors suggested the need to use an additional BIM tool to carry out the LCI and the LCA. Notwithstanding, SBTool^{PT}-H is focused on the cradle-to-gate analysis, which means that only the materials related environmental impacts are taken into account in the assessment of the building's life cycle impacts. Since the SBTool^{PT}-H spreadsheet gathers embodied LCIA data per square meter of most common building elements and kg of different buildings materials, it is possible to assess criterion P1 using the material take-off schedule from Autodesk Revit. A limitation identified in the existing approach is the need of UI to assign the related LCIA data manually to each building element or material. The main reason for this situation is the use of different description in the BIM model and the LCIA database for the same objects. The integration of a complete LCA (considering more life cycle stages and data provided by a specific LCA BIM tool) could complement and turn more comprehensive the sustainability analysis [189].

5.3.2 Category C2

5.3.2.1 P2 – urban density

To assess P2, SBTool^{PT}-H compares the building Land Use Index (ratio between the gross construction area and the site area) with the Maximum Land Use Index allowed by the local Municipal Urban Plan. The areas can be obtained by Autodesk Revit and were extracted using the Topography Schedule from the conversion spreadsheet. The Maximum Land Use Index was obtained from the city of Braga's Urban Plan, which is 0,75 for the location of the building. According to the SBTool^{PT}-H evaluation guide, the ratio between both indexes (P_{AUL}), must be compared with two benchmarks: the national best (P_{AUL}* = 90 %) and conventional (P_{AUL*} = 50 %) practices.

Using the areas from the Topography Schedule, the SBTool^{PT}-H spreadsheet allows to automatically calculate PAUL index by using equation (2).

$$P_{AUL} = \frac{Land\ Use\ Index}{Maximum\ Land\ Use\ Index} \times 100 = \frac{\frac{197{,}30}{635{,}43}}{0{,}75} = 41{,}4\% \quad (2)$$

The comparison with the benchmarks is made using equation (1). The case study has reached an E mark for P2.

$$\overline{P_{AUL}} = \frac{P_{AUL} - P_{AUL*}}{P_{AUL} * - P_{AUL*}} = \frac{41{,}4 - 50}{90 - 50} = -0{,}22$$

5.3.2.2 P3 – soil sealing index development

For criterion P3, SBTool^{PT}-H calculates the soil sealing index (P_{IMP}) by comparing the ratio between the total soil sealed area and the site area. As the Topography Schedule presents the different site regions by name and area, the user must only select the sealed areas for the calculation, as well as the total site area. Then, by comparing the soil sealing index with the national best (P_{IMP}* = 30 %) and conventional (P_{IMP*} = 60 %) practices defined in SBTool^{PT}-H, a classification is reached for P3. The calculation performed by the SBTool^{PT}-H spreadsheet is presented in equation (3).

$$P_{IMP} = \frac{Sealed\ soil\ area}{Site\ area} \times 100 = \frac{197{,}30}{635{,}43} = 31\% \quad (3)$$

By applying equation (1), the normalised value for P3 is 0,97, which corresponds to an A qualitative level.

$$\overline{P_{IMP}} = \frac{P_{IMP} - P_{IMP*}}{P_{IMP}\ * - P_{IMP*}} = \frac{31 - 60}{30 - 60} = 0{,}97$$

5.3.2.3 P4 – use of pre-contaminated land

The goal of criterion P4 is to promote the construction in brownfields or the rehabilitation of existing buildings. The require information is the pre-contaminated land area – previous occupied land by constructions, waste deposits, etc. – and the site area. This criterion compares the ratio (P_{ACE}) between the pre-contaminated area and the site area, with the national best (P_{ACE}* = 90 %) and conventional (P_{ACE^*} = 0%) practices. Since the case study is new construction, no pre-contaminated area was considered. However, in the Project Information Schedule, a new Shared Parameter was introduced to enable the user to define if there was any pre-contaminated area (Figure 28). Another path to reach this value in Autodesk Revit could be the creation of another surface in the building site and defining it as "existing" in the phasing properties. According to SBTool^{PT}-H, equation (4) provides the results for the assessment of criterion P4.

$$P_{ACE} = \frac{Pre - contaminated\ area}{Site\ area} \times 100 = \frac{0}{635{,}43} = 0\% \quad (4)$$

For a P_{ACE} value of 0, the normalised value is also 0, which corresponds to a D level for P4.

5.3.2.4 P5 – use of native plants

The criterion P5 evaluates the area of native plants in relation to the site green area. This ratio (P_{AUT}) is then compared with the benchmarks defined in SBTool^{PT}-H, best (P_{AUT}* = 90 %) and conventional (P_{AUT^*} = 30 %) practices. As the Topography Schedule considers both surfaces by name and area, the data for the assessment is easily obtained. The calculation process is presented in equation (5).

$$P_{AUT} = \frac{Native\ plants\ area}{Site\ green\ area} \times 100 = \frac{21}{438{,}13} = 4{,}9\ \% \quad (5)$$

The normalised value for P5 is presented below according to equation (1) and corresponds to an E mark.

$$\overline{P_{AUT}} = \frac{P_{AUT} - P_{AUT*}}{P_{AUT} * -P_{AUT*}} = \frac{4{,}9 - 30}{90 - 30} = -0{,}42$$

5.3.2.5 P6 – heat-island effect

To assess P6, it is necessary to calculate the ratio (P_{RFL}) between the areas with reflectance over 60 % and the site area and to compare the result with the national benchmarks. For the areas with reflectance over 60 %, a Yes/No *Shared Parameter* was created to the model topography, in order that the user can define which surfaces have such kind of reflectance. For the case study, only the sidewalks area was considered to have reflectance over 60 %. Besides this value, also the site green area must be considered as a reflectance over 60 % area for the calculation. All of the required data is properly presented in the extracted Topography Schedule, and the following calculations of equation (6) can be performed.

$$P_{RFL} = \frac{Reflectance\ over\ 60\%\ area}{Site\ area} \times 100 = \frac{15{,}41 + 438{,}13}{635{,}43} = 71{,}4\% \qquad (6)$$

By using equation (1) to compare the result with the national best (P_{RFL}* = 90 %) and conventional (P_{RFL^*} = 40 %) practices, a normalised value of 0,63 (B level) is obtained for P6.

$$\overline{P_{RFL}} = \frac{P_{RFL} - P_{RFL*}}{P_{RFL} * -P_{RFL*}} = \frac{71{,}4 - 40}{90 - 40} = 0{,}63$$

The results of the sustainability Category C2 – Land Use and Biodiversity are presented in Table 17.

Table 17 – Results of the Category C2

Category C2 – Land Use and Biodiversity				
P2	P3	P4	P5	P6
E	A	D	E	B

5.3.3 Category C4

5.3.3.1 P9 – reused material

The total materials bill and the cost of reused materials are required to assess P9. According to SBTool^{PT}-H, the performance at the level of P9 is related to the percentage in cost of reused materials (P_{CREU}), where the ratio between the cost of reused materials and the materials total cost is compared with the national best (P_{CREU}* = 15 %) and conventional (P_{CREU*} = 0%) practices. Using the Material Take-off Schedule data related to the created *Shared Parameter* – reused material – it is possible to quickly identify which materials are being reused from the site or nearby location. For the present case study, the doors and windows frames were considered as reused from a nearby location. The Material Take-off Schedule also presents the materials total cost by category. Equation (7) presents the calculation process to assess P9.

$$P_{CREU} = \frac{Reused\ material\ cost}{Total\ material\ cost} \times 100 = \frac{3216{,}33}{43260{,}52} = 7{,}44\% \quad (7)$$

The normalised value for P9, also results from the application of equation (1) and, a B mark was reached.

$$\overline{P_{CREU}} = \frac{P_{CREU} - P_{CREU*}}{P_{CREU}\ * - P_{CREU*}} = \frac{7{,}44 - 0}{15 - 0} = 0{,}50$$

For this criterion it was previously identified a need to use extra software to estimate the total building cost, as Vico. However, it was found that Autodesk Revit can provide all the data for the assessment. Anyway, the use of Vico allows the user to reach more reliable results, as it performs a more realistic cost estimation.

5.3.3.2 P10 – use of materials with recycled content

The assessment process of P10 requires to know the recycled content (in percentage of mass) of each used material, as well as the total material weight. This criterion defines the percentage of recycled content of the building (P_{CRE}). As presented before, for the case study, it was adopted a concrete with 35 % of recycled content, thermal insulation with 25 %, bricks with 50 % and glass with 10 %. In order to properly extract this data from Autodesk Revit, the material mass was first calculated by using the material density property. A *Shared Parameter* was also created, where the user defines the percentage of recycled content. Then, it is possible to extract the schedule "ready to use" and an assessment can be reached. The calculations presented in Table 18 were made using the SBTool^{PT}-H spreadsheet. Note that only the stated materials were

considered for this case study, and each type of material has different benchmarks, defined in SBTool[PT]-H. The presented normalised value results also from equation (1).

Table 18 – Results of the P10 criterion

Product	Material	Recycled content (% of mass)			Normalised value [A]	Quantity (kg) [B]	= [A] x [B]
		Conventional	Best	Used			
Concrete	C25 or lower	15	90	35	0,2667	145776,5	38873,73
Thermal insulation	Rigid Insulation (EPS)	0	25	25	1	624,35	624,35
Bricks and blocks	Common brick	0	30	50	1,6667	25116,1	41860,167
Glass	Glass	0	10	10	1	196,05	196,05
	Total					171742	81554,3

The final normalised value is given by equation (8), corresponding to a B mark for P10.

$$\overline{P_{CRE}} = \frac{[A] \times [B]}{Total\ material\ quantity\ with\ recyced\ content} \times 100 = \frac{81554,3}{171742} = 0,48 \quad (8)$$

5.3.3.3 P11 – use of certified organic materials

P11 is related to the percentage in cost of organic-based products that are certified (P_{CER}). The criterion compares the ratio between the wood certified products cost and the total cost of organic-based products, with the national best (P_{CER}* = 5%) and conventional (P_{CER^-} = 0%) practices. For this case study, only the wood finishing floor was considered as certified, and that data is presented in the Material Take-off Schedule through a *Shared Parameter*. All the other wood products were considered for this criterion. The calculation procedure is presented in equation (9).

$$P_{CER} = \frac{Certified\ organic\ based\ products\ cost}{Organic\ based\ products\ total\ cost} \times 100 = \frac{5850}{12297,61} = 47,57\% \quad (9)$$

By comparing the result with the national best and conventional practice (equation (1)), a normalised value of 0,63 is obtained, corresponding to an A + mark for P11.

$$\overline{P_{CER}} = \frac{P_{CER} - P_{CER*}}{P_{CER}\ * - P_{CER*}} = \frac{47,57 - 0}{5 - 0} = 9,5$$

5.3.3.4 P12 – use of cement substitutes in concrete

The criterion P12 compares the percentage of cement substitutes in concrete elements (P_{SUB}), with the national benchmarks. The P_{SUB} is given by the ratio between the total weight of cement substitutes and the total binder weight. Both values can be obtained by the Material Take-off Schedule, where *Shared Parameters* were created, so the user can define them in the 3D model. In the case study, both building slabs were made of concrete with a binder quantity of 400 kg/m^3, where 300 kg/m^2 are cement, and 100 kg/m^2 are fly ashes. Using these figures and equation (10), it is possible to calculate the percentage of cement substitutes used. Note that an extra variable was introduced in Autodesk Revit, to perform the calculation of this percentage.

$$P_{SUB} = \frac{Cement\ substitutes\ weight}{Total\ binder\ weight} \times 100 = \frac{7200}{28800} = 25\% \quad (10)$$

Equation (1) was used to compare the result with the national best (P_{SUB}* = 30 %) and conventional (P_{SUB^-} = 0%) practices. A normalised value of 0,83 was obtained, corresponding to an A mark for P12.

$$\overline{P_{SUB}} = \frac{P_{SUB} - P_{SUB*}}{P_{SUB} * - P_{SUB*}} = \frac{25 - 0}{30 - 0} = 0{,}83$$

5.3.3.5 P13 – waste management during operation

According to SBTool^{PT}-H, P13 is assessed by filling a checklist that considers the characteristics of the building that influence the recycling potential of operational waste. As the checklist requires some data from outside the building boundaries, the user is requested to collect them. Therefore, the aim of using BIM was to provide as much information as possible about the building, to support the assessment of this criterion. To do so, four *Shared Parameters* were created for the model Project Information Schedule, where the user can answer Yes/No about the building recycling interior conditions (Figure 28). With the data provided by Autodesk Revit, all the checklist elements about the interior conditions can be answered.

The user then collects data about the external recycling conditions to fully assess P13. Nevertheless, if more *Shared Parameters* were created about the exterior conditions, all the data to assess P13 can be directly introduced in Autodesk Revit. Yes/No shared parameters are used to input the external recycling

conditions, e.g. the type of recycled waste collection system and door to external recycling containers distance. This process also requires the user to collect the data for the software, and the possible time-savings are not so noticeable.

It was assumed the existence of recycling bins containers for waste disposal in the distance to the building door lower than 500 m to reach an assessment for this study. Thus, a total score of 40 was reached. Comparing with the national best (P_{RSU}* = 50) and conventional practices (P_{RSU^*} = 10), according to equation (1) a normalised value of 0,75, corresponding to an A mark, was obtained for P13.

$$\overline{P_{RSU}} = \frac{P_{RSU} - P_{RSU*}}{P_{RSU} * - P_{RSU*}} = \frac{40 - 10}{50 - 10} = 0{,}75$$

Table 19 presents the results for the category C4 – Materials and waste management.

Table 19 – Results of the Category C4

Category C4 – Materials and waste management				
P9	P10	P11	P12	P13
B	B	A+	A	A

5.3.4 Category C6

5.3.4.1 P16 – natural ventilation efficiency

As in the last criterion, P16 is also assessed using a checklist. The required data for the assessment, concerns to the building interior conditions that promote efficient natural ventilation (P_{VN}). To gather that data, some *Shared Parameters* were created for the building Project Information Schedule and Room Schedule. For the first, a Yes/No question about the existence of mechanical ventilation was created. For the Room Schedule, another Yes/No question was created about the possibility of cross ventilation. The openings and floor area, as well as the windows frame type, can be extracted from the Material Take-off Schedule. With all that information, it was possible to reach a score of 40 points for P_{VN}. By using equation (1) to compare the result with the national best (P_{VN}* = 60) and conventional (P_{VN^*} = 30) practices, a normalised value of 0,33 (D mark) was reached for P 16.

$$\overline{P_{VN}} = \frac{P_{VN} - P_{VN*}}{P_{VN} * - P_{VN*}} = \frac{40 - 30}{60 - 30} = 0{,}33$$

5.3.4.2 P17 – indoor air quality

The P17 compares the percentage of finishing elements with low VOC content (P_{COV}), with the Portuguese best (P_{COV}* = 90 %) and conventional (P_{COV-} = 0%) practices. PCOV is given by the ratio between the finishing material weight with low VOC and the total finishing material weight. In the case study, the following finishing materials were considered: Interior painting, exterior painting (low VOC) and the pinewood floor (low VOC). A Yes/No *Shared Parameter* was created, so the user can specify this data for materials. The calculation procedure performed by SBTool^{PT}-H is presented in equation (11).

$$P_{COV} = \frac{Finishing\ material\ weight\ with\ low\ VOC}{Total\ finishing\ material\ weight} \times 100 = \frac{2998{,}74}{6346{,}41} = 47{,}25\% \quad (11)$$

By applying the normalisation equation (1), a value of 0,73 is obtained, corresponding to an B mark for P17.

$$\overline{P_{COV}} = \frac{P_{COV} - P_{COV*}}{P_{COV} * - P_{COV*}} = \frac{47{,}25 - 0}{90 - 0} = 0{,}53$$

The assessed criteria from Category C6 - Occupant's health and comfort, and their marks are presented in Table 20. Two out of five criteria were possible to be evaluated in this study using only the support of Autodesk Revit. Nevertheless, other BIM tools have already been identified to assist in the assessment of the remaining criteria. The software Cypetherm REH can provide data to assess criterion P18 – Thermal Comfort partially and to assess criterion P19 – Natural lightning performance fully. For criterion P20, Cypesound RRAE delivers all the required data for the assessment. Note that Cype environment has a plug-in for Autodesk Revit to export BIM models quickly.

Table 20 – Criteria evaluation – Category C6

Category C6 – Occupant's health and comfort				
P16	P17	P18	P19	P20
D	B	Not assessed	Not assessed	Not assessed

5.4 Discussion

By using several capacities of Autodesk Revit, 13 out of 25 SBTool^{PT}-H criteria could be evaluated. These criteria belong to the categories of Climate change and outdoor air quality (1/1), Urban density (5/5), Materials and waste management (5/5) and Occupant's health and comfort (2/5). Climate change and outdoor air quality are assessed using the Material Take-Off schedule. The urban density category can be fully assessed with the Topography Schedule, as it only requires the site and building footprint areas. For the other categories, all the extracted schedules were necessary. A total of 14 Shared Parameters were created to detail the model with the data needed for the SBTool^{PT}-H assessment. Thus, a considerable LOD was required for the model to support the sustainability assessment properly, since several different types of data are required to describe the building, elements and materials properties. The model should be of LOD 300 or above since this level already contains accurate data in terms of quantities, size, location, orientation and material properties [80,109].

The theoretical proposal presented in [20], has been fully confirmed for 10 criteria – P2, P3, P4, P5, P6, P10, P11, P12, P13 and P17. Although, new findings were made for three criteria – P1, P9 and P16. For P1, no additional software is required, since SBTool^{PT}-H is focused on the embodied impact of the construction materials and Autodesk Revit can provide a detailed list of materials. Additionally, there is the need for UI, since the environmental impacts (from the LCIA database) must be manually assigned to materials. Regarding the P9, it was found that Autodesk Revit can provide by itself the data for the assessment. The theoretical proposal suggested that Vico (or similar software) should be used in addition to Autodesk Revit to obtain precise quantities and costs. It may provide more reliable results, but Autodesk Revit allows to have a satisfactory scenario for the assessment. In the case of P16, it was found that the user only needs to proper detail the 3D model to extract the required data for the assessment. On the theoretical proposal, the UI was suggested to collect data regarding the characteristics of the building openings. Overall, the achieved results for SBTool have reached identical scenarios to the ones of other researches that analysed other BSA methods, as LEED and BEAM Plus [21,25]. A large number of criteria from a BSA method can be assessed with Autodesk Revit schedule function, mainly when related to the quantitative model data. Furthermore, the possibility to create personalised parameters allows to assess a wider range of different data. BIM platforms

capacities can have a crucial role in improving the sustainability of buildings and supporting the sustainability certification.

In what respects to other SBTool^{PT}-H criteria, Autodesk Revit can also support their assessment in two different ways: by providing some of the required data for the sustainability assessment (such as the construction cost for the economy category – 2 criteria – or the sanitary equipment efficiency and water collection area for the water-related category – 2 criteria) and; by exporting the BIM model to specific analysis tools (required for the assessment of the energy efficiency category – 2 criteria, and of the occupant's health and comfort category – 3 criteria). The checklist of the building manual criteria can also be included in Autodesk Revit through personalised parameters, but all the information must be collected by the user. Finally, the accessibility category – 2 criteria – requires the use of a GIS system or Google Maps to assess distances from the building entrance to, for example, public transportation stops, and Autodesk Revit cannot be used to support this assessment. When facing the presented process with the traditional method to perform a Building Sustainability Assessment, the most noticeable advantages are:

- Modelling and coordination – All the projects disciplines can be made together, avoiding errors, omissions or interferences. Precise schedules containing all the building disciplines can be extracted to perform a comprehensive sustainability assessment;
- Materials characterisation for all the project disciplines – Designers can create personalised materials or add specific characteristics according to the BSA method requirements. From Yes/No parameters to formulas parameters can be created in Autodesk Revit for materials, building elements, spaces, etc. Project families are then automatically updated for all disciplines. Personalised materials libraries containing all required information for the BSA can be created to maximise potential benefits;
- Material quantity and characteristics assessment – The software determines automatically all the project material quantities and characteristics, according to the designer's requirements. Reliable schedules can be quickly extracted and are automatically updated when changes are introduced (i.e. improvement measures);

- Building Sustainability Assessment – Since all the required data was carefully prepared, defined and grouped in schedules, it can be connected to SBTool^{PT}-H spreadsheet to reach an automatic assessment.

By providing such features, the proposed framework can significantly reduce the assessment time in comparison with the traditional process. There is no need to manually assess all the required building materials, dimensions and quantities since the architectural design is already in the BIM model. In this case, the dimensions of the building elements, as well as the material characteristics and quantities are automatically given by Autodesk Revit. It also automates all the calculations for the sustainability assessment and project modifications can be easily updated and assessed, avoiding the actual process repetition. The BIM model can also be useful to assess the remaining criteria, either by proving the model for specific simulations or by providing some of the required data. Overall, while the traditional assessment required a whole week of work, the proposed framework reduces it to a couple of days, getting one step closer in providing a real time supporting tool for SBTool^{PT}-H. Nevertheless, a full comparison can only be made when assessing all the criteria with and without BIM.

However, there are some setbacks on this process. It is possible to highlight the initial time and knowledge requirements to create the Shared Parameters, as well as the need to prepare and extract 4 different schedules, for an easier connection with SBTool^{PT}-H. This task must be performed once, as both (Shared Parameters and schedules) can be saved as "template" and used in other projects. Additionally, the probability of connection lost between both excel spreadsheets (SBTool^{PT}-H and schedules) can be an issue when a schedule is replaced by a new one, creating the need to double-check the spreadsheets linkage. An automated way to extract, adapt and link spreadsheets (SBTool^{PT}-H and schedules) is further required for extensive use of Autodesk Revit for sustainability certification purposes, as the creation of an API.

5.5 Conclusions

The principal objective of this study was to confirm in the project practice the adequacy of the theoretical proposal proposed in a former study [20], concerning the capabilities of the BIM platform Autodesk Revit to assess a set of criteria from the Building Sustainability Assessment method SBTool^{PT}-H.

A case study was implemented in Autodesk Revit, and by creating 14 Shared Parameters, the data to assess 13 out of 25 SBTool^{PT}-H criteria was gathered using schedules. The theoretical proposal has been fully confirmed for 10 criteria and adapted for 3 criteria. Overall, the theoretical proposal has identified the core and paths for the assessment, with small adjustments during the practical application. The evaluation of the categories Climate change and outdoor air quality (1), Urban density (5) and Materials and Management (5) can be supported by Autodesk Revit, while it is possible to assess 2 out of 5 criteria in the Occupant's health and comfort category.

Concerning the applied process itself, it has the potential to support design teams in improving and certifying the sustainability of their projects. By using a proper (or personalised) software template, designers can detail their models with green building characteristics and then quickly assess all the required data to perform a Building Sustainability Assessment. The common use of Autodesk Revit by designers and its sustainability capabilities can be a great opportunity to efficiently implement BSA methods during the project phase and enhance building sustainability. As this assignment can be included in a BIM project procedure, BIM companies can easily adopt it, adding considerable value to their processes. Furthermore, as BSA methods usually have similar criteria, the applied process can provide new insights or be replicable for other sustainability schemes.

The applied framework can also be easily adapted to assess other buildings, including large construction projects. For other building typologies, personalised project parameters must be created or adapted according to the assessment method requirements, which is usually based on a different type of data. It is only a matter of creating the necessary parameters and endow building elements and materials with data to fulfil those parameters. Regarding large residential construction projects, only an increase of the amount of data is expected, since the existing parameters are enough to apply SBTool^{PT}-H to that type of projects. As for other building types, the only requirement is to properly characterise the model and materials.

Despite the general improvements in the assessment, the automation process can still bring more advantages. An API can be created to automate the schedule extraction and connection process with SBTool^{PT}-H. After preparing the schedules and solving the possible problems related to the connection between the outputs of the BIM software and the assessment methodology of the BSA method, a substantial amount of time can be saved during the design stage. Furthermore, the API can display an instant

classification for a set of criteria, while designers are making changes in their projects, providing real-time decision support. The creation of an API specifically for the case of SBTool (SBTool^{BIM}) was also proposed in former research [20] and future research will address this topic.

6. BIM-BASED ENERGY ANALYSIS AND SUSTAINABILITY ASSESSMENT – APPLICATION TO PORTUGUESE BUILDINGS

Buildings are responsible for several negative impacts on the environment, most of them related to non-renewable 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 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^{PT}-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^{PT}-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 into BIM environment, providing new insights for complete integration.

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

This Chapter is based in the article: Carvalho, J.P.; Almeida, M.; Bragança, L.; Mateus, R. BIM-Based Energy Analysis and Sustainability Assessment–Application to Portuguese Buildings. Buildings 2021, 11, 246. https://doi.org/10.3390/buildings11060246

6. BIM-BASED ENERGY ANALYSIS AND SUSTAINABILITY ASSESSMENT – APPLICATION TO PORTUGUESE BUILDINGS

6.1 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 [234]. 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 [234,252]. 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, 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 BIM for the construction industry, designers and researchers are extensively applying it to manage building data and improve efficiency and global quality [80]. During the last five years, the use of BIM for sustainable construction purposes has also witnessed exponential growth [17]. BIM allows storing multi-disciplinarily information into a single model, promoting a real-time collaboration environment among stakeholders through the building life cycle [14]. Between BIM most known applications, its connection with 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 [164,165]. 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 [22].

6. BIM-BASED ENERGY ANALYSIS AND SUSTAINABILITY ASSESSMENT – APPLICATION TO PORTUGUESE BUILDINGS

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 [47]. 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 [198,253], 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.

6.2 Literature Review

6.2.1 Buildings Energy Performance

The 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 [1,32,33]. The European building stock is still responsible for 40% of the total energy use and 36% of CO_2 emissions [254]. 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 EPBD, updated in 2010 [255]. 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) [256]. 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 [257] 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%).

6.2.2 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 [17,154,168]. 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 [15]. BIM can improve design and management processes productivity, with stakeholders working in real-time collaboration [17,247]. BIM implies a building information model, which is an object-oriented parametric model, with all the project data. The model LOD, which ranges from 100 to 500, specifies and articulates the content and reliability of the BIM model [106].

BIM creates an excellent opportunity to incorporate sustainable measures throughout the design process [25]. Some authors have already identified the preconstruction and project phases as the critical ones, where the main decisions regarding building sustainability must be taken [153–155]. 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 [20]. BIM can provide information about the estimated building performance even in the very early design stages [258].

In 2008, Krygiel and Nies [156] 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 [253], leading to several BIM-based energy-related research—BEM [164,165]. 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 [165].

Within the context of BIM, model interoperability between software is usually made with IFC, 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 [164,196,259]. Kamel and Memari [122] highlighted the differences between both when used for energy simulation purposes. Despite the use of the gbXML schema 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 [260]. Farzaneh et al. [104] 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 [14]. 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 [109].

On the application field, several reviews have been made comparing the analysis capabilities and end-users of energy analysis tools, highlighting the capabilities of GBS and IESVE [157,159]. Regarding the modulation software, Autodesk Revit is one of the most used, capable, and embracing BIM platforms [60,167,205]. 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 [81] concluded that a building's orientation can have a considerable impact on the building energy consumption. Gourlis and Kovacic [167] 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. [198] 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. [168] 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. [211] 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 [155,184,261]. 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 [259].

Gao et al. [165] 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 [262]. Furthermore, the existence of several BIM energy tools, parameters and approaches [263] 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 [122,253,263].

6.2.3 Building Sustainability Assessment

6.2.3.1 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 [6,264,265]. Some of their benefits include environmental conservation; improved building performance and occupants' comfort, health and safety [66].

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 [53]. The most known BSA methods, which provide a basis to all the other approaches, are BREEAM from the BRE, LEED from the USGBC and SBTool from the iiSBE [8,266].

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 [12]. 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 [13,267], making it necessary to search for more efficient and expeditious approaches. For instance, Zhang et al. [12] 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 [45,65]. These types of errors can have great impact on the environment, since these methods are the main source of shaping sustainable decisions in projects [22]. User-friendly restrictions, the complex credit structure and the required user knowledge are also common issues that hinder the use of BSA methods [66].

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^{PT}-H, LiderA and Domus Natura [67,68]. According to Pires and Fidélis [72], 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 [6,69,70].

6.2.3.2 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 [17]. Regardless of the potential benefits, so far, BIM has not been used comprehensively to obtain the required information for a sustainability assessment [20]. The existing BIM software stills lacks sustainability issues, and exchange format files are still in need of further developments [8,16]. 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 [17].

Currently, BIM is most commonly used to support the assessment of LEED, mainly in the categories of energy and atmosphere and materials and resources [60,196]. Nevertheless, several authors [16,21,23,24,219] 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 [19,22,199,219]. Edwards et al. [22] 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 [25] 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 [200] used BIM to evaluate 66% of the office building scheme credits. GhaffarianHoseini et al. [201] suggested that BIM can also support the assessment of 75% of New Zeeland Green Star Certification with the development of proper guidelines. Concerning SBTool, Carvalho et al. [9,20] developed a conceptual framework for the integration of BIM with the Portuguese BSA method for residential buildings— SBTool^{PT}-H. The assessment procedure of almost all the SBTool^{PT}-H criteria can significantly benefit from the use of BIM. They also compared the feasibility of using BIM in SBTool^{PT}-H with its use in other BSA methods, such as LEED and BREEAM [60].

Despite the benefits, a common conclusion is that BIM is not properly oriented and has not achieved its full potential to sustainable building design [20,22,26]. 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 [17,90,208]. Chong et al. [90] argued that future BIM standards should consider a requirement for sustainability assessment, while Gandhi and Jupp [200] asked for specific BIM coordination and execution plans.

6.2.3.3 SBTool^{PT}-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 [6,8]. 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 [73,74]. The transposition of the SBTool to the Portuguese residential scenario (SBTool^{PT}-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^{PT}-H, there are a total of 25 parameters, sorted by nine categories, which are divided into three sustainability dimensions: Environment, Society and Economy. 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 [75]. 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^{PT}-H energy efficiency-related criteria.

The energy efficiency category (C3) from SBTool^{PT}-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 (12). Then, the final result ($\overline{P_{ENR}}$) is reached by converting the normalised value into a qualitative scale, according to Table 21.

$$\overline{P_{ENR}} = \frac{P_{ENR} - P_{ENR*}}{P_{ENR}* - P_{ENR*}} \quad (12)$$

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.

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 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 (13)), and the final result ($\overline{P_{ER}}$) is according to the qualitative scale of Table 21.

$$\overline{P_{ER}} = \frac{P_{ER} - P_{ER*}}{P_{ER}* - P_{ER*}} \quad (13)$$

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.

Table 21 – Conversion from the quantitative to the qualitative performance scales in SBToo^{PT}-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	$P < 0.00$

6.3 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 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. [20] 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 ItеCons and University of Coimbra [268]. 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^{PT}-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^{PT}-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 31.

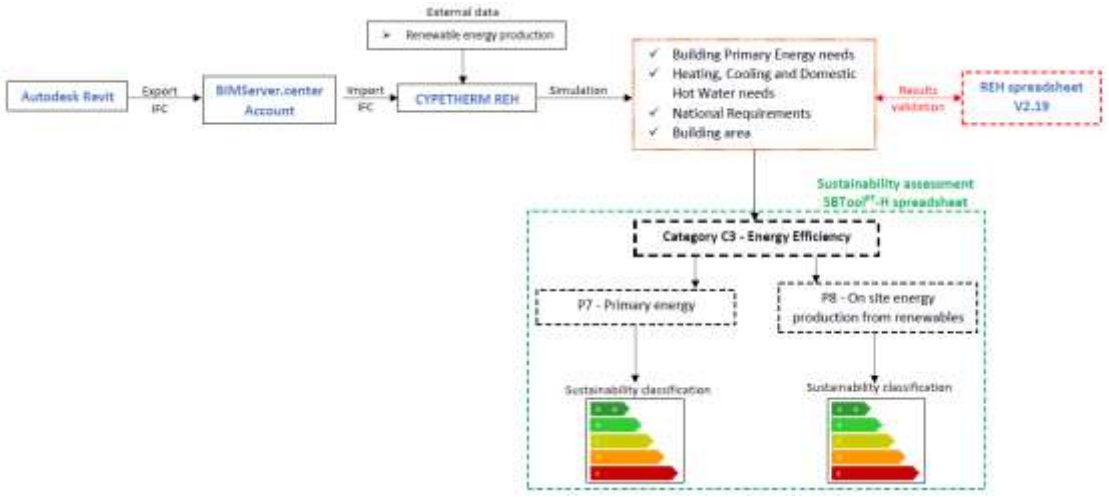


Figure 31 – Simulation procedure

To apply the suggested procedure a case study is required. It must be framed under the scope of both REH and SBTool^{PT}-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 32).



Figure 32 – Floor plan of the case studies: existing model and new building model

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 [269,270] 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^2). Since the first Portuguese thermal regulation was only introduced in 1990 [271],

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^2, the interior floor to ceiling height is 3.05 m and the glazed area is 6.3 m^2. 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.

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 [270]: 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^2). The building total net area is 143.53 m^2, the interior floor-to-ceiling height is 2.60 m and the glazed area is 39.66 m^2. 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.

The thermal characteristics of both case studies scenarios are presented in Table 22. 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 22 – Construction solutions and systems

Element	Existing Building		New Building
	Reference Model	Optimised Model	
Exterior walls	Simple brick wall (15 cm) U = 1.69 W/(m²K)	Double brick wall (15 + 11) with XPS insulation (6 cm) in the middle U = 0.40 W/(m²K)	Double brick wall (15 + 11) with XPS insulation (5 cm) in the air cavity (2 cm) U = 0.38 W/(m²K)
Interior walls	Simple brick wall (11 cm) U = 1.78 W/(m²K)		
Floor slab	Lightweight block and beam slab (20 cm) and wooden floor finishing (3 cm) U = 1.60 W/(m²K)	Lightweight block and beam slab (20 cm), with interior XPS insulation (7 cm) and wooden floor finishing (3 cm) U = 0.34 W/(m²K)	Lightweight block and beam slab (25 cm), with interior XPS insulation (4 cm) and wooden floor finishing (3 cm) U = 0.30 W/(m²K)
Roof slab	Lightweight block and beam slab (25 cm) U = 2.02 W/(m²K)	Lightweight block and beam slab (25 cm), with exterior XPS insulation (8.5 cm) and waterproof membrane U = 0.35 W/(m²K)	Lightweight block and beam slab (25 cm), with exterior XPS insulation (8.5 cm), waterproof membrane and gravel (5 cm) U = 0.35 W/(m²K)
Sloped roof	Lightweight block and beam slab (25 cm) with ceramic tile U = 2.02 W/(m²K)	Lightweight block and beam slab (25 cm) with ceramic tile U = 2.02 W/(m²K)	-
Windows–glass	Single glass 6 mm (Solar factor 0,85) U = 2.50 W/(m²K)	Double-glass 6 mm + 4 mm (Solar factor 0,78) U = 1.50 W/(m²K)	
Windows–frame	Wooden frame (w/ exterior shutter) U = 2.50 W/(m²K)	Aluminium frame with thermal break (w/ exterior shutter) U = 1.50 W/(m²K)	
Exterior doors	French wooden door U = 1.50 W/(m²K)		
Interior doors	Wooden light door U = 2.50 W/(m²K)		

6.4 BIM Model for Energy Simulation

6.4.1 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) [250], 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 [109]. 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.

6.4.2 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.

6.4.3 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 23. 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 23 – 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 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° 15793-K/2013 [272].

6.5 Results and Discussion

6.5.1 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^2 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 24. 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 (14).

$$N_{tc} = \frac{1 * N_{ic}}{\eta i} * fpui + \frac{1 * N_{vc}}{\eta v} * fpuv + \frac{1 * N_{ac}}{\eta a} * fpua - \frac{E_{ren} + E_{solar}}{A_p} \quad (14)$$

where:
N_{tc}—building primary energy (PE) needs ($kWh_{PE}/(m^2.year)$);
N_{ic}—building heating needs ($kWh/(m^2.year)$);
N_{vc}—building cooling needs ($kWh/(m^2.year)$);
N_{ac}—building DHW needs ($kWh/(m^2.year)$);
fpui—conversion factor to convert the final heating energy into PE;
fpuv—conversion factor to convert the final cooling energy into PE;
fpua—conversion factor to convert the final DHW energy into PE;
ηi—heating system effieicny;
ηv—cooling sysrem efficiency;
ηa—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^2).

The conversion factors f_{pui}, f_{puv} and f_{pua} 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 η_i for the heating system (with a value of 1), η_v for the cooling system (with a value of 3) and η_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.

Table 24 – Cypetherm REH results

	Energy Needs	Existing Building		New Building
		Reference Model	Optimised Model	
	N_{ic} kWh/(m².year)	201.21	38.61	27.12
Limit value	N_i kWh/(m².year)	49.00		68.07
	N_{vc} kWh/(m².year)	4.98	4.35	7.91
Limit value	N_v kWh/(m².year)	9.15		9.15
	N_{tc} kWh_{PE}/(m².year)	518.29	111.26	80.17
Limit value	N_t kWh_{PE}/(m².year)	165.79		195.61
	Q_a (kWh/year)	2139.85		
	N_{ac} kWh/(m².year)	28.56		

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.

6.5.2 BIM-Based Energy 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 Table 25 and Table 26 for the existing building and new building, respectively.

Table 25 – 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 26 – Comparison between the Cypetherm REH results and REH spreadsheet – 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 [273]. 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 Ni-value, a difference of the same magnitude in the Nt-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^2 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 27 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 27 – Rouding differences between Cypetherm REH and the REH spreadsheet

	Cypetherm REH	**REH Spreadsheet**
Effective glazed area facing south (m^2)	6.75	6.75
	×	×
Average south radiation (kWh/m^2.month)	130.00	130.00
	x	x
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.

6.5.3 Sustainability Assessment

Finally, it is possible to approach RQ3 and look for a sustainability assessment. Following the conceptual framework from Carvalho et al. [20], the energy simulation results from Cypetherm REH were used to assess the SBTool^{PT}-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^{PT}-H parameters P7 and P8. For timesaving, the results were exported from Cypetherm REH to an XML document and then linked to the SBTool^{PT}-H Excel spreadsheet.

6.5.3.1 Parameter 7

The Cypetherm REH results were linked to the SBTool^{PT}-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^2 for the existing model and 143.53 m^2 for the new building model), primary energy needs (and respective limit) and dwelling typology (three-bedroom dwelling). According to the SBTool^{PT}-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:

$$P_{ENR} = N_{tc} = 518.29\ kWh_{PE}/(m^2.year)$$

$$P_{ENR^*} = N_t = 165.79\ kWh_{PE}/(m^2.year)$$

$$P_{ENR}{}^* = 0.25 \times N_t = 41.45\ kWh_{PE}/(m^2.year)$$

The comparison against the benchmarks for the existing reference model is made using a normalised value, provided by equation (12).

$$\overline{P_{ENR}} = \frac{518.29 - 165.79}{41.45 - 165.79} = -2.84$$

To reach the final score for P7, the normalised value must be converted into a qualitative scale, as presented in Table 28. 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:

$$P_{ENR} = N_{tc} = 111.26\ kWh_{PE}/(m^2.year)$$

$$P_{ENR^*} = N_t = 165.79\ kWh_{PE}/(m^2.year)$$

$$P_{ENR}{}^* = 0.25 \times N_t = 41.45\ kWh_{PE}/(m^2.year)$$

The normalised value for the existing optimised model is also provided by equation (12).

$$\overline{P_{ENR}} = \frac{111.26 - 165.79}{41.45 - 165.79} = 0.4$$

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.

$$P_{ENR} = N_{tc} = 80.17\ kWh_{PE}/(m^2.year)$$

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

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

By normalising the results using equation (12) 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 28.

$$\overline{P_{ENR}} = \frac{80.17 - 195.61}{48.90 - 195.61} = 0.79$$

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^{PT}-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.

6.5.3.2 Parameter 8

Concerning SBTool^{PT}-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 DGEG 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^{PT}-H to perform this evaluation are: dwelling typology (three-bedroom), total net floor area (74.92 m^2 for the existing model and 143.53 m^2 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 (15) — must be compared with the conventional national practice ($P_{ER'}$) — equation (16) — and best practice ($P_{ER}*$) — equation (17).

The following calculations were performed for the existing reference model:

$$P_{ER} = \frac{E_{solar} + E_{ren}}{A_p} \quad (15)$$

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

$$P_{ER*} = 0.5 \times \frac{Q_a}{0.95 \times A_p} \quad (16)$$

where:
P_{ER*}—national conventional practice for P8;
Q_a—building DHW needs (kWh/year);
A_p—building total net area (m^2).

$$P_{ER*} = 0{,}5 \times \frac{2139.85}{0.95*74.92} = 14.35 \text{ kWh}_{PE}/(\text{m}^2.\text{year})$$

$$P_{ER} * = N_{tc}' = 1.2 \times \left(\frac{N_{ic}}{1} \times 2.5 + \frac{N_{vc}}{2.8} \times 2.5 + \frac{Q_a}{(0.95 \times A_p)} \times 1.0\right) \quad (17)$$

$$P_{ER} * = 1.2 \times \left(\frac{201.21}{1} \times 2.5 + \frac{4.98}{3} \times 2.5 + \frac{2139.85}{(0.95 \times 74.92)} \times 1.0\right) = 644.69/2.5 = 257.88$$

$\text{kWh}_{PE}/(\text{m}^2.\text{year})$

With all the variables, it is possible to compare the building's renewable energy production with both benchmarks using equation (13). 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 28.

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 (17) — by introducing the existing optimised model heating and cooling needs.

$$P_{ER} = 18.23 \text{ kWh}_{PE}/(\text{m}^2.\text{year})$$

$$P_{ER*} = 14.35 \text{ kWh}_{PE}/(\text{m}^2.\text{year})$$

$$P_{ER}* = 1.2 \times \left(\frac{38.61}{1} \times 2.5 + \frac{4.35}{3} \times 2.5 + \frac{2139.85}{(0.95 \times 74.92)} \times 1.0\right) =$$

$$156.26/2.5 = 62.50 \text{ kWh}_{PE}/(\text{m}^2.\text{year})$$

The comparison between the building renewable energy production and both benchmarks was performed by using the normalisation equation (13).

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

The qualitative score for the existing optimised model is presented in Table 28. Only by improving the thermal insulation of the building envelope was it possible to im-prove 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 up-per 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 SBTool^{PT}-H for the assessment of P8. As the building area is different, the benchmarks must be defined again.

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

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

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

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

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

$$P_{ER} * = 1.2 \times \left(\frac{27.12}{1} \times 2.5 + \frac{7.91}{3} \times 2.5 + \frac{2139.85}{(0.95 \times 143.53)} \times 1.0\right) =$$

$$108.1/2.5 = 43.24 \text{ kWh}_{PE}/(\text{m}^2.\text{year})$$

The normalised value for P8 is given by the application of equation (13). 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 28.

$$\overline{P_{ER}} = \frac{9.52 - 7.85}{43.24 - 7.85} = 0.05$$

Table 28 – 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^{PT}-H.

6.6 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^{PT}-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^{PT}-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 23), 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^{PT}-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^{PT}-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^{PT}-H, e.g., in the assessment of the acoustic performance (using Cypesound RRAE).

7. AUTOMATING BUILDING SUSTAINABILITY ASSESSMENT

Facing the increased pursuit for more sustainable buildings and procedures, the construction industry has been adopting new project approaches and technologies. BSA methods are a key tool to spread and evaluate building's sustainability, but its use is hindered by the time-consuming assessment process and required data for the analysis. Thus, BSA methods are typically used in project later stages just to rank the building sustainability score and improvements measures are often unfeasible or neglected. With the emergence of BIM, new potentialities have been found, such as continuously data storage and integrated building design optimisation. The opportunity arises to integrate BSA into the BIM environment and take advantage of the later to promote building sustainability by automating the assessment procedure. In this regard, this research aims to automate the assessment of a BSA scheme by creating a BIM-based application for the project early stages. By translating SBTool^{PT}-H criteria requirements into computable rules, Visual Programming Language was used to create an end-user application to evaluate building sustainability – SBTool^{BIM}. Results show the feasibility of automating BSA with BIM, by integrating 19 criteria into a single application and establishing a BIM connection for the remaining 6 criteria. Building data can be easily extracted from BIM models while building performance data still requires the use of additional BIM software. Moreover, the applied procedure has established a new framework to carry out BSA within the BIM environment in a faster reliable way and marks the beginning of a new era for sustainability assessment.

Keywords: Building information modelling (BIM); Building sustainability assessment (BSA); Sustainability; SBTool; Dynamo

This Chapter is based on a current submission to Journal of Building Engineering.

7.1 Introduction

General society and worldwide authorities are increasingly looking for more sustainable buildings [39]. 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 [14,80]. To turn buildings more efficient and ecological, there is a need to act since early project stages by introducing and analysing different sustainability measures, to effectively enhance building sustainability. To support decision-making regarding effective sustainable measures and to monitor building's sustainable performance, BSA methods have been developed all over the world and adapted to the specific conditions of each location and building [6,264]. They provide the opportunity for buildings to demonstrate their environmental, social, and economic benefits to the local community [53]. 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 later stages after finishing the project design, where modifications are unbearable or too expensive [9,10]. 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 [267]. 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 [51].

Buildings also need to comply with several requirements and criteria, such as normative standards, comfort and safety specifications, industry guidelines, and project requirements [135,142]. 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 [27]. 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.

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 [80,83]. BIM creates an excellent opportunity to incorporate sustainable measures throughout the design process, especially during the project early stages, promoting the development of high-performance buildings. It allows to store multidisciplinary information and

encourages real-time collaboration among stakeholders [9,14]. BIM potential for automated rule checking has been recognised and together with VPL, several compatible rules have been developed, creating better, faster, and more comprehensive assessment procedures [27].

Despite the existing research on the connection of BIM with BSA, a proper framework for this integration has not been established [20]. Authors tend to purpose theoretical methods, which allow gathering BSA data through BIM, but any automatic evaluation has been made. 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 a BSA scheme into a computer application integrated into the Open BIM environment, a fast and reliable sustainability analysis can be made during the project early stages. Designers will be provided with an intuitive tool to analyse their building sustainable performance, allowing them to introduce and compare improvement measures with few resources. Moreover, by creating an automated assessment procedure for the project 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.

7.2 Literature Review

7.2.1 Sustainability and building sustainability assessment (BSA) methods

Following the need to achieve more sustainable buildings, BSA methods have been developed worldwide by public authorities, international organisations, and private consultancy companies [6,58]. 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 [54,56] Moreover, more than 600 assessment schemes have been developed globally for BSA [56], addressing environmental, social, and economic aspects [45]. BSA methods aim at implementing and evaluating the building's sustainable performance by assessing a set of partial building features and aggregating results into a sustainability score [6,45]. These rating systems are organised in evaluation areas/categories, which include criteria and multiple indicators on several topics, such as energy, waste, water, material impacts, transport, accessibility, social aspects, life cycle assessment or indoor environment [54,58,59]. BSA has an important role in sustainable building development, providing support for designers and building owners when dealing with life cycle design, construction, and operation [51]. Among some of the most known BSA methods are BREEAM, LEED, SBTool, CASBEE, DGNB, Green Star, HQE and BEAM [54,58]. The first three assessment schemes – BREEAM, LEED, and SBTool – have been considered the basis for all other approaches [7].

Currently, BSA is used as a voluntary approach taken by owners and/or developers to demonstrate their building's sustainable features [59]. 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 [51]. Furthermore, BSA is usually applied during the project later stages or even after the construction itself, where improvement changes are often unfeasible [12]. 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 in performing BSA during the project initial stages [13,267]. Moreover, improvement modifications require an integral repetition of the assessment procedure, discouraging designers to use it [60]. Zhang et al. [12] 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 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 and calculation mistakes, user-friendly restrictions and complex credit structures [65,66,258].

7.2.2 BIM and applications for building sustainability

With the growing digitalisation of the construction sector [76], 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 [15]. BIM is an integrated process where the building characteristics and data are digitally represented to improve interoperability and real-time collaboration among stakeholders [89]. 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 [142]. It is created based on a parametric and object-oriented approach, where parameters are defined to characterise the relation between the model objects [103]. 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 [81]. The BIM model is classified according to its content and information through the 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 usability and limitations [106]. The LOD classification identifies the specific minimum content requirements for a certain use, and it is defined based on the objects graphic and data information [14]. For instance, the United States General Services Administration [108] has provided a guide regarding the minimum capabilities of the BIM model at different development stages. For instance, 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 or 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 [9]. Autodesk Insight, IESVE or Solibri are examples of BIM tools. Interoperability between BIM platforms and tools is often made through an 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 [26].

The use of BIM for sustainability purposes has also gained exponential attention in the past years [204,274]. 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 [20,275]. Authors [155,276] have identified the preconstruction and project phases as key stages to act on building sustainability. With BIM benefits also being more noticeable during the same phases, BIM influence on building sustainability becomes clear [20]. Among the most known 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 being directly calculated and documented in a short period with few resources [205]. Moreover, BSA exploits the full potential of the BIM method, requiring building multi-disciplinary data and building performance simulation results [60]. Direct benefits of BIM application concern decision support, automatic data extraction, automatic assessment, process efficiency and resource-use reduction. In a systematic review from Carvalho et al. [60], LEED has been identified as the most addressed BSA method regarding BIM integration. Several authors [16,21,24,137] have purposed the use of BIM to assess LEED credits and prerequisites, mainly in the categories of Energy and Atmosphere, as well as 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 [19,20,22,25,200–202]. The majority of these approaches have developed a theoretical framework where the assessment data can be gathered from BIM models and tools. Practical applications can also be found in a minor amount and 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 [20,22,26]. There is a need to extend current research, by including all sustainability dimensions and topics, as well as comprehensively integrating BIM for sustainability assessment [53]. BIM software should also embrace more sustainability issues and improve interoperability between them, avoiding the need for model checking and remodelling [16,17,19,90]. It is also frequently necessary to use several software to gather assessment data for the evaluation of only one BSA scheme [60]. Consequently, investigators [25,200] 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 [90].

7.2.3 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 [135,136]. VPL allows programming with a two-dimensional notation using visual elements instead of textual ones, allowing users to interpret it in a much faster and easier way [83,135,277]. 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 [137,138]. VPL provides transparency, flexibility and portability as design rules are machine and human-readable [135].

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 years, as the process consists of repetitive tasks that can be automatically performed with proper codification [135]. Burggraf et al. [27] have created an automatic system for checking semantic data of BIM-based factory designs through Dynamo. Cavalliere et al. [138] 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. [135] 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 [28] and, they can be used

to rapidly elaborate LCI. Villaschi et al. [134] 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 [138,139]. BSA methods have also been addressed with VPL. Kensek et al. [137] 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 [83]. Sheikhkhoshkar et al [140] 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 [141] have used VPL and a 3D real-time platform to obtain extended reality oriented to 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 FM, with several links between BIM models, databases, and sensors data [136,142]. Moreover, Tsai [278] has suggested that VPL should be included in architecture, design, and engineering courses to facilitate the programming learning process. VPL has a steeper learning curve than text-based languages, lowering the barriers when entering into programming [83].

Among the most recognised VPL tools are Grasshopper for Rhinoceros3D, Dynamo for Autodesk Revit, Marionette for Vectorworks, Generative components, Digital Project, and Yeti [143].

7.2.4 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, or 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 [6,8,73]. 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. In the Portuguese version of SBTool ($SBTool^{PT}$), each sustainability criterion is then classified with a quantitative score that 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 to establish a dimensionless value and to easily express the building score to non-experts, according to Table 29. In the qualitative scale, D corresponds to the national conventional practice, while A corresponds to the national best practice. After weighing all the parameters, a final sustainable classification is given to the building [6].

Table 29 – SBTool 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	$\overline{P} < 0.00$

The transposition of SBTool for the Portuguese context was made at different levels for residential buildings, service buildings, urban areas, among others [69–71]. Between the local versions, SBTool^{PT}-H stands out since 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 30. 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.

Table 30 – 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

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. Moreover, the application of BSA methods is also usually incompatible with project short deadlines, leading to their application only in the project latter stages. 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 early stages – supporting eventual modifications with few resources – and effectively enhancing buildings sustainability.

7.3 Material and methods

7.3.1 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 application – SBTool^{BIM} – to automate the assessment of SBTool^{PT}-H. Moreover, it is also intended to efficiently integrate BSA into the BIM environment and project early stages, to effectively enhance building sustainability. The following specific objectives are intended for the SBTool^{BIM} approach and application:

- Simple and intuitive method to promote and encourage BSA implementation by designers;

- Applicable in the project early stages to effectively act on building sustainability, as most sustainable solutions should be introduced during project early stages, 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 an early project 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 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 [27]. 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 sustainable 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 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 all 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. A template will also be created to establish a set of new shared parameters, according to the sustainability assessment requirements. 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 the required assessment data from the BIM model and user inputs, group it according to each criterion's needs, perform the assessment calculations and display the building score.

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 which data 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.

7.3.2 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 [60,205]. It has the capacity to import and export several file formats, including IFC and, to develop personalised interfaces to perform specific tasks through Dynamo. Software capabilities have been found appropriate for SBTool assessment [60] 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 [140]. Dynamo provides a user-friendly workspace where the code is presented as nodes connected with wires [83,142]. Personalised interfaces can be created for the querying and manipulating of the BIM model data [27]. 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, and displaying 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. For this effect, 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 the 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.

7.3.3 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 31. 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.

Table 31 – Case study topography characterisation

Site surface	Area (m^2)	Sealed soil	Reflectance ≥ 60%
Grass	416.78	No	Yes
Native plants	21.35	No	Yes
Sidewalks	15.41	Yes	Yes
Building footprint	97.76	Yes	No
Car access road	84.13	Yes	No

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 Figure 33.

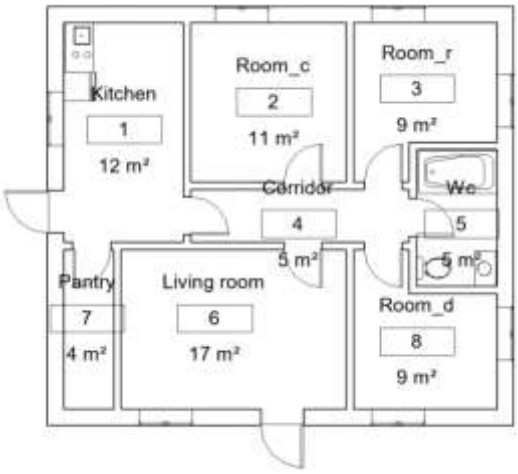


Figure 33 – Case study floor plan

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 32, as well as the adopted construction solutions.

Table 32 – Case study material characterisation

		Material	Area (m^2)	Environmental impact categories quantification (per m^2)						Cost	Density (kg/m^3)
				GWP ($kgCO_2$)	ODP (kgCFC-11)	AP ($kgSO_2$)	POCP (kgC_2H_4)	EP ($kgPO_4$)	FFDP (MJ)		
Exterior walls		Common brick 15.0 cm + 11.0 cm	198.78	2.20E-01	1.58E-08	5.48E-04	4.00E-05	6.71E-05	2.58E+00	4.75 €/m^2	700
		Rigid insulation 4.0 cm	99.40	4.14E+00	1.10E-07	1.49E-02	6.75E-03	1.24E-03	1.05E+02	4.00 €/m^2	23
	Finishing	Cement plaster (1.5 cm each side)	198.78	1.95E-01	8.00E-09	3.15E-04	1.29E-05	4.87E-05	1.31E+00	17.00 €/m^2	1100
	Finishing	Painting (1.0 cm each side)	198.79	2.46E+00	3.69E-07	1.69E-02	7.72E-04	4.23E-03	4.78E+01	8.00 €/m^2	1188
Interior walls		Common brick 11.0 cm	91.16	2.20E-01	1.58E-08	5.48E-04	4.00E-05	6.71E-05	2.58E+00	4.75 €/m^2	700
	Finishing	Cement plaster (1.5 cm each side)	182.30	1.95E-01	8.00E-09	3.15E-04	1.29E-05	4.87E-05	1.31E+00	17.00 €/m^2	1100
	Finishing	Painting (1.0 cm each side)	182.32	2.46E+00	3.69E-07	1.69E-02	7.72E-04	4.23E-03	4.78E+01	4.50 €/m^2	1188
Floor slab	Finishing	Oak floor	90.00	-1.20E+00	1.28E-08	8.05E-04	7.29E-05	1.29E-04	1.98E+00	65.00 €/m^2	750
		Cement plaster 2.0 cm	90.00	1.95E-01	8.00E-09	3.15E-04	1.29E-05	4.87E-05	1.31E+00	17.00 €/m^2	1100
		Rigid insulation 4.0 cm	90.00	4.14E+00	1.10E-07	1.49E-02	6.75E-03	1.24E-03	1.05E+02	4.00 €/m^2	23
		Reinforced concrete 40.0 cm	90.00	1.48E-01	3.55E-09	5.56E-04	5.28E-05	5.76E-05	1.24E+00	70.00 €/m^2	1300
Windows		Glass	13.15	9.73E-01	8.01E-08	8.51E-03	2.86E-04	6.53E-04	1.15E+01	440.00 €/un	2480
		Sash/wood	48.52	-1.20E+00	1.28E-08	8.05E-04	7.29E-05	1.29E-04	1.98E+00		560
Doors		Aluminium (exterior)	12.57	4.28E+00	1.84E-06	3.80E-02	2.23E-03	1.21E-03	6.28E+01	432.00 €/un	2700
		Wood panel	26.39	-1.20E+00	1.28E-08	8.05E-04	7.29E-05	1.29E-04	1.98E+00	432.00 €/un	560
		Wood frame	14.85	-1.20E+00	1.28E-08	8.05E-04	7.29E-05	1.29E-04	1.98E+00		560
Roof	Finishing	Concrete tile	98.16	2.12E-01	1.11E-08	4.47E-04	2.34E-05	7.64E-05	1.73E+00	25.00 €/m^2	1300
		Rigid insulation 5.0 cm	98.16	4.14E+00	1.10E-07	1.49E-02	6.75E-03	1.24E-03	1.05E+02	4.00 €/m^2	23
		Flexible membrane with bitumen	98.16	5.81E-01	7.27E-07	7.27E-03	1.94E-03	3.02E-04	5.33E+01	6.00 €/m^2	1700
		Steam PVC barrier	98.16	1.97E+00	2.84E-09	5.35E-03	3.12E-04	7.59E-04	4.69E+01	13.00 €/m^2	1500
		Reinforced concrete 20.0 cm	98.16	1.48E-01	3.55E-09	5.56E-04	5.28E-05	5.76E-05	1.24E+00	70.00 €/m^2	1300

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 integrated in door and window frames;
- Painting and wood floor used indoors are low VOC materials;
- The materials with recycled content are presented in Table 33. This table also presents the market best and conventional practices of the recycled content of each material and the recycled content of the used material.

Table 33 – 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

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 34 and the rainwater satisfaction coefficient (CSAT) was considered 100% for analysis purposes. Recycled water from the identified fixtures is used for irrigation purposes.

Table 34 – 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

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 35.

Table 35 – Complementary data for SBTool[BIM]

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 150m	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 €	

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 36 and 37, respectively.

Table 36 – Case study public transport stations

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

Table 37 – 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

All the presented data must be given for SBTool[BIM] to carry out the sustainability analysis. Some of it can be introduced through the 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 33, 35, 36 and 37.

7.4 Results

7.4.1 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 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 the exportation of 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 38, 39 and 40, 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 for performance simulations, as well as the direct connection with Autodesk Insight to get an Energy Plus model.

According to Table 38, for the environmental dimension, 11 criteria will have their required data 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 the 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 the renewable energy production, which are beyond Autodesk Revit capabilities. Overall, 13 out of 15 environmental criteria will be directly addressed by the SBTool^{BIM} application.

When concerning the social dimension in Table 39, it can be noticed the higher requirements of 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 can gather their requirements through an interface, while the remaining 3 criteria will require the use of external tools. For this case, thermal, visual, and acoustic performance results are needed 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 40, will have different assessment modes. The first 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.

Table 38 – 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.			

Table 39 – 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 40 - 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

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 Figure 34. 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 respectively Dynamo file and can be made before or after the model creation/import. SBTool^{BIM} template aims to create new shared parameters that will be filled with the required data for the SBTool^{PT}-H assessment. This will be specific green building data, which parameters are not found in the Autodesk Revit base template.

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 respectively 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 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 score of 19 criteria and global qualitative and quantitative building score, extracted in an Excel spreadsheet.

The first outcome is intended to be used as a fast decision support method during project design, providing the users with a reliable and real-time sustainability assessment to compare different solutions. The second outcome is intended to be used for the full SBTool^{PT}-H evaluation. The extracted Excel spreadsheet will be connected to the existing SBTool^{PT}-H spreadsheet through macros functions. By automatically filling 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 then 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 EnegryPlus file (IDF format) can be automatically obtained to carry out dynamic simulations. After performing all the required simulations, results must be gathered manually 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.

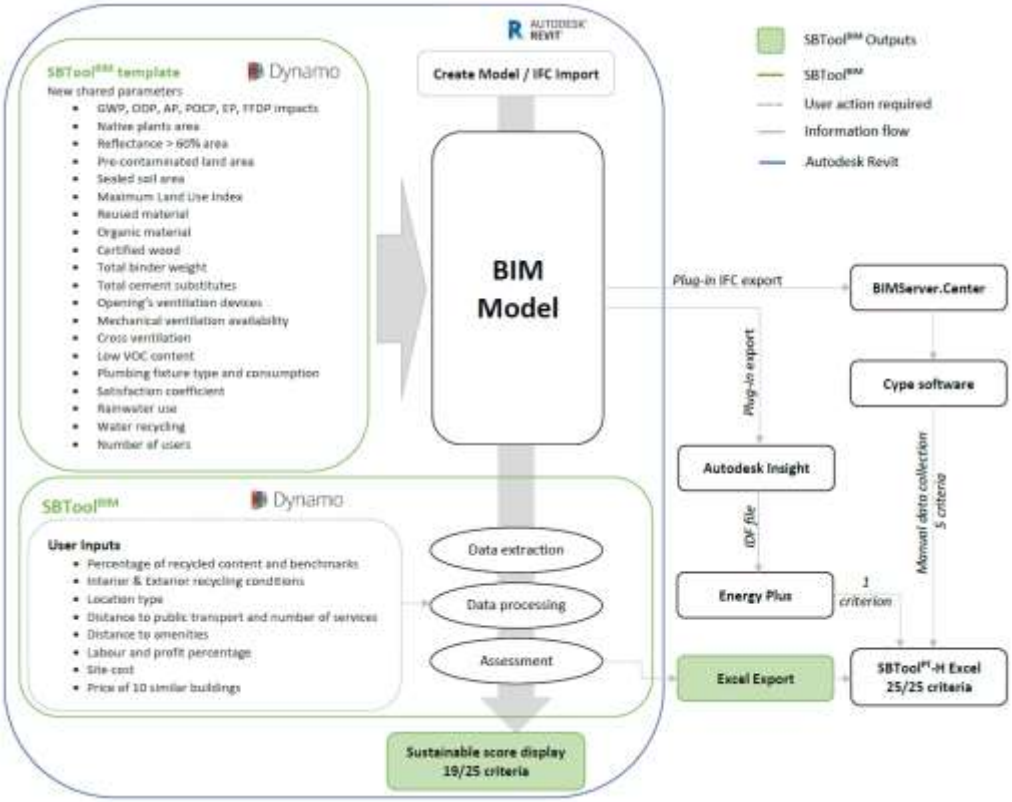


Figure 34 – SBTool^{BIM} process map

7.4.2 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 needs. Facing the need to properly describe a BIM model for the sustainability evaluation, the SBTool^{BIM} template was developed. In short, the template was developed in Dynamo (VPL language) considering the architectural template as a basis and, can be run before or after the model creation. New shared parameters are automatically created according to the identified input requirements for SBTool^{PT}-H. Table 41 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.

Table 41 – Created parameters for SBTool[BIM]

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
Litres 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

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 parametric modelling and should include the site topography and constructions. Each topography zone – 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. Figure 35 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 (Figure 35 b), red square, under Autodesk Revit manage tab.

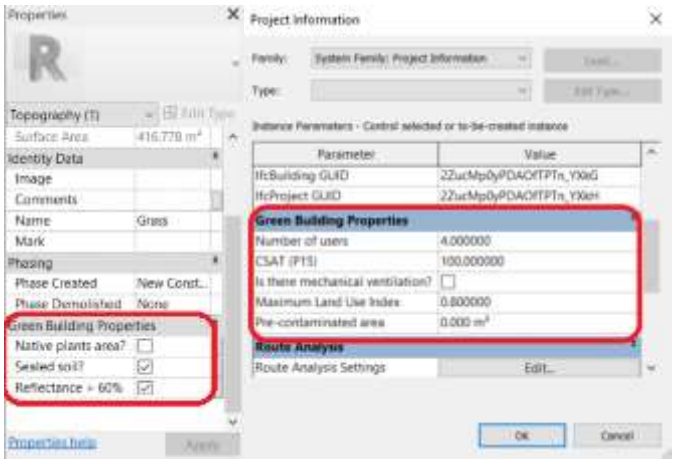


Figure 35 – (a) Topography and (b) Project Information data

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 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 previous element's materials and defining their main characteristics for the sustainability assessment, as presented in Figure 36. 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 Figure 36 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.

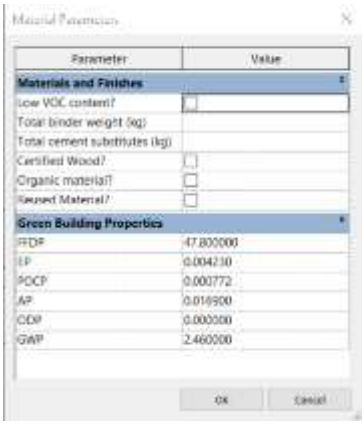


Figure 36 – Material characterisation

The building's interior and exterior openings (windows and doors) must also be modelled and characterised. Besides the material selection (and respectively 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 finishings 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 Figure 37 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 induvial space, according to Figure 37 b). Moreover, the “room” function will also be mandatory when exporting the BIM model for 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, sizes, shape, location, and orientation. Sustainability data has been included as non-graphic information, with precise quantities and properties of building materials for a sustainability assessment [108,279]. According to different authors [80,109], the LOD 300 is also the minimum specification to proceed with building performance analysis in specified BIM tools.

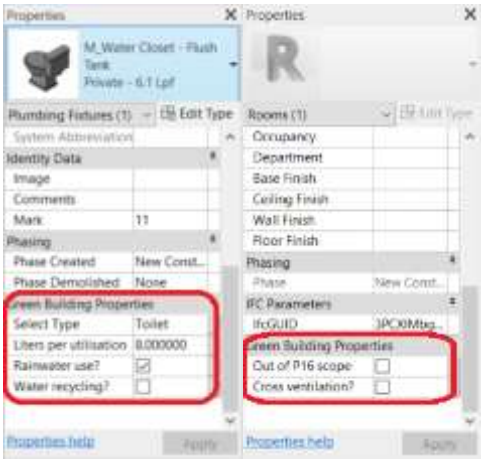


Figure 37 – (a) Plumbing fixtures characterisation and (b) Room characterisation

7.4.3 SBTool[BIM]

7.4.3.1 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. Figure 38 presents an example of the basic nodes which starts 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.

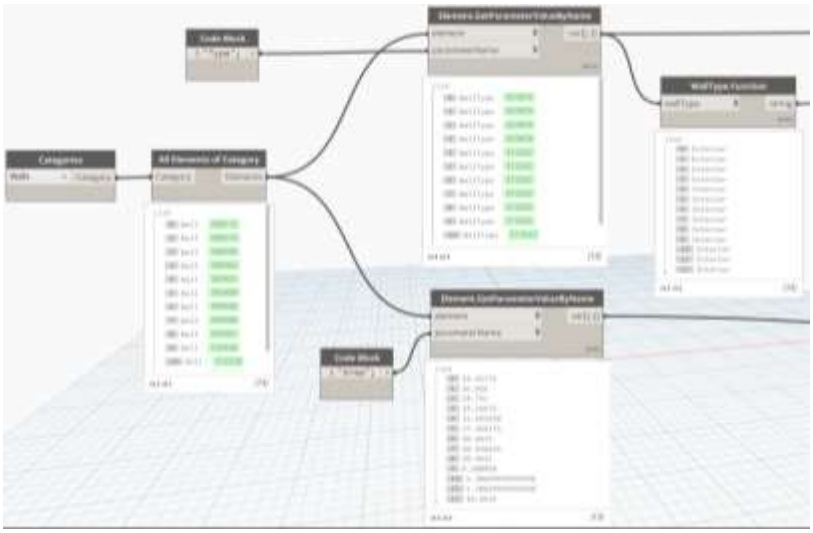


Figure 38 – Collecting and processing data in Dynamo

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 Figure 39. Specific popup windows were developed for criteria P10, P13, P21, P22, P23 and P24.

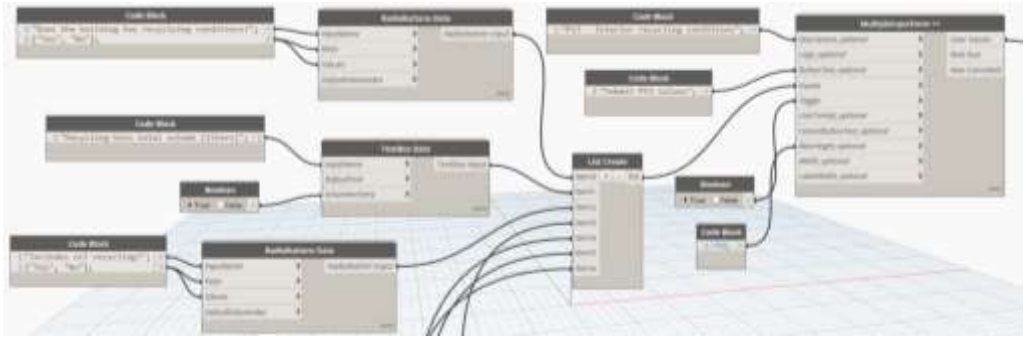


Figure 39 – User interface creation in Dynamo

After getting the required data for each criterion, SBTool[BIM] performs the assessment calculations, normalisations, and qualitative quantification, as presented in Figure 40.

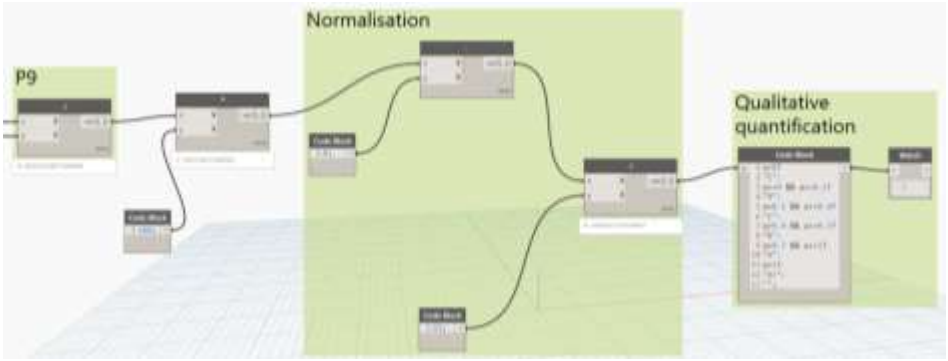


Figure 40 – Result normalisation and qualitative quantification in Dynamo

Finally, SBTool^{BIM} displays a pop-up window into 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 score 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 for the research scope:

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

7.4.3.2 Case study application

The case study presented in section 6.3 was modelled in Autodesk Revit under the SBTool^{BIM} template and according to the procedure presented in section 7.4.1. 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 Figure 41.



Figure 41 – Dynamo Player in Autodesk Revit

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. Figure 42 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 (column 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.

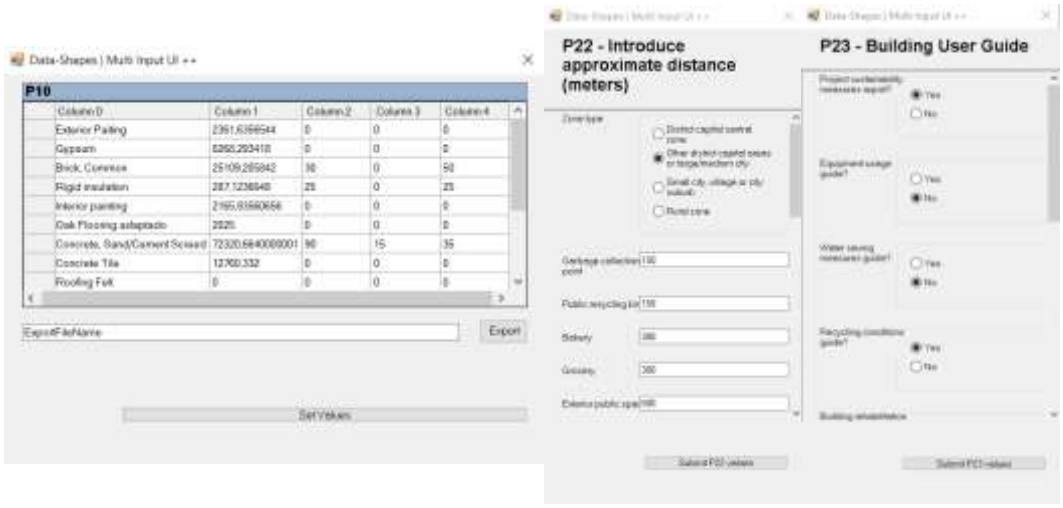


Figure 42 – input forms though user interfaces in Autodesk Revit

Combining and processing the introduced data with the BIM model data, SBTool[BIM] proceed with the assessment and normalisation of all 19 criteria, displaying the final case study result in the Autodesk Revit environment, according to Figure 43. Both the individual score of each criterion and the global building score are presented, indicating a B mark for the building sustainability score.

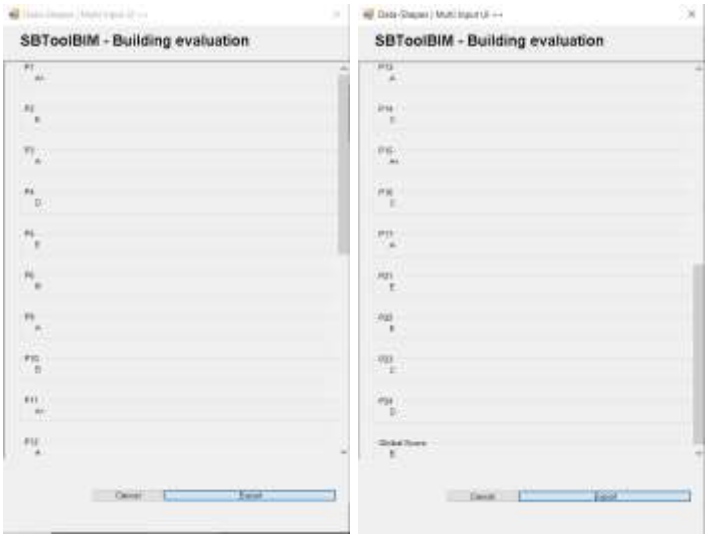


Figure 43 – SBTool[BIM] results in Autodesk Revit

Simultaneously, an Excel is produced and exported with the detailed building score, as presented in Figure 44. Both the qualitative and quantitative score of each criterion is presented to further allow a full evaluation of SBTool[PT]-H. Such a procedure is explained during the next section.



Figure 44 – Excel report produced by SBTool[BIM]

To introduce improvement measures, designers must only change the building design or the characteristics of the materials directly in the BIM model and according to their intentions. Then, SBTool[BIM] must be used again, to achieve the sustainability score of the improved desgin. Note that the user inputs in the SBTool[BIM] application (Figure 42) 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 the required information. Modifications in the inputs are still available. Therefore, only a few efforts in editing the BIM model are needed to compare the sustainability results 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 42, where the quantitative score of each criterion is faced. SBTool[BIM] results were gathered from the extracted Excel spreadsheet (Figure 44). 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 numbers), 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 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 similar scores.

Table 42 – 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	-

7.4.4 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 provide 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 the IFC to BIMServer.center 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, which are 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 needed 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 [126].

For the assessment of criterion P18, the BIM model must reach Energy Plus software to determine the thermal comfort level and the hourly operational temperature. This is made by exporting the BIM model for Autodesk Insight, which then allows extracting 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} through macros. The manual requirement is due to the need to assess data from Cype and Energy Plus software environment and simulation reports, which are not capable to be further connected. Cype software provides direct data for the complete evaluation of P7, P8, P19 and P20, making a total of 23 criteria fully automated. 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.

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

7.5 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 and novel BIM-based approach and application 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.

7. AUTOMATING BUILDING SUSTAINABILITY ASSESSMENT

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, 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. Such template has created 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, and it can be used before or after the BIM model creation. Moreover, 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 assessed by the user and then introduced 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. Despite it does not assess all SBTool^{PT}-H criteria, the application analysis relies on 75% of its criteria and can be faced 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 data from the remaining six to achieve the building 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 less than 2% were faced 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 few 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 Open BIM concept by being 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 then 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 SBTool^{BIM} template, to fill building performance data directly in 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 project later stages, i.e., the building thermal comfort can only be known when all the building envelope and systems are well defined. To act in project early stages with real-time feedback, SBTool^{BIM} application does not considered such building performance criteria but offers the additional BIM links to assess them. 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 early stages, where such data is usually unavailable. Regarding its functionality, SBTool^{BIM} requires a couple of

minutes to start, freezing Autodesk Revit during this time. An additional interface is still needed to facilitate comparisons when analysing modification measures, showing the previous assessment result.

The research outputs have presented a novel BIM-based application which provides a real-time assessment of building sustainability. Up to date, BIM approaches to automate BSA concern the use of BIM-based analysis results for the evaluation of BSA criteria, without automated data collection, processing, or evaluation. This BIM-based application reflects the assessment procedure of SBTool^{PT}-H and provides instant feedback for designers, making it a cutting-edge tool for building sustainability. Project designs can be easily analysed and compared with few resources, creating the opportunity to integrate new sustainability measures and improve building efficiency. 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 the realisation of specific performance evaluations. Subsequent analysis on the same project only takes a couple of minutes. When integrated into BIM environment, the prior existence of a BIM model can further reduce the assessment time. Nevertheless, the SBTool^{BIM} application will always work with constant input values when trying to optimise a certain building feature, obtaining real-time feedback about its evaluation.

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 the 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 the 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.

7.6 Conclusions

This research has applied the BIM method to automate the assessment of SBTool^{PT}-H criteria. By developing an application – SBTool^{BIM} – in Dynamo through VPL, it was possible to reflect and automate the requirements of a sustainability assessment. A total of 19 criteria were fully included and automated, while for the remaining 6 criteria a BIM linkage was identified for the assessment.

A novel and cutting-edge application was developed constituted of two different files: the SBTool^{BIM} template, which allows characterising the BIM model with sustainability requirements and, the SBTool^{BIM} application, which automatically extracts and aggregates building data to determine the building sustainability score. SBTool^{BIM} has the potential to be a powerful tool for designers, providing real-time feedback about the building sustainability level in the very early project stages, and promoting the introduction of new improvement measures. The automatic evaluation of 19 criteria provides a reliable indication of the building sustainability level, allowing designers to know in advance their project's sustainability performance before the construction itself. Furthermore, it also allows exporting the analysis results to proceed with a complete analysis, avoiding double work and reducing the assessment time from a whole week to a couple of days, as well as the required human, time and financial resources.

Unfortunately, it was not possible to automate the 25 criteria of SBTool^{PT}-H within the application. Some criteria require specific input data, such as building performance simulation results, which are out of Autodesk Revit scope. Nevertheless, an alternative BIM procedure was identified to collect the required information, establishing a straightforward connection with the BIM model. Thus, all the assessment procedure can be made inside the BIM environment.

Overall, it is expected that SBTool^{BIM} will be an essential tool to evaluate and optimise building sustainability, proving valuable insights to achieve sustainable buildings and meet decarbonisation and climate targets. Moreover, the research outputs provide a novel framework for a new era of performing building sustainability assessments. Besides process automation, it can effectively be integrated into the BIM working process, promoting its fully incorporation as part of a project development process. Furthermore, with the current software developments, SBTool^{BIM} will eventually handle all criteria, making available a full sustainable evaluation in a matter of minutes.

8. CONCLUSIONS, CONTRIBUTIONS AND FUTURE WORK

This Chapter summarises the main conclusions and contributions of the research and the recommendations for future work.

8.1 Conclusions and main contributions

The research content is highly based on published or under submission articles, where the analysis and conclusions of each chapter are already presented. To avoid duplications, this chapter is focused on the investigation general conclusions.

There is an urgent need and demand for sustainable buildings, both to provide a healthy and comfortable built environment, as well as to achieve world and European common goals of decarbonisation and climate neutrality. The building sector has been recognised as a key industry when dealing with environmental impacts, requiring specific oriented actions and higher stakeholders' awareness and engagement.

The current state of the literature shows the potentialities of BIM and BSA as a pathway to enhance building sustainability but is still missing a common and well-established approach both to use BIM for sustainability assessment automation and to integrate BSA into the BIM environment. Moreover, BIM is still not properly oriented to building sustainability and has not been comprehensively used in the evaluation process of BSA methods. Consequently, the maximum capabilities of both concepts are being hampered and often neglected due to the lack of knowledge. With this concern, this research has developed a novel BIM-based approach to simplify and automate the assessment of the SBTool^{PT}-H – SBTool^{BIM} application. The aim was to provide a real-time decision support tool regarding building sustainability for the project early stages and to frame the integration of BIM in BSA. Thus, designers will be able to compare the performance of different sustainability measures to effectively enhance building sustainability and BSA will be properly framed into a BIM environment, so it could be eventually part of the common project workflow.

By analysing the existing approaches to integrate BIM in the most noticeable BSA methods – LEED, BREEAM and SBTool – the attractiveness of a real-time application for SBTool has been proved, allowing to assess the same or more criteria than the other two BSA schemes. Moreover, Autodesk Revit was found appropriate to host SBTool^{BIM}, due to its capabilities to store multi-disciplinary information, handle BIM model data through VPL and import/export IFC (both to import BIM models from other platforms, as well as to export BIM models to specific BIM tools for building performance analysis).

To develop SBTool^{BIM}, a rule-automation checking procedure was used. First, SBTool^{PT}-H criteria were carefully analysed – input data requirements and calculation procedure – to define the "rule interpretation" phase.

Then, the BIM model was created in Autodesk Revit, where specific parameters were necessary to characterise the model with the required data for the sustainability assessment. To do so, a template was developed in Dynamo to automatically create 28 shared parameters, which the user must complete to proceed with the analysis. These parameters reflect the input requirements of SBTool^{PT}-H, especially for quantitative criteria. The next stage, the "rule interpretation" consisted of the materialisation of the interpreted rules, by developing the SBTool^{BIM} application in Dynamo. VPL was used due to its faster and easier interpretation for non-experts. To assess a set of qualitative criteria, a way to transform qualitative variables into measurable quantitative predictions was required. In SBTool^{BIM}, a couple of pop windows show up in the Autodesk Revit environment, asking the user for qualitative information and external/region-specific factors. This data is then converted into a quantitative value to aggregate the analysis results. Finally, the "rule report" or sustainability score was also automated in Dynamo and a specific window shows up at the end of the analysis with the final sustainability score. Moreover, an Excel spreadsheet is also created with the results to further extend the analysis outcomes.

SBTool^{BIM} application itself allows to automatically assess 19 out of 25 criteria from SBTool^{PT}-H, providing a concise and reliable indication of the building sustainability level. The application is intended to act in the project early stages as a decision support tool with real-time feedback regarding building sustainability, as this is the most critical phase for integrating sustainable measures. By properly characterising the BIM model, designers are provided with real-time analysis of the sustainability level of their projects, allowing for the introduction and comparison of different improvement measures. Moreover, SBTool^{BIM} demonstrates the feasibility and potentialities of BIM integration in BSA, by significantly reducing the assessment time and efforts. Consequently, it allows to shift the BSA to early project stages to effectively enhance building sustainability, instead of just classifying the building sustainability level in the project latter stages. By being inserted into a BIM environment, SBTool^{BIM} also improves coordination and communication among other project disciplines, allowing it to carry out a more comprehensive, inclusive, and detailed assessment. It will also provide the opportunity to effectively integrate BSA in current BIM-based project procedures, making it an integral component of common building projects. With the use of SBTool^{BIM}, both BIM and BSA benefits will be granted for building projects.

SBTool^{BIM} saves substantial efforts and resources when performing BSA, although designers still need to collect material data and region-specific factors to serve as input for the application. The human factor will

still be essential to perform and achieve reliable assessment results, both for data collection, assessment supervision and result analysis. SBTool^{BIM} main setback concerns the impossibility of automatically assessing all the 25 criteria from SBTool^{PT}-H. Six of these criteria require the results of building performance simulations, which are out of Autodesk Revit scope. A BIM linkage was established to identify a pathway to collect the remaining data within the BIM environment, creating a straightforward method to collect the information in additional BIM tools and conclude the evaluation when combined with SBTool^{BIM} Excel outcomes. Furthermore, building performance data is usually unavailable in the project early stages and its integration in SBTool^{BIM} would hamper both the possibility to use the application in such stages and to have real-time feedback. Additionally, SBTool^{BIM} does not consider some aspects of the SBTool^{PT}-H evaluation guide, such as structural columns. Other structural elements can be considered if modelled as walls, floors, or roofs. Once again, detailed structural data is often available in project later stages and its integration in SBTool^{BIM} would circumscribe the assessment for such phase, which does not meet the research objectives. Finally, SBTool^{BIM} functionally is somehow dependent on the model complexity and the computer system features. When used, SBTool^{BIM} freezes Autodesk Revit for a couple of minutes, which can be longer if the model complexity is higher and/or the system features are not adequate. Generally, the system requirements are the same as for Autodesk Revit use.

SBTool^{BIM} was successfully validated against the traditional assessment process, with results differences below 2% in 3 out of 19 criteria, mainly due to rounding issues when assessing material quantities and building dimensions. Overall, the main differences between both assessments, as well as the benefits and setbacks, are presented in Table 43.

Table 43 – SBTool^{BIM} vs traditional assessment

BIM assessment	Traditional assessment
Application in the project early stages	Application in the project latter stages
Automatic quantification of materials and dimensions	Manual quantification of materials and dimensions
Automated calculation procedure	Manual calculation procedure
Easy introduction of improvement measures	Discourage the introduction of improvement measures
BIM model can be directly used for building performance analysis	Building performance analysis requires model creation
It does not consider some of the SBTool^{PT}-H details	SBTool^{PT}-H is fully considered
Total assessment time: 1- 2 days[1] (Including data collection, model creation, calculation procedure and building performance analysis)	Total assessment time: 5-7 days (Including data collection, materials and dimensions quantifications, calculation procedure and building performance analysis)

[1] Estimated time for the first project analysis. Following analysis on the same project usually take a couple of minutes.

Currently, SBTool^{BIM} is ready to use in new and existing residential Portuguese buildings and adapted to the Portuguese scenario and standards. Foreign buildings can use SBTool^{BIM} to understand how to improve building sustainability, but the final sustainable score may not represent the building reality. Although, method replicability was found very accessible. SBTool^{BIM} file can be easily edited and adapted in Dynamo and new criteria can be included through similar established procedures. SBTool^{BIM} also holds the flexibility of the SBTool international system, allowing it to replicate the research outcomes in other building types and countries with few efforts. SBTool^{BIM} process map and ideology can also be used to automate other BSA schemes, as long as they are also based on key performance indicators.

Note also for the applied software. Autodesk Revit has been revealed to be a proper BIM platform to host SBTool^{BIM}. It allows the creation and characterisation of BIM models with all the required data for the assessment (as personalised parameters can be included) or import a complete BIM model through IFC, integrating SBTool^{BIM} into the BIM environment. It allows the development of custom interfaces through Dynamo which provides control and customisability of BIM models and allows the creation of personalised algorithms. The identified software for the BIM linkage – Cype software – has presented satisfactory interoperability with Autodesk Revit, allowing to exchange BIM models with few resources. Cype software is adapted to the Portuguese standards and the required building performance simulations also provide data for project submission. Overall, similar conclusions have been reached as other related studies – BIM software is not properly oriented to BSA, and several software is still needed to fully assess one BSA scheme. Note also that all this software requires a user license which can have high investment costs. To properly

guide the use of SBTool^{BIM} and gather the remaining data for a full evaluation, SBTool^{BIM} User Guide was developed and attached to this research – Appendix A.

Which concerns to the research procedure, a slight deviation was noticed from the initial plan. SBTool^{BIM} was intended to be divided into 3 assessment stages and embrace 24 criteria, as presented in Chapter 4. However, with the research evolution, a set of qualitative data and building performance results were noticed to require specific BIM tools, which provide results by means of reports or directly in the software environment. Such fact, hinders the possibility of further exchanging that data automatically back to SBTool^{BIM}. Additionally, building performance simulations are usually made in a more advanced stage of the project, as they need specific knowledge of different project disciplines. Moreover, the final result shows the unpredictability of the automation process, especially for non-expert users, as some of the intended actions for SBTool^{BIM} were not feasible to be automated.

Nevertheless, the SBTool^{BIM} application is able to provide reliable real-time feedback with a strong prediction of the building sustainability level in early project stages, acting as a decision support tool even for non-experts designers on sustainability. It has successfully established a novel and common approach for integrating BIM in BSA for process simplification and automation, which can serve as a systematic framework to apply BIM in other BSA schemes, as well as an example to frame BSA in future BIM standards. The use of SBTool^{BIM} will represent a pathway to reduce the building sector impacts and provide valuable contributions for reaching the EU and UN climate neutrality and decarbonisation goals by producing highly efficient and ecological buildings.

8.2 Further research

This research has provided valuable insights for the theory and practical application of the integration of BIM in BSA methods. Although, there are still a couple of subjects in need of further development, such as:

- SBTool^{BIM} needs a new interface to facilitate the comparison of improvement measures with the previous analysis. Currently, the user must "manually" compare the achieved results of each simulation scenario. Such an interface will require saving the simulation results in a local file to later assess and present them in the new analysis final report;

- SBTool^{BIM} Dynamo algorithm should be optimised to minimise the assessment time of large and complex buildings. With the increasing knowledge, new ways to create Dynamo algorithms will be presented and innovative techniques can be used to reflect the existing algorithm;
- SBTool^{BIM} should be extended to embrace other building types, such as offices, schools, or medical buildings. At the first stage, it is recommended to explore other Portuguese versions of SBTool and, later, versions from other countries;
- SBTool^{BIM} was successfully tested by master students in different residential buildings. However, real scenario applications are still required, such as in design offices. This will be a critical issue to understand if SBTool^{BIM} meets practitioners needs, as well as to improve the tool itself;
- Inclusion of the remaining six criteria in SBTool^{BIM}. With the increasing software developments and informatics knowledge, SBTool^{BIM} will eventually handle all criteria, making available a full sustainable evaluation in a matter of minutes;
- Replicate SBTool^{BIM} framework in other BSA schemes, such as LEED and BREEAM to increase BIM integration in other worldwide recognised schemes. Otherwise, the potential impact of the integration of BIM in BSA will not be achieved and, consequently, the sector environmental targets.

References

[1] Y. Li, X. Chen, X. Wang, Y. Xu, P.-H. Chen, A review of studies on green building assessment methods by comparative analysis, Energy Build. 146 (2017) 152–159. https://doi.org/10.1016/J.ENBUILD.2017.04.076.

[2] United Nations Environment Programme, 2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector, Nairobi, 2021.

[3] BPIE (Buildings Performance Institute Europe), A Guidebook to European Buildings Efficiency: Key regulatory and policy developments Report on the evolution of the European regulatory framework for buildings efficiency, 2022. https://www.bpie.eu/publication/a-guidebook-to-european-buildings-efficiency-key-regulatory-and-policy-developments/ (accessed September 2, 2022).

[4] E. Commission, From where do we import energy?, (n.d.). https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2c.html (accessed October 26, 2022).

[5] BPIE (Buildings Performance Institute Europe), Thinking Ahead for Buildings, Climate and People – BPIE Biennial report 2020 – 2021, 2022.

[6] R. Mateus, L. Bragança, Sustainability assessment and rating of buildings: Developing the methodology SBToolPT–H, Build Environ. 46 (2011) 1962–1971. https://doi.org/10.1016/J.BUILDENV.2011.04.023.

[7] L.P.N. Sanhudo, J.P. da S.P. Martins, Building information modelling for an automated building sustainability assessment, Civil Engineering and Environmental Systems. 35 (2018) 99–116. https://doi.org/10.1080/10286608.2018.1521393.

[8] S.N. Kamaruzzaman, H. Salleh, E.C. Weng Lou, R. Edwards, P.F. Wong, Assessment Schemes for Sustainability Design through BIM: Lessons Learnt, in: S.N.B. Kamaruzzaman, A.S.B. Ali, N.F.B. Azmi, S.J.L. Chua (Eds.), MATEC Web of Conferences, The 4th International Building Control Conference, EDP Sciences, Kuala Lumpur, Malaysia, 2016: p. 00080. https://doi.org/10.1051/matecconf/20166600080.

[9] J.P. Carvalho, L. Bragança, R. Mateus, Sustainable building design: Analysing the feasibility of BIM platforms to support practical building sustainability assessment, Comput Ind. 127 (2021) 103400. https://doi.org/10.1016/j.compind.2021.103400.

[10] S. Maltese, L.C. Tagliabue, F.R. Cecconi, D. Pasini, M. Manfren, A.L.C. Ciribini, Sustainability Assessment through Green BIM for Environmental, Social and Economic Efficiency, Procedia Eng. 180 (2017) 520–530. https://doi.org/10.1016/J.PROENG.2017.04.211.

[11] Ecorys, Resource efficiency in the building sector, Rotterdam, 2014.

[12] D. Zhang, J. Zhang, J. Guo, H. Xiong, A Semantic and Social Approach for Real-Time Green Building Rating in BIM-Based Design, Sustainability. 11 (2019) 3973. https://doi.org/10.3390/su11143973.

[13] A.M.I. Raouf, S.G. Al-Ghamdi, Building information modelling and green buildings: challenges and opportunities, Architectural Engineering and Design Management. 15 (2019) 1–28. https://doi.org/10.1080/17452007.2018.1502655.

[14] B. Soust-Verdaguer, C. Llatas, A. García-Martínez, Critical review of bim-based LCA method to buildings, Energy Build. 136 (2017) 110–120. https://doi.org/10.1016/J.ENBUILD.2016.12.009.

[15] B. Succar, Building information modelling framework: A research and delivery foundation for industry stakeholders, Autom Constr. 18 (2009) 357–375. https://doi.org/10.1016/J.AUTCON.2008.10.003.

[16] S. Azhar, W.A. Carlton, D. Olsen, I. Ahmad, Building information modeling for sustainable design and LEED® rating analysis, Autom Constr. 20 (2011) 217–224. https://doi.org/10.1016/J.AUTCON.2010.09.019.

[17] R. Santos, A.A. Costa, J.D. Silvestre, L. Pyl, Informetric analysis and review of literature on the role of BIM in sustainable construction, Autom Constr. 103 (2019) 221–234. https://doi.org/10.1016/j.autcon.2019.02.022.

[18] C. Díaz-López, M. Carpio, M. Martín-Morales, M. Zamorano, Analysis of the scientific evolution of sustainable building assessment methods, Sustain Cities Soc. 49 (2019) 101610. https://doi.org/10.1016/j.scs.2019.101610.

[19] B. Ilhan, H. Yaman, Green building assessment tool (GBAT) for integrated BIM-based design decisions, Autom Constr. 70 (2016) 26–37. https://doi.org/10.1016/J.AUTCON.2016.05.001.

[20] J.P. Carvalho, L. Bragança, R. Mateus, Optimising building sustainability assessment using BIM, Autom Constr. 102 (2019) 170–182. https://doi.org/10.1016/J.AUTCON.2019.02.021.

[21] F. Jalaei, A. Jrade, Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings, Sustain Cities Soc. 18 (2015) 95–107. https://doi.org/10.1016/J.SCS.2015.06.007.

[22] R.E. Edwards, E. Lou, A. Bataw, S.N. Kamaruzzaman, C. Johnson, Sustainability-led design: Feasibility of incorporating whole-life cycle energy assessment into BIM for refurbishment projects, Journal of Building Engineering. 24 (2019) 100697. https://doi.org/10.1016/j.jobe.2019.01.027.

[23] M. Marzouk, S. Azab, M. Metawie, BIM-based approach for optimizing life cycle costs of sustainable buildings, J Clean Prod. 188 (2018) 217–226. https://doi.org/10.1016/J.JCLEPRO.2018.03.280.

[24] J. Li, N. Li, K. Afsari, J. Peng, Z. Wu, H. Cui, Integration of Building Information Modeling and Web Service Application Programming Interface for assessing building surroundings in early design stages, Build Environ. 153 (2019) 91–100. https://doi.org/10.1016/j.buildenv.2019.02.024.

[25] J.K.-W. Wong, K.-L. Kuan, Implementing 'BEAM Plus' for BIM-based sustainability analysis, Autom Constr. 44 (2014) 163–175. https://doi.org/10.1016/J.AUTCON.2014.04.003.

[26] T. El-Diraby, T. Krijnen, M. Papagelis, BIM-based collaborative design and socio-technical analytics of green buildings, Autom Constr. 82 (2017) 59–74. https://doi.org/10.1016/J.AUTCON.2017.06.004.

[27] P. Burggräf, M. Dannapfel, M. Ebade-Esfahani, F. Scheidler, Creation of an expert system for design validation in BIM-based factory design through automatic checking of semantic information, Procedia CIRP. 99 (2021) 3–8. https://doi.org/10.1016/J.PROCIR.2021.03.012.

[28] B. Oliver Rapf, A zero carbon and circular built environment – Policy options for the EU and its Member States, 2019. https://globalabc.org/resources/publications/zero-carbon-and-circular-economy-challenge-built-environment-policy-options (accessed September 5, 2022).

[29] United Nations, Sustainable buildings | UNEP - UN Environment Programme, (n.d.). https://www.unep.org/explore-topics/resource-efficiency/what-we-do/cities/sustainable-buildings (accessed September 9, 2022).

[30] European Commission, A new Circular Economy Action Plan, (2020). https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN (accessed September 6, 2022).

[31] European Environment Agency, Building renovation: where circular economy and climate meet — European Environment Agency, Briefing No. 12/2022. (2022). https://www.eea.europa.eu/publications/building-renovation-where-circular-economy (accessed September 6, 2022).

[32] Y.H. Dong, S.T. Ng, A life cycle assessment model for evaluating the environmental impacts of building construction in Hong Kong, Build Environ. 89 (2015) 183–191. https://doi.org/10.1016/J.BUILDENV.2015.02.020.

[33] T. Jia Wen, H. Chin Siong, Z.Z. Noor, Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: Case studies of residential buildings in Iskandar Malaysia, Energy Build. 93 (2015) 295–302. https://doi.org/10.1016/J.ENBUILD.2014.12.002.

[34] European Construction Sector Observatory, Stimulating favourable investment conditions, 2018. https://single-market-economy.ec.europa.eu/sectors/construction/observatory/analytical-reports_en (accessed September 9, 2022).

[35] G. Ragonnaud, Strategy for a Sustainable Built Environment, Carriage Details | Legislative Train Schedule. (2022). https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-strategy-for-a-sustainable-built-environment (accessed September 7, 2022).

[36] G.S. Matiazzi, L. Bragança, Metodologia para análise, planejamento e monitoramento de resiliência urbana, in: Congresso Internacional SUSTENTABILIDADE URBANA - 14ª Jornada URBENERE e 2ª Jornada CIRES, 2018.

[37] G.H. Brundtland, Our Common Future: Report of the World Commission on Environment and Development, Oslo, 1987. https://doi.org/10.1080/07488008808408783.

[38] T. Saraiva, M. Almeida, L. Bragança, The importance of the category of consciousness and education for sustainability in methodologies for eco-efficiency in school buildings, in: Proceedings of EURO ELECS 2015, Guimarães, 2015.

[39] C. Araújo, M. Almeida, L. Bragança, Analysis of some Portuguese thermal regulation parameters, Energy Build. 58 (2013) 141–150. https://doi.org/10.1016/J.ENBUILD.2012.11.024.

[40] Y. Dutil, D. Rousse, G. Quesada, Sustainable Buildings: An Ever Evolving Target, Sustainability 2011, Vol. 3, Pages 443-464. 3 (2011) 443–464. https://doi.org/10.3390/SU3020443.

[41] C.J. Kibert, Establishing principles and a model for sustainable construction, in: Sustainable Construction : Proceedings of the First International Conference of CIB TG 16, November 6-9, Center for Construction and Environment, M.E. Rinker Sr. School of Building Construction, College of Architecure, University of Florida, Tampa, Florida, 1994: p. 888.

[42] G. John, D. Clements-Croome, G. Jeronimidis, Sustainable building solutions: a review of lessons from the natural world, Build Environ. 40 (2005) 319–328. https://doi.org/10.1016/J.BUILDENV.2004.05.011.

[43] World Green Building Council, What is green building?, (n.d.). https://www.worldgbc.org/what-green-building (accessed September 9, 2022).

[44] T. Häkkinen, K. Belloni, Barriers and drivers for sustainable building, Building Research & Information. 39 (2011) 239–255. https://doi.org/10.1080/09613218.2011.561948.

[45] A. Haapio, P. Viitaniemi, A critical review of building environmental assessment tools, Environ Impact Assess Rev. 28 (2008) 469–482. https://doi.org/10.1016/J.EIAR.2008.01.002.

[46] K. Figueiredo, R. Pierott, A.W.A. Hammad, A. Haddad, Sustainable material choice for construction projects: A Life Cycle Sustainability Assessment framework based on BIM and Fuzzy-AHP, Build Environ. 196 (2021) 107805. https://doi.org/10.1016/J.BUILDENV.2021.107805.

[47] L. Bragança, R. Mateus, H. Koukkari, Building Sustainability Assessment, Sustainability. 2 (2010) 2010–2023. https://doi.org/10.3390/su2072010.

[48] N. Wang, H. Adeli, Sustainable building design, Journal of Civil Engineering and Management. 20 (2014) 1–10. https://doi.org/10.3846/13923730.2013.871330.

[49] International Organization for Standardization, ISO - ISO/TC 59/SC 17 - Sustainability in buildings and civil engineering works, (n.d.). https://www.iso.org/committee/322621.html (accessed September 9, 2022).

[50] World Green Building Council, The benefits of green buildings, (n.d.). https://www.worldgbc.org/benefits-green-buildings (accessed September 9, 2022).

[51] L.C. Tagliabue, F.R. Cecconi, S. Maltese, S. Rinaldi, A.L.C. Ciribini, A. Flammini, Leveraging Digital Twin for Sustainability Assessment of an Educational Building, Sustainability 2021, Vol. 13, Page 480. 13 (2021) 480. https://doi.org/10.3390/SU13020480.

[52] G. Castanheira, L. Bragança, The Evolution of the Sustainability Assessment Tool SBTool PT : From Buildings to the Built Environment, The Scientific World Journal. 2014 (2014) 1–10. https://doi.org/10.1155/2014/491791.

[53] J.K.W. Wong, J. Zhou, Enhancing environmental sustainability over building life cycles through green BIM: A review, Autom Constr. 57 (2015) 156–165. https://doi.org/10.1016/J.AUTCON.2015.06.003.

[54] T. Sartori, R. Drogemuller, S. Omrani, F. Lamari, A schematic framework for Life Cycle Assessment (LCA) and Green Building Rating System (GBRS), Journal of Building Engineering. 38 (2021) 102180. https://doi.org/10.1016/J.JOBE.2021.102180.

[55] N. Lazar, K. Chithra, A comprehensive literature review on development of Building Sustainability Assessment Systems, Journal of Building Engineering. 32 (2020) 101450. https://doi.org/10.1016/j.jobe.2020.101450.

[56] B. Wen, N. Musa, C.C. Onn, S. Ramesh, L. Liang, W. Wang, Evolution of sustainability in global green building rating tools, J Clean Prod. 259 (2020) 120912. https://doi.org/10.1016/J.JCLEPRO.2020.120912.

[57] S. Mahmoud, T. Zayed, M. Fahmy, Development of sustainability assessment tool for existing buildings, Sustain Cities Soc. 44 (2019) 99–119. https://doi.org/10.1016/j.scs.2018.09.024.

[58] M. Shan, B. gang Hwang, Green building rating systems: Global reviews of practices and research efforts, Sustain Cities Soc. 39 (2018) 172–180. https://doi.org/10.1016/J.SCS.2018.02.034.

[59] Y. He, T. Kvan, M. Liu, B. Li, How green building rating systems affect designing green, Build Environ. 133 (2018) 19–31. https://doi.org/10.1016/J.BUILDENV.2018.02.007.

[60] J.P. Carvalho, L. Bragança, R. Mateus, A Systematic Review of the Role of BIM in Building Sustainability Assessment Methods, Applied Sciences. 10 (2020) 4444. https://doi.org/10.3390/app10134444.

[61] L. He, L. Chen, The incentive effects of different government subsidy policies on green buildings, Renewable and Sustainable Energy Reviews. 135 (2021) 110123. https://doi.org/10.1016/J.RSER.2020.110123.

[62] A. Rana, R. Sadiq, M.S. Alam, H. Karunathilake, K. Hewage, Evaluation of financial incentives for green buildings in Canadian landscape, Renewable and Sustainable Energy Reviews. 135 (2021) 110199. https://doi.org/10.1016/J.RSER.2020.110199.

[63] S. Azhar, J.W. Brown, A. Sattineni, A Case Study of Building Performance Analyses Using Building Information Modeling, in: Proceedings of the 27th International Symposium on Automation and Robotics in Construction (ISARC-27), Bratislava, Slovakia, 2010. https://doi.org/10.22260/ISARC2010/0023.

[64] J. Basbagill, F. Flager, M. Lepech, M. Fischer, Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts, Build Environ. 60 (2013) 81–92. https://doi.org/10.1016/j.buildenv.2012.11.009.

[65] R. Santos, A.A. Costa, J.D. Silvestre, T. Vandenbergh, L. Pyl, BIM-based life cycle assessment and life cycle costing of an office building in Western Europe, Build Environ. 169 (2020) 106568. https://doi.org/10.1016/j.buildenv.2019.106568.

[66] C.R.S. Varma, S. Palaniappan, Comparision of green building rating schemes used in North America, Europe and Asia, Habitat Int. 89 (2019) 101989. https://doi.org/10.1016/j.habitatint.2019.05.008.

[67] J. Ferreira, M.D. Pinheiro, J. de Brito, Portuguese sustainable construction assessment tools benchmarked with BREEAM and LEED: An energy analysis, Energy Build. 69 (2014) 451–463. https://doi.org/10.1016/j.enbuild.2013.11.039.

[68] N.S. Caetano, R.R. Carvalho, F.R. Franco, C.A.R. Afonso, C. Felgueiras, Sustainable engineering labs - A Portuguese perspective, in: Energy Procedia, Elsevier Ltd, 2018: pp. 455–460. https://doi.org/10.1016/j.egypro.2018.10.077.

[69] M. de F. Castro, R. Mateus, L. Bragança, Development of a healthcare building sustainability assessment method – Proposed structure and system of weights for the Portuguese context, J Clean Prod. 148 (2017) 555–570. https://doi.org/10.1016/J.JCLEPRO.2017.02.005.

[70] L. Bragança, SBTool Urban: Instrumento para a promoção da sustentabilidade urbana, in: I Simpósio Nacional de Gestão e Engenharia Urbana, São Carlos, 2017. http://civil.uminho.pt/urbenere/wp-content/uploads/2018/05/E28-SINGEURB-2017.pdf (accessed December 28, 2018).

[71] Saraiva, de Almeida, Bragança, Adaptation of the SBTool for Sustainability Assessment of High School Buildings in Portugal—SAHSBPT, Applied Sciences. 9 (2019) 2664. https://doi.org/10.3390/app9132664.

[72] S. Moreno Pires, T. Fidélis, Local sustainability indicators in Portugal: Assessing implementation and use in governance contexts, J Clean Prod. 86 (2015) 289–300. https://doi.org/10.1016/j.jclepro.2014.08.002.

[73] N. Larsson, SB Method and SBTool for 2011 - overview, 2011. http://www.iisbe.org/system/files/private/Nils%20Larsson_New%20SBTool%20Generic%20Framework.pdf (accessed December 11, 2018).

[74] M. Vonka, P. Hajek, A. Lupisek, SBToolCZ: Sustainability rating system in the Czech Republic, International Journal of Sustainable Building Technology and Urban Development. 4 (2013) 46–52. https://doi.org/10.1080/2093761X.2012.759888.

[75] M. Castro, R. Mateus, F. Serôdio, L. Bragança, M.D.F. Castro, R. Mateus, F. Serôdio, L. Bragança, Development of Benchmarks for Operating Costs and Resources Consumption to be Used in Healthcare Building Sustainability Assessment Methods, Sustainability. 7 (2015) 13222–13248. https://doi.org/10.3390/su71013222.

[76] A. Shi, S. Shirowzhan, A. Kaboli, 5D BIM Applications in Quantity Surveying: Dynamo and 3D Printing Technologies, in: S. Shirowzhan, K. Zhang (Eds.), Smart Cities and Construction Technologies, IntechOpen, 2020. https://doi.org/10.5772/INTECHOPEN.86103.

[77] D. Bryde, M. Broquetas, J.M. Volm, The project benefits of Building Information Modelling (BIM), International Journal of Project Management. 31 (2013) 971–980. https://doi.org/10.1016/J.IJPROMAN.2012.12.001.

[78] S. Hire, S. Sandbhor, K. Ruikar, Bibliometric Survey for Adoption of Building Information Modeling (BIM) in Construction Industry– A Safety Perspective, Archives of Computational Methods in Engineering. 29 (2022) 679–693. https://doi.org/10.1007/S11831-021-09584-9/TABLES/4.

[79] K. Ullah, I. Lill, E. Witt, An overview of BIM adoption in the construction industry: Benefits and barriers, Emerald Reach Proceedings Series. 2 (2019) 297–303. https://doi.org/10.1108/S2516-285320190000002052/FULL/EPUB.

[80] R. Santos, A.A. Costa, J.D. Silvestre, L. Pyl, Integration of LCA and LCC analysis within a BIM-based environment, Autom Constr. 103 (2019) 127–149. https://doi.org/10.1016/j.autcon.2019.02.011.

[81] F.H. Abanda, L. Byers, An investigation of the impact of building orientation on energy consumption in a domestic building using emerging BIM (Building Information Modelling), Energy. 97 (2016) 517–527. https://doi.org/10.1016/J.ENERGY.2015.12.135.

[82] H. Begić, M. Galić, A Systematic Review of Construction 4.0 in the Context of the BIM 4.0 Premise, Buildings 2021, Vol. 11, Page 337. 11 (2021) 337. https://doi.org/10.3390/BUILDINGS11080337.

[83] M. Salamak, M. Jasinski, T. Plaszczyk, M. Zarski, Analytical Modelling in Dynamo, Transactions of the VŠB – Technical University of Ostrava, Civil Engineering Series. 18 (2019). https://doi.org/10.31490/TCES-2018-0014.

[84] C. Sun, S. Jiang, M.J. Skibniewski, Q. Man, L. Shen, A literature review of the factors limiting the application of BIM in the construction industry, Vilnius Gediminas Technical University. 23 (2017) 764–779. https://doi.org/10.3846/20294913.2015.1087071.

[85] M. Venâncio, Avaliação da Implementação de Bim -Building Information Modeling em Portugal, FEUP, 2015. https://repositorio-aberto.up.pt/handle/10216/79329 (accessed September 13, 2022).

[86] D. Krug, M.N. Wierzbicki, BIM – History and Trends, in: CONVR2011, International Conference on Construction Applications of Virtual Reality, 2011. https://www.academia.edu/2070093/BIM_History_and_Trends (accessed September 13, 2022).

[87] National Institute of Building Sciences, About the National BIM Standard-United States® | National BIM Standard - United States, (n.d.). https://www.nationalbimstandard.org/about (accessed September 13, 2022).

[88] C.M. Eastman, BIM handbook : a guide to building information modeling for owners, managers, designers, engineers and contractors, John Wiley & Sons, 2011.

[89] W. Solihin, C. Eastman, Classification of rules for automated BIM rule checking development, Autom Constr. 53 (2015) 69–82. https://doi.org/10.1016/J.AUTCON.2015.03.003.

[90] H.-Y. Chong, C.-Y. Lee, X. Wang, A mixed review of the adoption of Building Information Modelling (BIM) for sustainability, J Clean Prod. 142 (2017) 4114–4126. https://doi.org/10.1016/J.JCLEPRO.2016.09.222.

[91] T.M. Froese, The impact of emerging information technology on project management for construction, Autom Constr. 19 (2010) 531–538. https://doi.org/10.1016/J.AUTCON.2009.11.004.

[92] F.H. Abanda, D. Mzyece, A.H. Oti, M.B. Manjia, A Study of the Potential of Cloud/Mobile BIM for the Management of Construction Projects, Applied System Innovation 2018, Vol. 1, Page 9. 1 (2018) 9. https://doi.org/10.3390/ASI1020009.

[93] Y.Y. Al-Ashmori, I. Othman, Y. Rahmawati, Y.H.M. Amran, S.H.A. Sabah, A.D. u. Rafindadi, M. Mikić, BIM benefits and its influence on the BIM implementation in Malaysia, Ain Shams Engineering Journal. 11 (2020) 1013–1019. https://doi.org/10.1016/J.ASEJ.2020.02.002.

[94] S. Azhar, Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry, Leadership and Management in Engineering. 11 (2011) 241–252. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127.

[95] M.J.F. Silva, F. Salvado, P. Couto, Á. Vale E Azevedo, Roadmap Proposal for Imple-menting Building Information Modelling (BIM) in Portugal, Open Journal of Civil Engineering. 6 (2016) 475–481. https://doi.org/10.4236/ojce.2016.63040.

[96] A.K.D. Wong, F.K.W. Wong, A. Nadeem, Attributes of Building Information Modelling Implementations in Various Countries, Https://Doi.Org/10.3763/Aedm.2010.IDDS6. 6 (2011) 288–302. https://doi.org/10.3763/AEDM.2010.IDDS6.

[97] General Services Administration, BIM guides, (n.d.). https://www.gsa.gov/real-estate/design-and-construction/3d4d-building-information-modeling/bim-guides (accessed September 13, 2022).

[98] G. Burgess, M. Jones, K. Muir, BIM in the UK house building industry: opportunities and barriers to adoption, 2018. https://www.cdbb.cam.ac.uk/system/files/documents/BIMandUKHouseBuildingFinalReportforCDBB.pdf (accessed September 13, 2022).

[99] J.C.P. Cheng, Q. Lu, A review of the efforts and roles of the public sector for BIM adoption worldwide, ITcon Vol. 20, Pg. 442-478 Http://Www.Itcon.Org/2015/27. 20 (2015) 442–478. http://www.itcon.org/paper/2015/27 (accessed September 13, 2022).

[100] Zigurat Global Institute of Technology, Implementação do BIM no Brasil e em Portugal, (2022). https://www.e-zigurat.com/blog/pt-br/implementacao-bim-brasil-portugal/ (accessed September 14, 2022).

[101] P. Carvalho, Análise Estatística do Estado de Implementação da Tecnologia Bim no Setor da Construção em Portugal, FEUP, 2016. https://hdl.handle.net/10216/82930 (accessed September 14, 2022).

[102] M. Godinho, R. Machete, M. Ponte, A.P. Falcão, A.B. Gonçalves, R. Bento, BIM as a resource in heritage management: An application for the National Palace of Sintra, Portugal, J Cult Herit. 43 (2020) 153–162. https://doi.org/10.1016/J.CULHER.2019.11.010.

[103] N. Li, Q. Li, Y.S. Liu, W. Lu, W. Wang, BIMSeek++: Retrieving BIM components using similarity measurement of attributes, Comput Ind. 116 (2020) 103186. https://doi.org/10.1016/j.compind.2020.103186.

[104] A. Farzaneh, D. Monfet, D. Forgues, Review of using Building Information Modeling for building energy modeling during the design process, Journal of Building Engineering. 23 (2019) 127–135. https://doi.org/10.1016/j.jobe.2019.01.029.

[105] S.H. Harness, 2008 AIA Documents Advance the Use of BIM and Integrated Project Delivery, 2008. https://www.aia.org/articles/68516-2008-aia-documents-advance-the-use-of-bim-an (accessed September 14, 2022).

[106] AIA, AIA Document G202-2013. Project Building Information Modeling Protocol Form, 2013.

[107] A. McPhee, Practical BIM: What is this thing called LOD, (2013). http://practicalbim.blogspot.com/2013/03/what-is-this-thing-called-lod.html (accessed September 14, 2022).

[108] U.S. General Services Administration, Approved Use Matrix | GSA, (n.d.). https://www.gsa.gov/real-estate/design-and-construction/3d4d-building-information-modeling/bim-software-guidelines/document-guides/level-of-detail/approved-use-matrix (accessed August 3, 2022).

[109] A. Aksamija, BIM-Based Building Performance Analysis: Evaluation and Simulation of Design Decisions, in: ACEEE Summer Study on Energy Efficiency in Buildings, 2012.

[110] S. Abdullah, N. Sulaiman, A. Latiffi, D. Baldry, Building Information Modeling (BIM) from the perspective of Facilities Management (FM) in Malaysia, in: International Real Estate Symposium 2014, Kuala Lumpur, 2014.

[111] J. Heaton, A.K. Parlikad, J. Schooling, Design and development of BIM models to support operations and maintenance, Comput Ind. 111 (2019) 172–186. https://doi.org/10.1016/j.compind.2019.08.001.

[112] A. Koutamanis, Dimensionality in BIM: Why BIM cannot have more than four dimensions?, Autom Constr. 114 (2020) 103153. https://doi.org/10.1016/J.AUTCON.2020.103153.

[113] C. Boje, A. Guerriero, S. Kubicki, Y. Rezgui, Towards a semantic Construction Digital Twin: Directions for future research, Autom Constr. 114 (2020) 103179. https://doi.org/10.1016/J.AUTCON.2020.103179.

[114] R. Charef, H. Alaka, S. Emmitt, Beyond the third dimension of BIM: A systematic review of literature and assessment of professional views, Journal of Building Engineering. 19 (2018) 242–257. https://doi.org/10.1016/J.JOBE.2018.04.028.

[115] B. Sertyesilisik, E. Sertyesilisik, H.T. Çetin, E. Ocakoglu, BIM Dimensions and Application Areas for Enhancing Sustainability and Affordability of Affordable Housing: As a Key for Effective Housing Policies, Periodica Polytechnica Architecture. 52 (2021) 85–93. https://doi.org/10.3311/PPAR.17081.

[116] M.A. Vigneault, C. Boton, H.Y. Chong, B. Cooper-Cooke, An Innovative Framework of 5D BIM Solutions for Construction Cost Management: A Systematic Review, Undefined. 27 (2019) 1013–1030. https://doi.org/10.1007/S11831-019-09341-Z.

[117] A.A. Wildenauer, Critical Assessment of the Existing Definitions of BIM Dimensions on the Example of Switzerland, International Journal of Civil Engineering and Technology. 11 (2020) 134–151. https://doi.org/10.34218/IJCIET.11.4.2020.012.

[118] I. Kamardeen, 8D BIM modelling tool for accident prevention through design, Association of Researchers in Construction Management, ARCOM 2010 - Proceedings of the 26th Annual Conference. (2010) 281–289. https://www.scopus.com/record/display.uri?eid=2-s2.0-84860910840&origin=inward&txGid=796df705d5a4c2b14d895e23ceec4f1d (accessed September 15, 2022).

[119] J. Darós, Guia completo: BIM 10D construção industrializada | Utilizando BIM, (2019). https://utilizandobim.com/blog/bim-10d-construcao-industrializada/ (accessed September 15, 2022).

[120] BibLus, The dimensions of BIM - 3D, 4D, 5D, 6D, 7D, 8D, 9D, 10D BIM explained, ACCAsoftware. (2017). https://biblus.accasoftware.com/en/bim-dimensions/ (accessed September 15, 2022).

[121] Y. Patel, BIM Tools, Platforms and Environment, (2020). https://www.bimtraining.in/post/bim-tools-platforms-and-environment (accessed September 15, 2022).

[122] E. Kamel, A.M. Memari, Review of BIM's application in energy simulation: Tools, issues, and solutions, Autom Constr. 97 (2019) 164–180. https://doi.org/10.1016/j.autcon.2018.11.008.

[123] G. Ma, M. Wu, Z. Wu, W. Yang, Single-shot multibox detector- and building information modeling-based quality inspection model for construction projects, Journal of Building Engineering. 38 (2021) 102216. https://doi.org/10.1016/J.JOBE.2021.102216.

[124] H. Söbke, P. Peralta, K. Smarsly, M. Armbruster, An IFC schema extension for BIM-based description of wastewater treatment plants, Autom Constr. 129 (2021) 103777. https://doi.org/10.1016/J.AUTCON.2021.103777.

[125] M. Barzegar, A. Rajabifard, M. Kalantari, B. Atazadeh, An IFC-based database schema for mapping BIM data into a 3D spatially enabled land administration database, Int J Digit Earth. 14 (2021) 736–765. https://doi.org/10.1080/17538947.2021.1875062.

[126] J.P. Carvalho, M. Almeida, L. Bragança, R. Mateus, BIM-Based Energy Analysis and Sustainability Assessment—Application to Portuguese Buildings, Buildings 2021, Vol. 11, Page 246. 11 (2021) 246. https://doi.org/10.3390/BUILDINGS11060246.

[127] S. Zhang, J. Teizer, J.K. Lee, C.M. Eastman, M. Venugopal, Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules, Autom Constr. 29 (2013) 183–195. https://doi.org/10.1016/J.AUTCON.2012.05.006.

[128] A.S. Ismail, K.N. Ali, N.A. Iahad, A Review on BIM-based automated code compliance checking system, International Conference on Research and Innovation in Information Systems, ICRIIS. (2017). https://doi.org/10.1109/ICRIIS.2017.8002486.

[129] C. Sydora, E. Stroulia, Rule-based compliance checking and generative design for building interiors using BIM, Autom Constr. 120 (2020) 103368. https://doi.org/10.1016/J.AUTCON.2020.103368.

[130] C. Eastman, J. min Lee, Y. suk Jeong, J. kook Lee, Automatic rule-based checking of building designs, Autom Constr. 18 (2009) 1011–1033. https://doi.org/10.1016/J.AUTCON.2009.07.002.

[131] X. Xie, J. Zhou, X. Fu, R. Zhang, H. Zhu, Q. Bao, Automated Rule Checking for MEP Systems Based on BIM and KBMS, Buildings 2022, Vol. 12, Page 934. 12 (2022) 934. https://doi.org/10.3390/BUILDINGS12070934.

[132] N. Khan, A.K. Ali, M.J. Skibniewski, D.Y. Lee, C. Park, Excavation Safety Modeling Approach Using BIM and VPL, Advances in Civil Engineering. 2019 (2019). https://doi.org/10.1155/2019/1515808.

[133] V. Getuli, S.M. Ventura, P. Capone, A.L.C. Ciribini, BIM-based Code Checking for Construction Health and Safety, Procedia Eng. 196 (2017) 454–461. https://doi.org/10.1016/J.PROENG.2017.07.224.

[134] F.S. Villaschi, J.P. Carvalho, L. Bragança, BIM-Based Method for the Verification of Building Code Compliance, Applied System Innovation 2022, Vol. 5, Page 64. 5 (2022) 64. https://doi.org/10.3390/ASI5040064.

[135] P. Ghannad, Y.C. Lee, J. Dimyadi, W. Solihin, Automated BIM data validation integrating open-standard schema with visual programming language, Advanced Engineering Informatics. 40 (2019) 14–28. https://doi.org/10.1016/J.AEI.2019.01.006.

[136] C. Quinn, A.Z. Shabestari, T. Misic, S. Gilani, M. Litoiu, J.J. McArthur, Building automation system - BIM integration using a linked data structure, Autom Constr. 118 (2020) 103257. https://doi.org/10.1016/J.AUTCON.2020.103257.

[137] K. Kensek, Y. Ding, T. Longcore, Green building and biodiversity: Facilitating bird friendly design with building information models, Journal of Green Building. 11 (2016) 116–130. https://doi.org/10.3992/jgb.11.2.116.1.

[138] C. Cavalliere, G.R. Dell'Osso, F. Favia, M. Lovicario, BIM-based assessment metrics for the functional flexibility of building designs, Autom Constr. 107 (2019) 102925. https://doi.org/10.1016/J.AUTCON.2019.102925.

[139] J.P. Carvalho, F.S. Villaschi, L. Bragança, Assessing Life Cycle Environmental and Economic Impacts of Building Construction Solutions with BIM, Sustainability 2021, Vol. 13, Page 8914. 13 (2021) 8914. https://doi.org/10.3390/SU13168914.

[140] M. Sheikhkhoshkar, F. Pour Rahimian, M.H. Kaveh, M.R. Hosseini, D.J. Edwards, Automated planning of concrete joint layouts with 4D-BIM, Autom Constr. 107 (2019) 102943. https://doi.org/10.1016/J.AUTCON.2019.102943.

[141] F. Banfi, M. Previtali, Human–Computer Interaction Based on Scan-to-BIM Models, Digital Photogrammetry, Visual Programming Language and eXtended Reality (XR), Applied Sciences 2021, Vol. 11, Page 6109. 11 (2021) 6109. https://doi.org/10.3390/APP11136109.

[142] R. Marmo, F. Polverino, M. Nicolella, A. Tibaut, Building performance and maintenance information model based on IFC schema, Autom Constr. 118 (2020) 103275. https://doi.org/10.1016/J.AUTCON.2020.103275.

[143] K. Negendahl, Building performance simulation in the early design stage: An introduction to integrated dynamic models, Autom Constr. 54 (2015) 39–53. https://doi.org/10.1016/J.AUTCON.2015.03.002.

[144] S. Liu, B. Xie, L. Tivendal, C. Liu, Critical Barriers to BIM Implementation in the AEC Industry, Int J Mark Stud. 7 (2015) p162. https://doi.org/10.5539/IJMS.V7N6P162.

[145] S. Ahmed, Barriers to Implementation of Building Information Modeling (BIM) to the Construction Industry: A Review, Journal of Civil Engineering and Construction. 7 (2018) 107–113. https://doi.org/10.32732/JCEC.2018.7.2.107.

[146] D.W.M. Chan, T.O. Olawumi, A.M.L. Ho, Perceived benefits of and barriers to Building Information Modelling (BIM) implementation in construction: The case of Hong Kong, Journal of Building Engineering. 25 (2019) 100764. https://doi.org/10.1016/J.JOBE.2019.100764.

[147] J.P. Carvalho, L. Bragança, R. Mateus, Information technology and the digital transformation of building design, in: Sustainable Urban Development, IOP Publishing, 2021. https://doi.org/10.1088/978-0-7503-3971-1CH11.

[148] C. Clevenger, M. Ozbek, H. Mahmoud, B. Fanning, Impacts and Benefits of Implementing Building Information Modeling on Bridge Infrastructure Projects, 2014. https://www.semanticscholar.org/paper/Impacts-and-Benefits-of-Implementing-Building-on-Clevenger-Ozbek/0fed28507b04992e20179795e2f9d9a297fe21f6 (accessed September 19, 2022).

[149] M.R. Hosseini, S. Banihashemi, N. Chileshe, M.O. Namzadi, C. Udaeja, R. Rameezdeen, T. McCuen, BIM adoption within Australian Small and Medium-sized Enterprises (SMEs): an innovation diffusion model, Construction Economics and Building. 16 (2016) 71–86. https://doi.org/10.5130/AJCEB.v16i3.5159.

[150] B. Manzoor, I. Othman, S.S.S. Gardezi, H. Altan, S.B. Abdalla, BIM-Based Research Framework for Sustainable Building Projects: A Strategy for Mitigating BIM Implementation Barriers, Applied Sciences 2021, Vol. 11, Page 5397. 11 (2021) 5397. https://doi.org/10.3390/APP11125397.

[151] T.O. Olawumi, D.W.M. Chan, J.K.W. Wong, A.P.C. Chan, Barriers to the integration of BIM and sustainability practices in construction projects: A Delphi survey of international experts, Journal of Building Engineering. 20 (2018) 60–71. https://doi.org/10.1016/J.JOBE.2018.06.017.

[152] K. din Wong, Q. Fan, Building information modelling (BIM) for sustainable building design, Facilities. 31 (2013) 138–157. https://doi.org/10.1108/02632771311299412/FULL/XML.

[153] M. Najjar, K. Figueiredo, M. Palumbo, A. Haddad, Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building, Journal of Building Engineering. 14 (2017) 115–126. https://doi.org/10.1016/j.jobe.2017.10.005.

[154] M. Reizgevičius, L. Ustinovičius, D. Cibulskienė, V. Kutut, L. Nazarko, M. Reizgevičius, L. Ustinovičius, D. Cibulskienė, V. Kutut, L. Nazarko, Promoting Sustainability through Investment in Building Information Modeling (BIM) Technologies: A Design Company Perspective, Sustainability. 10 (2018) 600. https://doi.org/10.3390/su10030600.

[155] L. Zhang, Z. Chu, Q. He, P. Zhai, L. Zhang, Z. Chu, Q. He, P. Zhai, Investigating the Constraints to Buidling Information Modeling (BIM) Applications for Sustainable Building Projects: A Case of China, Sustainability. 11 (2019) 1896. https://doi.org/10.3390/su11071896.

[156] E. Krygiel, B. Nies, Green BIM : successful sustainable design with building information modeling, 2008.

[157] S. Azhar, J. Brown, BIM for Sustainability Analyses, Int J Constr Educ Res. 5 (2009) 276–292. https://doi.org/10.1080/15578770903355657.

[158] I. Motawa, K. Carter, Sustainable BIM-based Evaluation of Buildings, Procedia Soc Behav Sci. 74 (2013) 419–428. https://doi.org/10.1016/J.SBSPRO.2013.03.015.

[159] Y. Lu, Z. Wu, R. Chang, Y. Li, Building Information Modeling (BIM) for green buildings: A critical review and future directions, Autom Constr. 83 (2017) 134–148. https://doi.org/10.1016/J.AUTCON.2017.08.024.

[160] L.P. Marques, L.M. Santos, J.P. Couto, The importance of integrated implementation of lean construction and bim for improving the sustainability of construction projects, in: SHEWC ` 2015 – XV SAFETY, HEALTH AND ENVIRONMENT WORLD CONGRESS, Science and Education Research Council (COPEC), 2016: pp. 152–156. https://doi.org/10.14684/SHEWC.15.2015.152-156.

[161] S. Egwunatum, E. Joseph-akwara, R. Akaigwe, Optimizing energy consumption in building designs using Building Information Model (BIM), Slovak Journal of Civil Engineering. 19 (2016) 19–28. https://doi.org/10.1515/sjce-2016-0013.

[162] M. Delavar, G.T. Bitsuamlak, J.K. Dickinson, L.M.F. Costa, Automated BIM-based process for wind engineering design collaboration, Build Simul. 13 (2020) 457–474. https://doi.org/10.1007/s12273-019-0589-2.

[163] S. Lee, D. Song, Prediction and evaluation method of wind environment in the early design stage using BIM-based CFD simulation, in: IOP Conf Ser Mater Sci Eng, Institute of Physics Publishing, 2014: p. 012035. https://doi.org/10.1088/1757-899X/10/1/012035.

[164] A. Chong, W. Xu, S. Chao, N.T. Ngo, Continuous-time Bayesian calibration of energy models using BIM and energy data, Energy Build. 194 (2019) 177–190. https://doi.org/10.1016/j.enbuild.2019.04.017.

[165] H. Gao, C. Koch, Y. Wu, Building information modelling based building energy modelling: A review, Appl Energy. 238 (2019) 320–343. https://doi.org/10.1016/j.apenergy.2019.01.032.

[166] J.B. Kim, W. Jeong, M.J. Clayton, J.S. Haberl, W. Yan, Developing a physical BIM library for building thermal energy simulation, Autom Constr. 50 (2015) 16–28. https://doi.org/10.1016/J.AUTCON.2014.10.011.

[167] G. Gourlis, I. Kovacic, Building Information Modelling for analysis of energy efficient industrial buildings – A case study, Renewable and Sustainable Energy Reviews. 68 (2017) 953–963. https://doi.org/10.1016/J.RSER.2016.02.009.

[168] F.J. Montiel-Santiago, M.J. Hermoso-Orzáez, J. Terrados-Cepeda, Sustainability and Energy Efficiency: BIM 6D. Study of the BIM Methodology Applied to Hospital Buildings. Value of Interior Lighting and Daylight in Energy Simulation, Sustainability. 12 (2020) 5731. https://doi.org/10.3390/su12145731.

[169] L. Díaz-Vilariño, S. Lagüela, J. Armesto, P. Arias, Indoor daylight simulation performed on automatically generated as-built 3D models, Energy Build. 68 (2014) 54–62. https://doi.org/10.1016/j.enbuild.2013.02.064.

[170] S. Kota, J.S. Haberl, M.J. Clayton, W. Yan, Building Information Modeling (BIM)-based daylighting simulation and analysis, Energy Build. 81 (2014) 391–403. https://doi.org/10.1016/J.ENBUILD.2014.06.043.

[171] F.M. Amoruso, U. Dietrich, T. Schuetze, Integrated BIM-Parametric Workflow-Based Analysis of Daylight Improvement for Sustainable Renovation of an Exemplary Apartment in Seoul, Korea, Sustainability. 11 (2019) 2699. https://doi.org/10.3390/su11092699.

[172] S. Kim, P.A. Zadeh, S. Staub-French, T. Froese, B.T. Cavka, Assessment of the Impact of Window Size, Position and Orientation on Building Energy Load Using BIM, in: Procedia Eng, Elsevier Ltd, 2016: pp. 1424–1431. https://doi.org/10.1016/j.proeng.2016.04.179.

[173] T. Wei, G. Chen, J. Wang, Application of BIM Technology in Building Water Supply and Drainage Design, in: IOP Conf Ser Earth Environ Sci, Institute of Physics Publishing, 2017: p. 12117. https://doi.org/10.1088/1755-1315/100/1/012117.

[174] Z. Liu, C. Zhang, Y. Guo, M. Osmani, P. Demian, A Building Information Modelling (BIM) based Water Efficiency (BWe) Framework for Sustainable Building Design and Construction Management, Electronics (Basel). 8 (2019) 599. https://doi.org/10.3390/electronics8060599.

[175] L. Zhao, Z. Liu, J. Mbachu, An Integrated BIM–GIS Method for Planning of Water Distribution System, ISPRS Int J Geoinf. 8 (2019) 331. https://doi.org/10.3390/ijgi8080331.

[176] C. Wu, M.J. Clayton, BIM-Based Acoustic Simulation Framework, in: Proceedings of the 30th CIB W78 International Conference, Beijing, China, 2013. https://www.researchgate.net/publication/304625903 (accessed November 12, 2019).

[177] Y. Tan, Y. Fang, T. Zhou, Q. Wanga, J. Chenga, Improve Indoor Acoustics Performance by Using Building Information Modeling, (2017).

[178] Y. Tan, Y. Fang, T. Zhou, V.J.L. Gan, J.C.P. Cheng, BIM-supported 4D acoustics simulation approach to mitigating noise impact on maintenance workers on offshore oil and gas platforms, Autom Constr. 100 (2019) 1–10. https://doi.org/10.1016/j.autcon.2018.12.019.

[179] B. Hardin, D. McCool, BIM and Construction Management: Proven Tools, Methods, and Workflows, 2nd Edition, 2009. https://www.wiley.com/en-us/BIM+and+Construction+Management%3A+Proven+Tools%2C+Methods%2C+and+Workflows%2C+2nd+Edition-p-9781118942765 (accessed December 7, 2020).

[180] J.C.P. Cheng, L.Y.H. Ma, A BIM-based system for demolition and renovation waste estimation and planning, Waste Management. 33 (2013) 1539–1551. https://doi.org/10.1016/J.WASMAN.2013.01.001.

[181] J. Won, J.C.P. Cheng, Identifying potential opportunities of building information modeling for construction and demolition waste management and minimization, Autom Constr. 79 (2017) 3–18. https://doi.org/10.1016/j.autcon.2017.02.002.

[182] O.O. Akinade, L.O. Oyedele, S.O. Ajayi, M. Bilal, H.A. Alaka, H.A. Owolabi, O.O. Arawomo, Designing out construction waste using BIM technology: Stakeholders' expectations for industry deployment, J Clean Prod. 180 (2018) 375–385. https://doi.org/10.1016/j.jclepro.2018.01.022.

[183] J.A. Bamgbade, M.N.M. Nawi, A.M. Kamaruddeen, A.Q. Adeleke, M.G. Salimon, Building sustainability in the construction industry though firm capabilities, technology and business innovativeness: empirical evidence from Malaysia, International Journal of Construction Management. (2019). https://doi.org/10.1080/15623599.2019.1634666.

[184] T.O. Olawumi, D.W.M. Chan, Identifying and prioritizing the benefits of integrating BIM and sustainability practices in construction projects: A Delphi survey of international experts, Sustain Cities Soc. 40 (2018) 16–27. https://doi.org/10.1016/J.SCS.2018.03.033.

[185] F. Rezaei, C. Bulle, P. Lesage, Integrating building information modeling and life cycle assessment in the early and detailed building design stages, Build Environ. 153 (2019) 158–167. https://doi.org/10.1016/j.buildenv.2019.01.034.

[186] E. Wang, Z. Shen, C. Barryman, A Building LCA Case Study Using Autodesk Ecotect and BIM Model, Papers in Construction Management. (2011). https://digitalcommons.unl.edu/constructionmgmt/6 (accessed November 12, 2019).

[187] A. Hollberg, G. Genova, G. Habert, Evaluation of BIM-based LCA results for building design, Autom Constr. 109 (2020). https://doi.org/10.1016/j.autcon.2019.102972.

[188] A. Naneva, M. Bonanomi, A. Hollberg, G. Habert, D. Hall, Integrated BIM-Based LCA for the Entire Building Process Using an Existing Structure for Cost Estimation in the Swiss Context, Sustainability. 12 (2020) 3748. https://doi.org/10.3390/su12093748.

[189] J.P. Carvalho, I. Alecrim, L. Bragança, R. Mateus, Integrating BIM-Based LCA and Building Sustainability Assessment, Sustainability. 12 (2020) 7468. https://doi.org/10.3390/su12187468.

[190] A. Jrade, F. Jalaei, Integrating building information modelling with sustainability to design building projects at the conceptual stage, Build Simul. 6 (2013) 429–444. https://doi.org/10.1007/s12273-013-0120-0.

[191] A. Vilches, A. Garcia-Martinez, B. Sanchez-Montañes, Life cycle assessment (LCA) of building refurbishment: A literature review, Energy Build. 135 (2017) 286–301. https://doi.org/10.1016/j.enbuild.2016.11.042.

[192] M.N. Nwodo, C.J. Anumba, A review of life cycle assessment of buildings using a systematic approach, Build Environ. 162 (2019) 106290. https://doi.org/10.1016/j.buildenv.2019.106290.

[193] Y. Cao, S.N. Kamaruzzaman, N. Mardhiyah Aziz, Green Building Construction: A Systematic Review of BIM Utilization, Buildings. 12 (2022) 1205. https://doi.org/10.3390/BUILDINGS12081205.

[194] G. Akhanova, A. Nadeem, J.R. Kim, S. Azhar, M. Khalfan, Building information modeling based building sustainability assessment framework for Kazakhstan, Buildings. 11 (2021) 384. https://doi.org/10.3390/BUILDINGS11090384/S1.

[195] A. al Sehrawy, O. Amoudi, M. Tong, A review of the challenges to integrating BIM and building sustainability assessment, in: : : AIP Conference Proceedings 2428, 2021: p. 20001. https://doi.org/10.1063/5.0071055.

[196] M.K. Ansah, X. Chen, H. Yang, L. Lu, P.T.I. Lam, A review and outlook for integrated BIM application in green building assessment, Sustain Cities Soc. 48 (2019) 101576. https://doi.org/10.1016/j.scs.2019.101576.

[197] T.H. Nguyen, Sh.H. Toroghi, F. Jacobs, Automated Green Building Rating System for Building Designs, Journal of Architectural Engineering. 22 (2015) A4015001. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000168.

[198] H.-S. Ryu, K.-S. Park, H.-S. Ryu, K.-S. Park, A Study on the LEED Energy Simulation Process Using BIM, Sustainability. 8 (2016) 138. https://doi.org/10.3390/su8020138.

[199] A.H. Oti, W. Tizani, F.H. Abanda, A. Jaly-Zada, J.H.M. Tah, Structural sustainability appraisal in BIM, Autom Constr. 69 (2016) 44–58. https://doi.org/10.1016/J.AUTCON.2016.05.019.

[200] S. Gandhi, J. Jupp, BIM and Australian Green Star Building Certification, in: Computing in Civil and Building Engineering (2014), American Society of Civil Engineers, Reston, VA, 2014: pp. 275–282. https://doi.org/10.1061/9780784413616.035.

[201] A. GhaffarianHoseini, D. Tien Doan, N. Naismith, J. Tookey, A. GhaffarianHoseini, Amplifying the practicality of contemporary building information modelling (BIM) implementations for New Zealand green building certification (Green Star), Engineering, Construction and Architectural Management. 24 (2017) 696–714. https://doi.org/10.1108/ECAM-02-2016-0043.

[202] Z. Liu, K. Chen, L. Peh, K.W. Tan, A feasibility study of Building Information Modeling for Green Mark New Non-Residential Building (NRB): 2015 analysis, in: Energy Procedia, Elsevier Ltd, 2017: pp. 80–87. https://doi.org/10.1016/j.egypro.2017.12.651.

[203] M. Solla, L.H. Ismail, R. Yunus, Investigation on the potential of integrating BIM into green building assessment tools, ARPN Journal of Engineering and Applied Sciences. 11 (2016) 2412–2418. https://doi.org/10.13140/RG.2.1.4114.0881}.

[204] Z.M. Salehabadi, R. Ruparathna, User-centric sustainability assessment of single family detached homes (SFDH): A BIM-based methodological framework, Journal of Building Engineering. 50 (2022) 104139. https://doi.org/10.1016/J.JOBE.2022.104139.

[205] S. Eleftheriadis, D. Mumovic, P. Greening, Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities, Renewable and Sustainable Energy Reviews. 67 (2017) 811–825. https://doi.org/10.1016/J.RSER.2016.09.028.

[206] A. Gökgür, Current and future use of BIM in renovation projects Ata Gökgür, Chalmers University of Technology, 2015. http://publications.lib.chalmers.se/records/fulltext/218421/218421.pdf (accessed November 13, 2018).

[207] S. Balye, Shanghai Tower, (2019). https://unsplash.com/photos/cYne7_kcI80 (accessed September 21, 2022).

[208] Z. Liu, M. Osmani, P. Demian, A. Baldwin, A BIM-aided construction waste minimisation framework, Autom Constr. 59 (2015) 1–23. https://doi.org/10.1016/J.AUTCON.2015.07.020.

[209] BRE, BREEAM API - BREEAM, (n.d.). https://www.breeam.com/tools/breeam-api/ (accessed August 12, 2019).

[210] S. Holmes, Green tools for LEED users: LEED apps and the LEED Dynamic Plaque | U.S. Green Building Council, (n.d.). https://www.usgbc.org/articles/green-tools-leed-users-leed-apps-and-leed-dynamic-plaque (accessed August 12, 2019).

[211] J.P. Carvalho, S.M. Silva, R. Mateus, Using BIM to streamline the energy renovation processes of residential buildings during the early design stages, in: Green Lines Institute for Sustainable Development (Ed.), International Conference on Sustainable Housing Planning, Management and Usability (Sustainable Housing 2016), Porto, 2016: pp. 435–444. http://repositorium.sdum.uminho.pt/handle/1822/43388 (accessed March 13, 2019).

[212] BRE, How BREEAM Certification Works, (2018). https://www.breeam.com/discover/how-breeam-certification-works/ (accessed December 27, 2018).

[213] F. Asdrubali, F. D'Alessandro, S. Schiavoni, A review of unconventional sustainable building insulation materials, Sustainable Materials and Technologies. 4 (2015) 1–17. https://doi.org/10.1016/J.SUSMAT.2015.05.002.

[214] BRE, BIM | BRE Group, (n.d.). https://www.bregroup.com/expertise/bim/ (accessed August 12, 2019).

[215] USGBC, LEED is green building, (2018). https://new.usgbc.org/leed (accessed December 27, 2018).

[216] G.M. Tawfik, K.A.S. Dila, M.Y.F. Mohamed, D.N.H. Tam, N.D. Kien, A.M. Ahmed, N.T. Huy, A step by step guide for conducting a systematic review and meta-analysis with simulation data, Trop Med Health. 47 (2019) 46. https://doi.org/10.1186/s41182-019-0165-6.

[217] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman, Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement, PLoS Med. 6 (2009) e1000097. https://doi.org/10.1371/journal.pmed.1000097.

[218] Y. Schwartz, R. Raslan, Variations in results of building energy simulation tools, and their impact on BREEAM and LEED ratings: A case study, Energy Build. 62 (2013) 350–359. https://doi.org/10.1016/J.ENBUILD.2013.03.022.

[219] I.B. Salgueiro, B. Ferries, An "Environmental BIM" Approach for the Architectural Schematic Design Stage, International Journal of Architectural Computing. 13 (2015) 299–312. https://doi.org/10.1260/1478-0771.13.3-4.299.

[220] T. Biswas, R. Krishnamurti, Data Sharing for Sustainable Building Assessment, International Journal of Architectural Computing. 10 (2012) 555–574. https://doi.org/10.1260/1478-0771.10.4.555.

[221] C. Zhang, J. Chen, X. Sun, A. Hammad, Lifecycle evaluation of building sustainability using BIM and RTLS, in: Proceedings of the Winter Simulation Conference 2014, IEEE, 2014: pp. 3236–3247. https://doi.org/10.1109/WSC.2014.7020159.

[222] F. Jalaei, A. Jrade, Integrating Building Information Modeling (BIM) and Energy Analysis Tools with Green Building Certification System to Conceptually Design Sustainable Buildings, Journal of Information Technology in Construction (ITcon). 19 (2014) 494–519. http://www.itcon.org/2014/29 (accessed August 12, 2019).

[223] S. Viani, G. Bergonzoni, Building Information Modeling (BIM) for LEED® IEQ category prerequisites and credits calculations, in: EWork and EBusiness in Architecture, Engineering and Construction, Taylor & Francis Group, 2016. https://www.academia.edu/28934605/Building_Information_Modeling_BIM_for_LEED_IEQ_category_prerequisites_and_credits_calculations (accessed August 12, 2019).

[224] H. Zainudin, N.A. Haron, S.H. Bachek, A. Jusoh, Utilization of building information modeling (BIM) in planning an adaptive reuse project of a Traditional Malay House (TMH), in: 2016 22nd International Conference on Virtual System & Multimedia (VSMM), IEEE, 2016: pp. 1–7. https://doi.org/10.1109/VSMM.2016.7863193.

[225] M. Marzouk, S. Azab, M. Metawie, Framework for Sustainable Low-Income Housing Projects using Building Information Modeling, Journal of Environmental Informatics. (2016). https://doi.org/10.3808/jei.201600332.

[226] P.H. Chen, T.C. Nguyen, Integrating BIM and Web Map Service (WMS) for Green Building Certification, in: Procedia Eng, Elsevier Ltd, 2016: pp. 503–509. https://doi.org/10.1016/j.proeng.2016.11.651.

[227] E.C. Akcay, D. Arditi, Desired points at minimum cost in the "Optimize Energy Performance" credit of leed certification, Journal of Civil Engineering and Management. 23 (2017) 796–805. https://doi.org/10.3846/13923730.2017.1319412.

[228] P.-H. Chen, T.C. Nguyen, Integrating web map service and building information modeling for location and transportation analysis in green building certification process, Autom Constr. 77 (2017) 52–66. https://doi.org/10.1016/J.AUTCON.2017.01.014.

[229] A. Raimondi, M. Aguerre, MSOT: Materials selection optimization in the LEED v4 protocol - A case study with BIM, Journal of Technology for Architecture and Environment. 16 (2018) 270–280. https://doi.org/10.13128/Techne-23107.

[230] M. AbouHamad, M. Abu-Hamd, Framework for construction system selection based on life cycle cost and sustainability assessment, J Clean Prod. 241 (2019) 118397. https://doi.org/10.1016/j.jclepro.2019.118397.

[231] P.H. Chen, T.C. Nguyen, A BIM-WMS integrated decision support tool for supply chain management in construction, Autom Constr. 98 (2019) 289–301. https://doi.org/10.1016/j.autcon.2018.11.019.

[232] R.J. Cole, Building environmental assessment methods: redefining intentions and roles, Building Research & Information. 33 (2005) 455–467. https://doi.org/10.1080/09613210500219063.

[233] T.F. da C.T. Lopes, Reabilitação sustentável de edifícios de habitação (Sustainable rehabilitation of residential buildings), Universidade Nova de Lisboa, 2010. https://run.unl.pt/handle/10362/4138 (accessed November 13, 2018).

[234] R.M.C. Horta, Construção sustentável de edifícios de balanço energético quase zero (Sustainable construction of nearly zero-energy buildings), Universidade Nova de Lisboa, 2012. https://run.unl.pt/handle/10362/9143 (accessed November 13, 2018).

[235] L.P.S. Cardoso, Reabilitação sustentável de edifícios anteriores a 1951 (Sustainable refurbishment of buildings built before 1951), Universidade do Minho, 2013. http://repositorium.sdum.uminho.pt/handle/1822/30877 (accessed November 13, 2018).

[236] P. Wilkinson, BIM: an overview, (2012). https://pt.slideshare.net/EEPaul/cimcig-bim-conference (accessed November 13, 2018).

[237] K. Ku, M. Taiebat, BIM Experiences and Expectations: The Constructors' Perspective, Int J Constr Educ Res. 7 (2011) 175–197. https://doi.org/10.1080/15578771.2010.544155.

[238] R. Eadie, M. Browne, H. Odeyinka, C. McKeown, S. McNiff, BIM implementation throughout the UK construction project lifecycle: An analysis, Autom Constr. 36 (2013) 145–151. https://doi.org/10.1016/J.AUTCON.2013.09.001.

[239] M. Rouse, What is application program interface (API)?, (2017). https://searchmicroservices.techtarget.com/definition/application-program-interface-API (accessed November 13, 2018).

[240] MuleSoft, What is an API? (Application Programming Interface), (2018). https://www.mulesoft.com/resources/api/what-is-an-api (accessed November 13, 2018).

[241] Autodesk Knowledge Network, What Can You Do with the Revit Platform API?, (2018). https://knowledge.autodesk.com/pt-br/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2018/PTB/Revit-API/files/GUID-154AB430-AC95-4CA7-B24A-BE56380B9D86-htm.html (accessed November 13, 2018).

[242] A.H. Oti, W. Tizani, BIM extension for the sustainability appraisal of conceptual steel design, Advanced Engineering Informatics. 29 (2015) 28–46. https://doi.org/10.1016/J.AEI.2014.09.001.

[243] S.M.S.A. Pereira, S.R.L. Amorim, O desenvolvimento de ferramenta de verificação de requisitos de projeto para o Revit® através de API (The development of a design verification tool for Revit® through API), in: ENCONTRO NACIONAL DE TECNOLOGIA DO AMBIENTE CONSTRUÍDO, 12 - 14 Novembro, Maceió, Brazil, 2014: pp. 2954–2963. https://doi.org/10.17012/entac2014.591.

[244] A.R. Justi, Implantação da plataforma Revit nos escritórios brasileiros (Revit platform deployment in Brazilian offices), Gestão & Tecnologia de Projetos. 3 (2008) 140–152. https://doi.org/10.4237/gtp.v3i1.56.

[245] F. Jalaei, A. Jrade, An Automated BIM Model to Conceptually Design, Analyze, Simulate, and Assess Sustainable Building Projects, Journal of Construction Engineering. 2014 (2014) 1–21. https://doi.org/10.1155/2014/672896.

[246] T.H. Nguyen, T. Shehab, Z. Gao, Evaluating Sustainability of Architectural Designs Using Building Information Modeling, The Open Construction and Building Technology Journal. 4 (2010) 1–8. https://doi.org/10.2174/1874836801004010001.

[247] C. Merschbrock, B.E. Munkvold, Effective digital collaboration in the construction industry - A case study of BIM deployment in a hospital construction project, Comput Ind. 73 (2015) 1–7. https://doi.org/10.1016/j.compind.2015.07.003.

[248] S. Song, J. Yang, N. Kim, Development of a BIM-based structural framework optimization and simulation system for building construction, Comput Ind. 63 (2012) 895–912. https://doi.org/10.1016/j.compind.2012.08.013.

[249] S. Wu, Q. Shen, Y. Deng, J. Cheng, Natural-language-based intelligent retrieval engine for BIM object database, Comput Ind. 108 (2019) 73–88. https://doi.org/10.1016/j.compind.2019.02.016.

[250] LNEC, Coeficientes de transmissão térmica de elementos da envolvente dos edifícios (Heat Transfer Coefficients from building envolope elements), (2006).

[251] L. Bragança, R. Mateus, Life-cycle analysis of buildings : envirnonmental impact of building elements, 2012. http://hdl.handle.net/1822/20481 (accessed October 1, 2020).

[252] R. Ruparathna, K. Hewage, R. Sadiq, Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings, Renewable and Sustainable Energy Reviews. 53 (2016) 1032–1045. https://doi.org/10.1016/J.RSER.2015.09.084.

[253] A. Andriamamonjy, D. Saelens, R. Klein, A combined scientometric and conventional literature review to grasp the entire BIM knowledge and its integration with energy simulation, Journal of Building Engineering. 22 (2019) 513–527. https://doi.org/10.1016/j.jobe.2018.12.021.

[254] European Comission, Climate strategies & targets, (n.d.). https://ec.europa.eu/clima/policies/strategies_en (accessed December 27, 2018).

[255] C. of the E.U. European Parliament, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), (2010).

[256] MEE, Regulamento dos Edifícios de Habitação - REH (Residential Buildings Regulation). Decreto-Lei nº 159/2013, (2013).

[257] Observatório da Energia, DGEG, ADENE, Energia em Números 2020, Lisboa, 2020. https://www.dgeg.gov.pt/media/43zf5nvd/energia-em-n%C3%BAmeros-edi%C3%A7%C3%A3o-2020.pdf (accessed October 21, 2020).

[258] R.E. Edwards, E. Lou, A. Bataw, S.N. Kamaruzzaman, C. Johnson, Sustainability-led design: Feasibility of incorporating whole-life cycle energy assessment into BIM for refurbishment projects, Journal of Building Engineering. 24 (2019) 100697. https://doi.org/10.1016/J.JOBE.2019.01.027.

[259] Z. Pezeshki, A. Soleimani, A. Darabi, Application of BEM and using BIM database for BEM: A review, Journal of Building Engineering. 23 (2019) 1–17. https://doi.org/10.1016/j.jobe.2019.01.021.

[260] F. Shalabi, Y. Turkan, Bim-energy simulation approach for detecting building spaces with faults and problematic behavior, Journal of Information Technology in Construction. 25 (2020) 342–360. https://doi.org/10.36680/J.ITCON.2020.020.

[261] H. Kim, Z. Shen, I. Kim, K. Kim, A. Stumpf, J. Yu, BIM IFC information mapping to building energy analysis (BEA) model with manually extended material information, Autom Constr. 68 (2016) 183–193. https://doi.org/10.1016/J.AUTCON.2016.04.002.

[262] C.F. Reinhart, C. Cerezo Davila, Urban building energy modeling – A review of a nascent field, Build Environ. 97 (2016) 196–202. https://doi.org/10.1016/J.BUILDENV.2015.12.001.

[263] T. Reeves, S. Olbina, R.R.A. Issa, Guidelines for using building information modeling for energy analysis of buildings, Buildings. 5 (2015) 1361–1388. https://doi.org/10.3390/buildings5041361.

[264] N. Ardda, R. Mateus, L. Bragança, Methodology to Identify and Prioritise the Social Aspects to Be Considered in the Design of More Sustainable Residential Buildings—Application to a Developing Country, Buildings. 8 (2018) 130. https://doi.org/10.3390/buildings8100130.

[265] O. Awadh, Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis, Journal of Building Engineering. 11 (2017) 25–29. https://doi.org/10.1016/j.jobe.2017.03.010.

[266] S.H. Alyami, Y. Rezgui, Sustainable building assessment tool development approach, Sustain Cities Soc. 5 (2012) 52–62. https://doi.org/10.1016/J.SCS.2012.05.004.

[267] R. Ade, M. Rehm, The unwritten history of green building rating tools: a personal view from some of the 'founding fathers,' Building Research & Information. 48 (2020) 1–17. https://doi.org/10.1080/09613218.2019.1627179.

[268] IteCons, University of Coimbra, Plataforma para a Eficiência Energética de Edifícios, (2020). http://www.itecons.uc.pt/p3e/index.php (accessed November 19, 2020).

[269] R. Mateus, S.M. Silva, M.G. de Almeida, Environmental and cost life cycle analysis of the impact of using solar systems in energy renovation of Southern European single-family buildings, Renew Energy. 137 (2019) 82–92. https://doi.org/10.1016/j.renene.2018.04.036.

[270] INE, LNEC, O Parque Habitacional e a sua Reabilitação - Análise e Evolução: 2001 - 2011 (Housing stock and rehabilitation – analysis and evolution: 2001-2011), Lisboa, 2013.

https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_publicacoes&PUBLICACOESpub_boui=165231362&PUBLICACOEStema=00&PUBLICACOESmodo=2 (accessed May 11, 2021).

[271] J.R.B. Sousa, S.M. Silva, M.G. de Almeida, Energy rehabilitation of Portuguese residential building stock through its transformation into NZEB, in: Seminário Reabilitação Energética de Edifícios, Universidade do Minho, 2012: pp. 41–48. https://repositorium.sdum.uminho.pt/handle/1822/21333 (accessed December 27, 2018).

[272] MAOTE-DGEG, Despacho nº 15793-K/2013, (2013).

[273] O. do T. e E. Ministério do Ambiente, Portaria 379-A/2015, 2015-10-22 - DRE, (2015) 9196(14)-9196(17). https://dre.pt/web/guest/pesquisa/-/search/70789581/details/normal?l=1 (accessed November 19, 2020).

[274] Z. Liu, Y. Lu, M. Shen, L.C. Peh, Transition from building information modeling (BIM) to integrated digital delivery (IDD) in sustainable building management: A knowledge discovery approach based review, J Clean Prod. 291 (2021) 125223. https://doi.org/10.1016/J.JCLEPRO.2020.125223.

[275] M. al Hattab, The dynamic evolution of synergies between BIM and sustainability: A text mining and network theory approach, Journal of Building Engineering. 37 (2021) 102159. https://doi.org/10.1016/J.JOBE.2021.102159.

[276] L. Nazarko, Technology Assessment in Construction Sector as a Strategy towards Sustainability, in: Procedia Eng, Elsevier Ltd, 2015: pp. 290–295. https://doi.org/10.1016/j.proeng.2015.10.038.

[277] P.E. Haeberli, ConMan: A Visual Programming Language for Interactive Graphics, Proceedings of the 15th Annual Conference on Computer Graphics and Interactive Techniques - SIGGRAPH '88. 22 (1988). https://doi.org/10.1145/54852.

[278] C.Y. Tsai, Improving students' understanding of basic programming concepts through visual programming language: The role of self-efficacy, Comput Human Behav. 95 (2019) 224–232. https://doi.org/10.1016/J.CHB.2018.11.038.

[279] J. Bedrick, W. Ikerd, J. Reinhardt, Level of Development (LOD) Specification for Building Information Models, Part I, Guide & Commentary, 2021. www.bimforum.org/lod (accessed August 3, 2022).

Publications

F.S. Villaschi, J.P. Carvalho, L. Bragança, BIM-Based Method for the Verification of Building Code Compliance. *Applied System Innovation*. 2022; 5(4):64. https://doi.org/10.3390/asi5040064

F.S. Villaschi, J.P. Carvalho, L. Bragança, Automatic verification of urban index compliance: A case study for Brazilian buildings, 2022 IOP Conf. Ser.: Earth Environ. Sci. 1078 012041. https://doi.org/10.1088/1755-1315/1078/1/012041

J.P. Carvalho, L. Bragança, R. Mateus, Information technology and the digital transformation of building design, 2021 Sustainable Urban Development, IOP Publishing. https://doi.org/10.1088/978-0-7503-3971-1CH11

J.P. Carvalho, F.S. Villaschi, L. Bragança, Assessing Life Cycle Environmental and Economic Impacts of Building Construction Solutions with BIM. *Sustainability*. 2021; 13(16):8914. https://doi.org/10.3390/su13168914

J.P. Carvalho, M. Almeida M, L. Bragança, R. Mateus, BIM-Based Energy Analysis and Sustainability Assessment–Application to Portuguese Buildings. *Buildings*. 2021; 11(6):246. https://doi.org/10.3390/buildings11060246

J.P. Carvalho, L. Bragança, R. Mateus, Sustainable building design: Analysing the feasibility of BIM platforms to support practical building sustainability assessment, *Computers in Industry* 127 (2021) 103400. https://doi.org/10.1016/j.compind.2021.103400

J.P. Carvalho, I. Alecrim, L. Bragança, R. Mateus, Integrating BIM-Based LCA and Building Sustainability Assessment. *Sustainability*. 2020; 12(18):7468. https://doi.org/10.3390/su12187468

J.P. Carvalho, L. Bragança, R. Mateus, A Systematic Review of the Role of BIM in Building Sustainability Assessment Methods. *Applied Sciences*. 2020; 10(13):4444. https://doi.org/10.3390/app10134444

J.P. Carvalho, L. Bragança, R. Mateus, Guidelines for analysing the building energy efficiency using BIM, 2020 *IOP Conf. Ser.: Earth Environ. Sci.* 588 022058. https://doi.org/10.1088/1755-1315/588/2/022058

I. Alecrim, J.P. Carvalho, L. Bragança, R. Mateus, Using BIM for Assessing Buildings Life Cycle Impacts, 2020 *IOP Conf. Ser.: Earth Environ. Sci.* 503 012005. https://doi.org/10.1088/1755-1315/503/1/012005

J.P. Carvalho, L. Bragança, R. Mateus, Optimising building sustainability assessment using BIM, Automation in Construction 102 (2019) 170-182. https://doi.org/10.1016/j.autcon.2019.02.021

J.P. Carvalho, K. Ridder, L. Bragança, R. Mateus, Using BIM to optimise and assess the energy efficiency category of SBToolPT-H, 2019 *IOP Conf. Ser.: Earth Environ. Sci.* 225 012072. https://doi.org/10.1088/1755-1315/225/1/012072

Appendix

Appendix A. SBTool^{BIM} User Guide

Context

SBTool^{BIM} was developed under a PhD thesis scope with the aim of automate and simplify the assessment of the Portuguese residential Building Sustainability Assessment (BSA) method SBTool^{PT}-H, as well as integrate it into BIM environment.

SBTool^{BIM} provides direct assessment of 19 out of 25 criteria from SBTool^{PT}-H and suggests an additional pathway to gather the required data for the assessment of the remaining 6 criteria, as presented in the process from Figure A1.

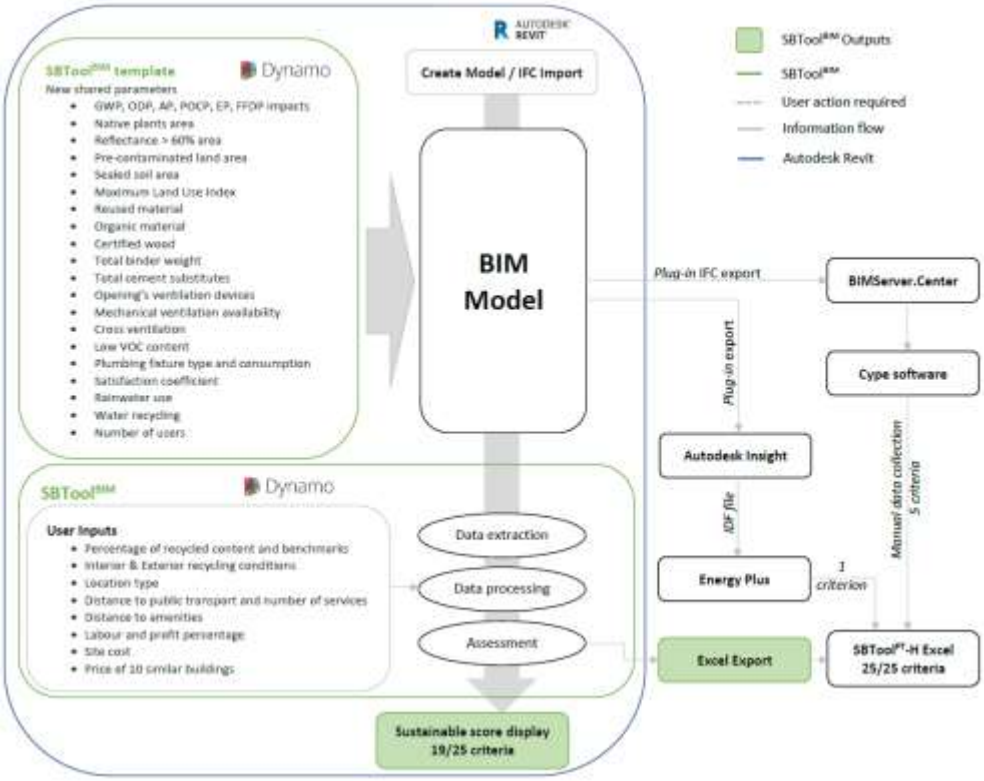


Figure A1 – SBTool^{BIM} process map

Table A1 identifies each criterion evaluated by SBTool^{BIM}, where the category and criteria weights were adjusted from SBTool^{PT}-H system. All excluded criteria had their weights equally distributed by the considered criteria from each category. Moreover, excluded categories also had their weights distributed by the other categories under the same dimension. For instance, category C6 has 5 criteria in SBTool^{PT}-H but only 2 are considered in the SBTool^{BIM} application, so the category weight and evaluation are only given by two criteria, each with a 50% ponderation, as both have the same impact in SBTool^{PT}-H. Likewise, category C3 is not considered, and its weight has been equally disturbed by the remaining categories of the Environment dimension.

Table A1 – SBTool^{BIM} considered criteria and weighting system

Dimension	Category	Criterion	Criterion weight	Category weight	Dimension weight
Environment	C1	P1	100%	21.75%	40%
	C2	P2	38%	28.75%	
		P3	5%		
		P4	6%		
		P5	24%		
		P6	27%		
	C4	P9	25%	31.75%	
		P10	25%		
		P11	28%		
		P12	18%		
		P13	4%		
	C5	P14	64%	17.75%	
		P15	36%		
Social	C6	P16	50%	60%	30%
		P17	50%		
	C7	P21	55%	30%	
		P22	45%		
	C8	P23	100%	10%	
Economic	C9	P24	100%	100%	30%

SBTool^{BIM} was fully developed in Dynamo and it is hosted by Autodesk Revit.

This document serves as guide for a proper implementation of SBTool^{BIM}. The information contained in this document does not relieve a careful reading of SBTool^{PT}-H Assessment Guide.

SBTool^{BIM} research was funded by the Portuguese Foundation for Science and Technology (FCT), grant number SFRH/BD/145735/2019.

1. SBTool^{BIM} folder

SBTool^{BIM} folder must be downloaded to the work environment and contains the following elements:

- SBTool^{BIM} template (dyn file)
- SBTool^{BIM} (dyn file)
- SBTool^{BIM} Excel spreadsheet (xml file)
- SBTool^{BIM} User Guide (pdf file)
- SBTool^{PT}-H Excel spreadsheet (xml file)
- SBTool^{PT}-H Assessment Guide (pdf file)

2. BIM model and SBTool^{BIM} template

To start using SBTool^{BIM}, a BIM model is required. The model can be developed from scratch in Autodesk Revit or imported via IFC from another BIM platform.

2.1 Modelling guidelines

The BIM model should be developed through a parametric modelling and must include the site topography and constructions, according to the following guidelines:

- Each topography surface – as green area, sidewalks, native plants area, entrance, building area, among others – should be defined as an individual topography surface, to define different characteristics between them.
- Building elements such as roofs, floors, stairs, walls, windows, and doors should be developed under their respective category and materials must be assigned.
- The building ground slab and between levels slabs must always be defined as "Floor", while the building top slab should be modelled as "Roof".
- Walls must be modelled under "Wall" category and its function defined (exterior or interior). Walls must be modelled through stacked walls instead of compound layers.
- Rooms must be defined for all the building compartments.
- Plumbing fixtures must be modelled.

2.2 SBTool^{BIM} template

To endow the BIM model with the required data for the assessment, SBTool^{BIM} template was created. It can be used after or before the model development and even marked as "standard" to develop projects in

Autodesk Revit. A total of 28 new shared parameters are automatically created according to the identified input requirements for SBTool^{PT}-H. Table A2 identifies all the programmed parameters, as well as their type and applicable category.

Table A2 – SBTool^{BIM} template parameters

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
Litres 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

SBTool^{BIM} template was developed in Dynamo and its structure can be seen or edited to include new parameters or adapt the existing ones.

All the created parameters are mandatory to be filled for a successful evaluation, as well as guarantee that the model fulfils the guidelines from the previous section.

To start, SBTool[BIM] template should be added by using Dynamo Player, as presented in Figure A2, which is located under the Manage tab of Autodesk Revit. Just browse for SBTool[BIM] folder and run SBTool[BIM] template by pressing the start button. The project characterisation can now begin.

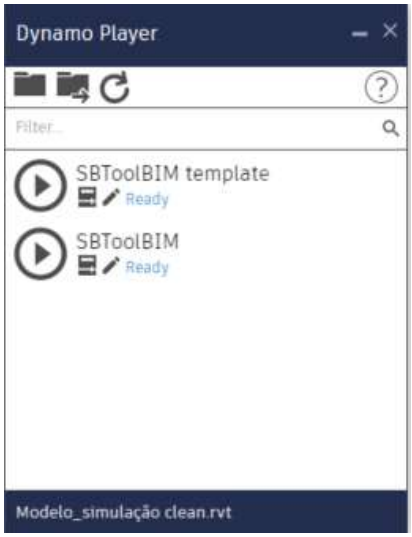


Figure A2 – Dynamo Player

Each topography surface should be characterised according to Figure A3. It is necessary to identify if the surface corresponds to a native plants area, to a sealed soil area or to a reflectance ≥ 60% area. Note that all non-sealed areas are considered as "Green Areas" for assessment purposes. Topography elements, such as sidewalks, should only be modelled as surface ("floors" should only be modelled for the building itself).

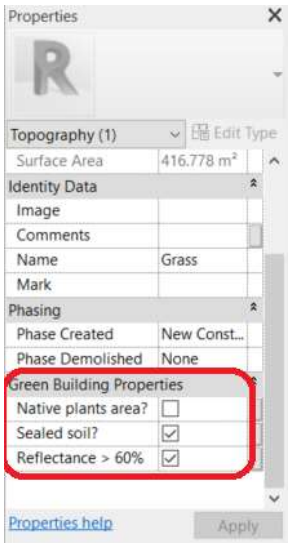


Figure A3 – Topography surface characterisation

Also note that during the characterisation process, the selection box should always have an identified option, without the grey background, according to the instructions of Figure A4.



Figure A4 – Instructions for parameter selection

Under the Manage tab of Autodesk Revit, Project Information data should also be completed according to Figure A5. The number of users can be defined, the satisfaction coefficient (%) of the Rainwater harvesting system can be set (P15), the pre-contaminated or reused area defined (P4), as well as the Maximum Land Use index, which should be gathered from the local master plan (P2). It is also identified if the building has mechanical ventilation / HVAC.

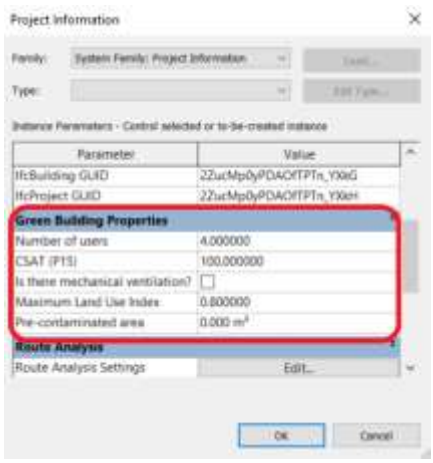


Figure A5 – Project Information characterisation

Next, it is necessary to characterise all the building element materials, according to Figure A6. The user must collect the required data according to the material type or a material database should be used. Each material must have the following data:

- Low VOC content characterisation for all finishing materials

- Total binder weight and cement substitutes for concrete materials (total binder weight or kg/m³)
- All certified wood or organic products must be identified
- Reused materials should be identified
- Environmental impacts should be defined for all materials. SBTool[PT]-H LCIA database can be used

If the red square option of Figure A6 is not available, SBTool[BIM] template was not successfully applied.

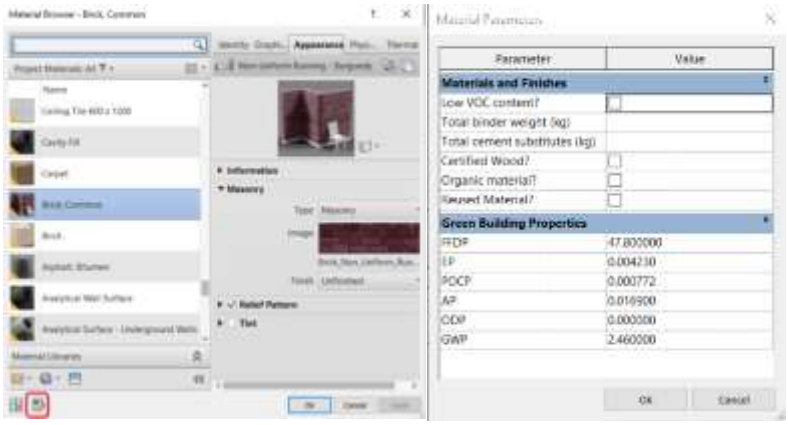


Figure A6 – Material characterisation

Note that the parameters from Figure A6 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. Openings must have their cost (per window or door) under the “Identity data” (Edit type > Identity Data > Cost) and information regarding ventilation devices (P16), as presented in Figure A7.

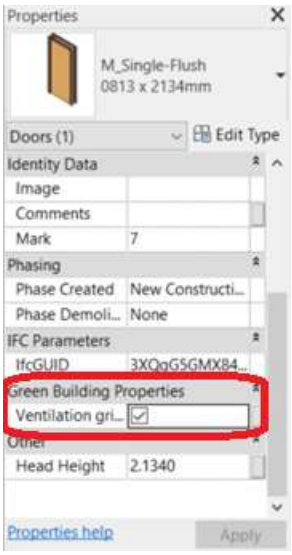


Figure A7 – Openings characterisation

Finally, plumbing fixtures must be characterised according to Figure A8. 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. Note that the plumbing type selection may disregard some types when characterising many fixtures. If so, the user can directly write the fixture type name (according to identified types earlier) instead of using the list selection.

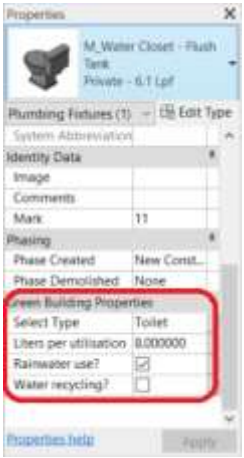


Figure A8 – Plumbing fixtures characterisation

At last, for every building compartment the “room” function should be used to characterise each induvial space for P16 assessment, according to Figure A9. Moreover, the “room” function will also be mandatory when exporting the BIM model for additional BIM tools.

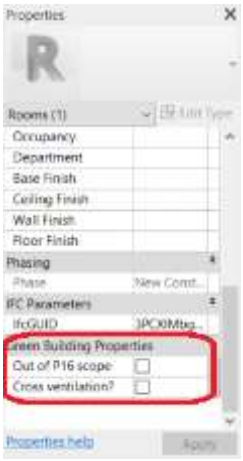


Figure A9 – Room characterisation

3. SBTool^{BIM} application

After characterising all the required parameters, SBTool^{BIM} can be started by selecting its respective file in the Dynamo Player and pressing the play button, as presented in Figure A2.

Attention: The display order of the following interfaces may be different from presented.

After a couple of minutes, the application starts by showing some pop-up windows for the user inputs. First, P10 data must be completed. Figure A10 presents the user interface for P10 assessment, where:

- Column 0 identifies all the existing materials in the BIM model
- Column 1 quantifies the total mass of each material
- Column 2 corresponds to the national benchmark for the best practice. It must be filled whenever a material with recycled content is used, in percentual value
- Column 3 corresponds to the national benchmark for the conventional practice. It must be filled whenever a material with recycled content is used, in percentual value
- Column 4 corresponds to the adopted recycled content percentage for the project materials

For instance, Figure A10 shows that the best practice concerning the recycled content for Bricks is 30%, the conventional practice is 0% and the project recycled content for bricks is 10%.

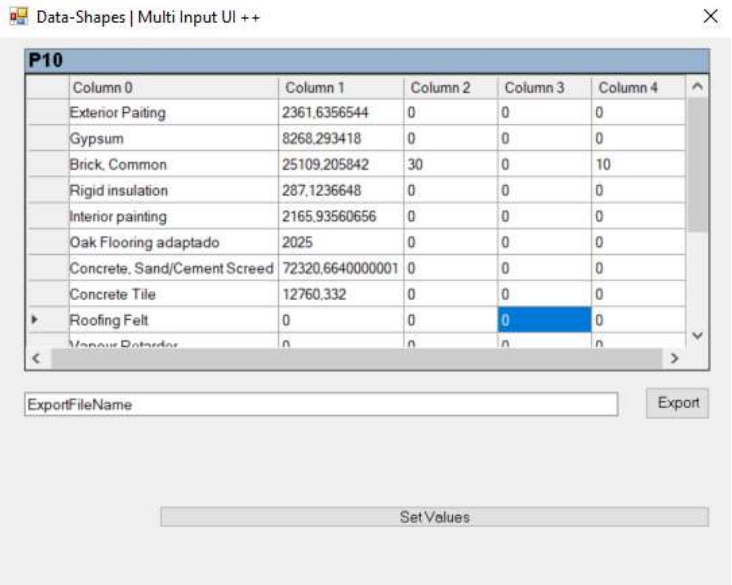


Figure A10 – SBTool[BIM] interface for P10 assessment

Then, P13 data must be completed, as presented in Figure A11. The user must identify if the building has interior recycling conditions, as well as the total volume (in liters) of all the recycling interior containers. The existence of oil and batteries containers should be identified, as well as the existence of a door-to-door collection or a personal collection plan. The distance to the exterior public containers must also be introduced (in meters).



Figure A11 – SBTool[BIM] interface for P13 assessment

Concerning to the Accessibility category, the user must complete information about P21, as presented in Figure A12. Besides the building zone type selection, the user must identify public transport stations and services, according to SBTool^{PT}-H guidelines. Up to 5 different stations can be introduced in SBTool^{BIM}.

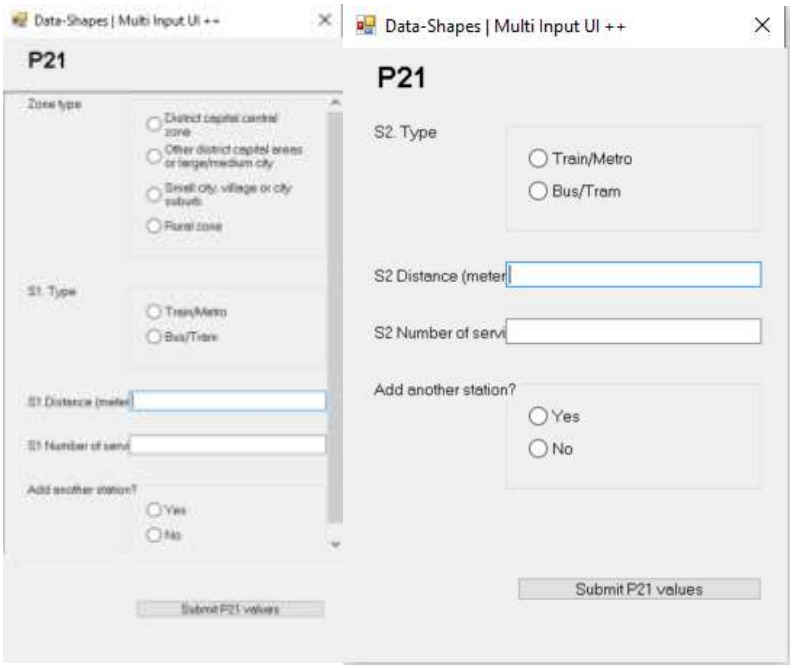


Figure A12 – SBTool^{BIM} interface for P21 assessment

Simultaneously, the user must gather amenities distances and introduce them in P23 interface, as presented in Figure A13. All distances must be filled (in meters).



Figure A13 – SBTool[BIM] interface for P22 assessment

Then, information regarding the building user guide should be completed in P23 interface through a checklist, as presented in Figure A14.



Figure A14 – SBTool[BIM] interface for P23 assessment

Finally, economic data should be included in P24 interface, according to Figure A15. The site cost can be included (in €) in the analysis and percentages of the building cost are considered for the man work and

profit. Note that the labour percentage is applied to the sum of all building materials and fixtures cost. The profit margin is applied to the material cost plus the labour cost. The national VAT tax of 23% is included in the analysis. Finally, the user must identify the average price of 10 similar dwellings sold nearby (€/m²), as well as the average price of the less expensive three (€/m²), according to SBTool^{PT}-H guidelines.

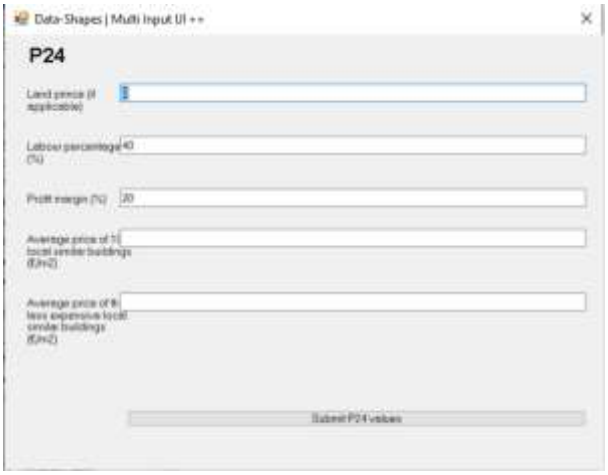


Figure A15 – SBTool^{BIM} interface for P24 assessment

After completing all the interfaces, SBTool^{BIM} automatically displays the building score, as presented in Figure A16. Both the qualitative individual score of each criterion and the building total score are presented.

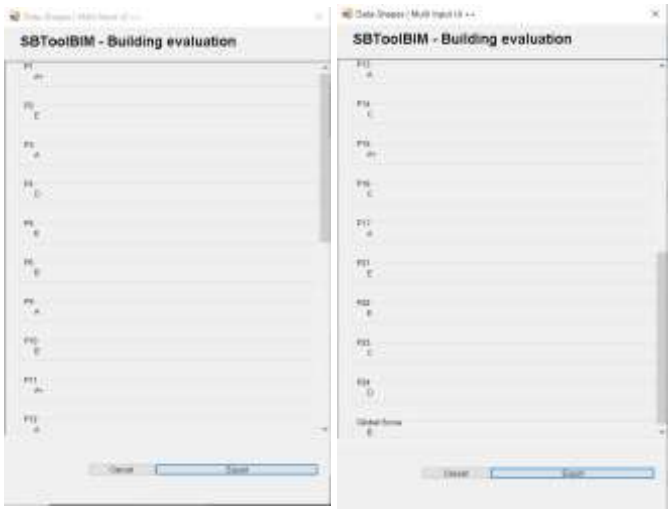


Figure A16 – SBTool^{BIM} results

Results can later be exported to SBTool^{BIM} Excel spreadsheet, as presented in Figure A17. Select this spreadsheet in SBTool^{BIM} folder as “File Path” and keep the same “Worksheet name”.

This is done for the user gather the quantitative score of each criterion, as well as to proceed with the full SBTool^{PT}-H analysis, after collection building performance data through additional BIM links.

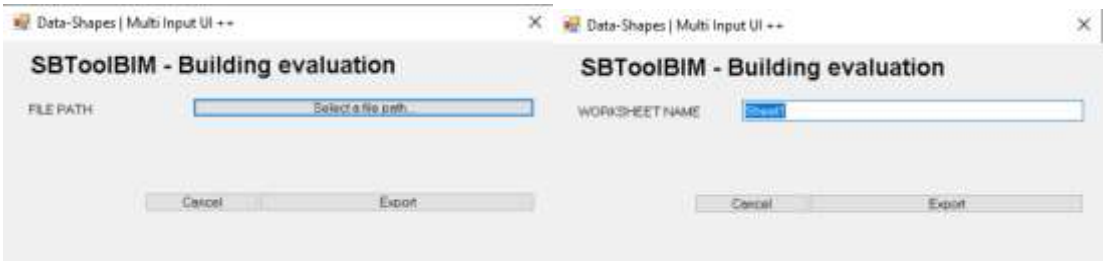


Figure A17 – Results exportation for SBTool^{BIM} Excel spreadsheet

Note that the SBTool^{BIM} Excel spreadsheet destination file must not be opened when saving new analysis results. Otherwise, saving operation will fail. Results in SBTool^{BIM} Excel spreadsheet will appear as presented in Figure A18.



Figure A18 – SBTool^{BIM} Excel Spreadsheet

4. BIM linkage for complete SBTool^{PT}-H assessment

To proceed with the full assessment inside BIM environment, six SBTool^{PT}-H criteria require the use of additional BIM tools.

To gather the required data for P7, P8, P19, P20 and P25, the BIM model must be exported to Cype software. To do so, it is recommended to use Cype plug-in, which can be downloaded here for Autodesk Revit and found under the Add-Ins tab. The plug-in instructions can be found here and must be followed accordingly.

Then, the following software and respective information will be required:

- Cypetherm REH for the assessment of P7, P8, P19 and P25
    - P7, P8 and P25 – The building primary energy needs (N_t and N_{tc}), heating needs (N_i and N_{ic}), cooling needs (N_v and N_{vc}), DHW needs (QA) and the building renewable energy production (E_{ren} or E_{solar}) should be collected after performing the energy analysis, as presented in the simulation report from Figure A19.

Fração	Tx. ren. (RPH,i)	Tx. ren. (RPH,v)	Nic (kWh/m².ano)	Ni (kWh/m².ano)	Nvc (kWh/m².ano)	Nv (kWh/m².ano)	QA (kWh/m².ano)	QA_{REF} (kWh/m².ano)	Ntc (kWh_{ER}/m².ano)	Nt (kWh_{ER}/m².ano)	Eren,p (*) (kWh/ano)	Eren,ext (**) (kWh/ano)
Habitação	0.61	0.61	81.36	90.61	5.00	9.15	24.38	27.08	217.61	262.67	977.00	0.00

Figure A19 – Simulation results in Cypetherm REH

- P19 – The horizon angle and horizontal obstruction angle from all windows should be collected from the room information in Cypetherm REH, as presented in Figure A20 (under the "zones" menu, open each compartment which has windows and select "openings". Make sure to activate "solar contribution" and "shadows"). If necessary, IFC Builder software from Cype may be used to correct the BIM model or add nearby obstacles

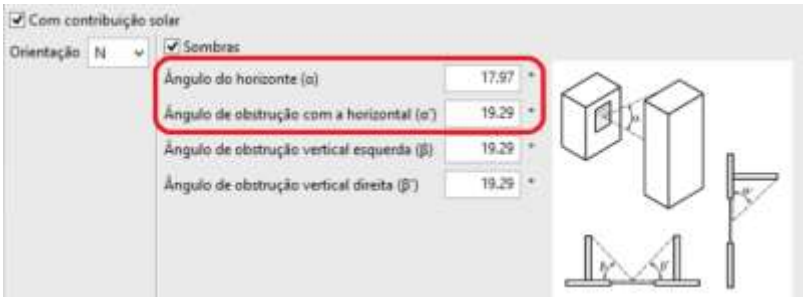


Figure A20 – Horizon and horizontal obstruction angle in Cypetherm REH

- Cypesound RRAE for the assessment of P20
  - P20 – Acoustic insulation index (airborne and, if applicable, impact) gathered from acoustic simulation result report, as presented in Figure A21.



Figure A21 – Simulation results in Cypesound RRAE

Cype provides a wide range of tutorials to use their software, which should be consulted to properly conduct building performance simulations.

Finally, to gather part of the assessment data for P18 assessment, the BIM model should be exported to Autodesk Insight, using Autodesk Revit plug-in under the Analyze tab, as presented in Figure A22.



Figure A22 – Plug-in to Insight in Autodesk Revit

Insight was used to allow the possibility to extract the BIM model through a IDF file, which can be used in Energy Plus software. This process is presented in Figure A23.

Before the energy analysis itself, IFD editor should be used to adapt the file for Energy Plus and further instructions can be found here. When uploaded and adapted, the user must follow SBTool^{PT}-H assessment guide to collect the assessment data for P18. Note that the "Running mean external temperature", which is required for P18, must manually be gathered by the user through other means.

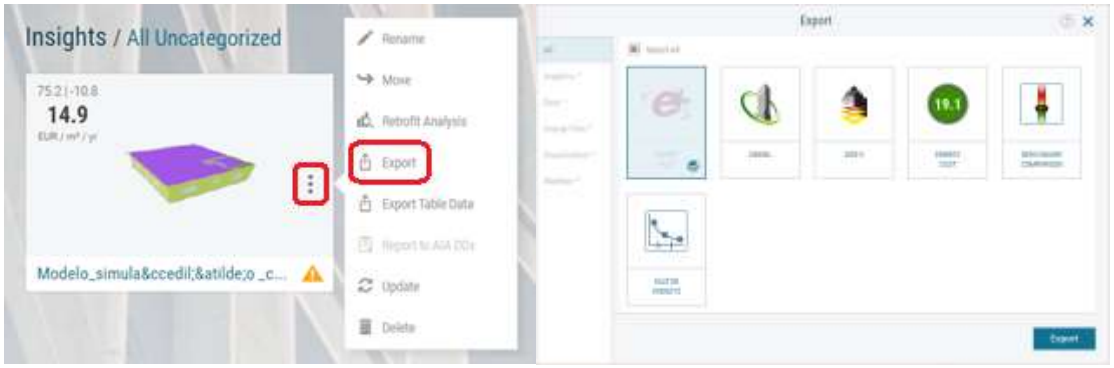


Figure A23 – IDF export in Insight

All the mentioned data should be collected and introduced in SBTool^{PT}-H Excel spreadsheet, which is already automated to collect the results from SBTool^{BIM} Excel spreadsheet. To do so, open SBTool^{PT}-H Excel Spreadsheet and go to "SBToolBIM" Sheet. Select all the entries and update them according to Figure A24.

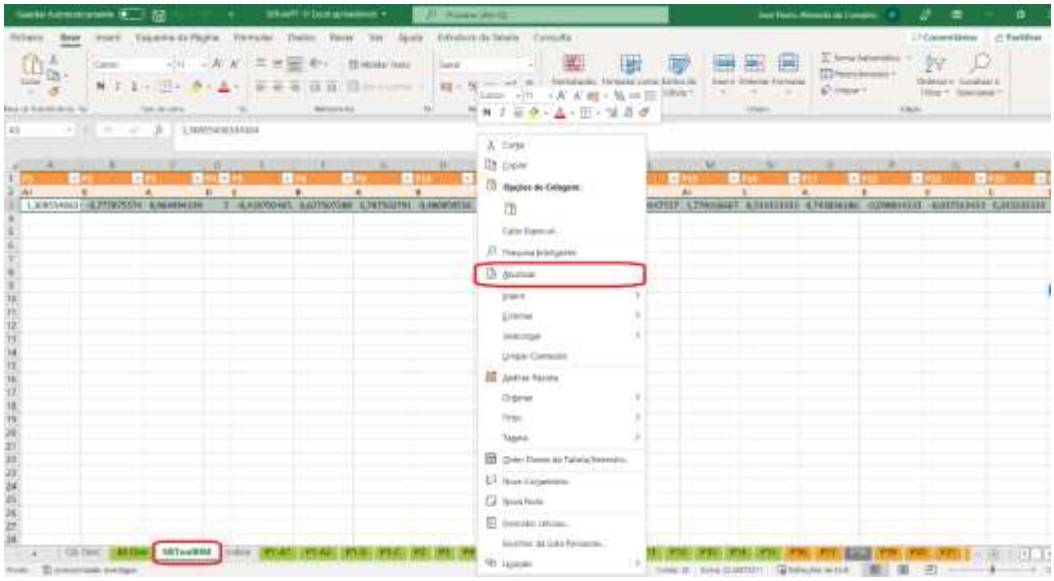


Figure A24 – Importing data in SBTool[PT]-H Excel spreadsheet

Then, criteria P1, P2, P3, P4, P5, P6, P9, P10, P11, P12, P13, P14, P15, P16, P17, P21, P22, P23 and P24 will be automatically filled with the last simulation results (green cells). The user must collect and introduce the data for the assessment of P7, P8, P18, P19, P20 and P25 (blue cells). The building final score can be seen in the last sheet (AG) of SBTool[PT]-H Excel spreadsheet.

5. Assumptions and exclusions

Please consider that SBTool[BIM] has the following assumptions and exclusions:

- 19 SBTool[PT]-H criteria have been successfully automated;
- 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.