Developing a BIM-Based Tool to Automate Green Buildings Assessment: The Case of Jordan Green Building Guide

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Abstract

Sustainable construction is often used to describe buildings designed according to criteria embedded in green building rating tools (GBRTs) systems. GBRTs often tackle multi-criteria, such as energy, water, indoor environment, and materials performance of buildings, requiring experienced professionals to conduct various assessment processes and simulations. Traditional CAD tools often produce different versions of building models for sustainability assessment to perform various performance simulations using building performance simulation tools (BPS) for cost estimates, structural analysis, building energy and daylighting performance. The manual assessment is often considered expensive and challenging, requiring extensive time and effort and, in some cases, could lead to errors and redundant work. The sustainability assessment of buildings is data-driven and highly relies on available building information and tools capable of processing and augmenting design data from the initial design phase.

The representation of project information in digital environments, such as Building Information Modelling (BIM), has shifted the industry towards a more efficient practice. BIM was adopted to facilitate green building assessment by integrating with BPS tools and providing data-rich models for various assessment processes. However, the currently developed approaches tackle a specific sustainability issue in a specific standard, such as LEED's energy assessment. The existing literature concludes that currently, there is no comprehensive assessment tool that can streamline green building evaluation. This thesis aims to develop a BIM-based sustainability assessment tool that facilitates the assessment of green buildings. In this regard, we question the ability of BIM technology to provide the necessary means to automate the assessment of GBRTs. Hence, the integrated sustainability assessment tool (iSAT) was developed by first conducting a comparative analysis between selected GBRTs to highlight the maturity and comprehensiveness of the JGBG compared to others, which helped formulate a better understanding of the factors assessed, processes and complexity involved in the assessment process. Secondly, an algorithm was developed using an information technology approach to allow the integration of BIM data, BPS tools, and GBRTs to eliminate the complexity of processes involved and, thus, streamline the assessment process for the targeted criteria. The proposed tool was tested on two case studies designed and certified based on the JGBG.

To conclude, BIM has shown a fundamental technical advancement over traditional CAD tools, allowing easier integration with BPS tools. However, not all GBRT criteria can be automated due to the nature of these criteria requiring professional body or expertise involvement. Nevertheless, the proposed tool can efficiently integrate BIM, BPS, and GBRTs, demonstrating that selected criteria are automatically assessed. Further efforts are still needed to overcome challenges while developing the

tool, such as improving the quality of BIM-exported data models, developing a middleware tool to fix these files, and allowing for actual data inputs to improve the accuracy of BPS further.

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1. Introduction

1.1 Research background

The construction industry is responsible for more than 36% of the final energy, accounted for nearly 40% of CO2 emissions in 2017 (IEA and UNEP, 2018) and consumes more than 30% of global resources (Rode, Burdett and Soares, 2011). In addition, the construction sector produces 40% of the solid waste in developed countries (Yılmaz and Bakış, 2015). To address these challenges and reduce the negative environmental impact of the building sector, numerous green building certificates, standards, and rating tools were introduced in the past 20 years (Vierra, 2016) as a step to address and cut the significant impact of the construction sector on the built and natural environment (Junnila and Horvath, 2003; Ebert, Eßig and Hauser, 2011). Green buildings must respond to various factors, including energy-efficient, water-conserving, durable and non-toxic, with high-quality spaces and high-recycled materials. However, the definitions and parameters for these factors vary remarkably from standard to standard and country to country.

Among the most common international tools: Leadership in Energy and Environmental Design (LEED) in the USA, which was also developed into many national versions; Building Research Establishment Environmental Assessment Method (BREEAM) in the United Kingdom; Green Star in Australia, which was further developed into national versions in New Zealand, and South Africa (Say and Wood, 2008; Doan *et al.*, 2017; He *et al.*, 2018; Mattoni *et al.*, 2018). Among the national rating systems is the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) in Japan; Green Building Evaluation Standard, and the 3-Star rating system in China; examples of rating systems in the Middle East are Jordan Green Building Guide (JGBG) in Jordan; Pearl for Estidama in Abu Dhabi. These rating systems require varying levels of knowledge in sustainable design to accomplish the most effective use (Fowler and Rauch, 2006).

Most of these Green building rating tools (GBRT) are voluntary tools that aim to assess and mitigate the performance of buildings regarding various sustainability factors. However, the assessment process tends to be very complex and challenging due to the vast number of factors that GBRT aims to assess. It requires various tools, knowledge, and resources to assess the building performance of the selected GBRT.

While GBRTs vary significantly from one standard to another in terms of their structure, category weighting, and assessment method, most of these standards share a significant portion of similar factors and goals and tackle similar issues. However, only a limited number of Building Performance Evaluation (BPE) tools can currently assess limited criteria within a limited number of GBRTs.

Therefore, the assessment process is considered a barrier to adopting these voluntary tools worldwide (Darko and Chan, 2017).

Various studies have investigated the integration of GBRT with Building Information Modelling (BIM) to facilitate the sustainability assessment of buildings (Azhar *et al.*, 2011; Jrade and Jalaei, 2013; Solla, Ismail and Yunus, 2016; Han *et al.*, 2017; Jalaei, Jalaei and Mohammadi, 2020). BIM, as a tool, offers great capabilities, ranging from technical superiority over traditional practice, cost and time savings, and, most importantly, the ability to allow all project design teams to work in one central model as an integrative process. Furthermore, the potential of BIM interoperability with BPE tools offers a great solution to adopting BIM for sustainable and green building projects. In this regard, various studies have investigated the potential of this integration between BIM and GBRT(Biswas, Wang and Krishnamurti, 2006, 2013; Raouf and Al-Ghamdi, 2019). However, most of these studies had only looked at the Energy performance using LEED criteria.

This research presents an approach to address the presented challenges by proposing a BIM-based approach that integrates BPE, BIM, and GBRTs within a computational workflow to automate the sustainability assessment of green building projects in their early design stage. The proposed workflow formulates a vital contribution to the sustainable construction industry, especially the architects, by facilitating the sustainability assessment for different factors in an automated process, significantly reducing the time and effort needed to conduct the required assessment compared to the manual assessment workflow. The proposed tool workflow is designed to facilitate sustainable project architects, who must work with specific tools to tackle different sustainability assessment factors prescribed by different GBRTs. For the demonstration, when working on a project that targets the JGBG certificate, the architect must assess different architectural aspects' impact on the overall building energy and daylight performance. Energy performance and daylight assessment are examples of different complex tasks required in the early stages of the project lifecycle. Different tools are needed to perform such tasks, requiring experienced users, and are described as time-consuming due to the efforts needed to generate different design and assessment models. Hence, the proposed workflow aims to facilitate the assessment workflow for the project architects to automate and reduce the time and effort needed for the assessment task.

1.2 Research problem

Green building rating tools (GBRTs) consist of numerous factors, many of which are complex. The assessment of green buildings is often described as manual, costly, time-consuming, and complex. It requires ultimate collaboration between design teams as early as the preparation and briefing stage of the project. It demands significant experience to prepare performance simulation models that can only tackle a few sustainability factors (Lu *et al.*, 2017; Ansah *et al.*, 2019). The research problem can be categorised into the following three sections that are associated with GBRT:

1.2.1 Traditional sustainability assessment of buildings

Traditionally, the project delivery process has depended highly on 2D drawings produced by CAD tools. This method can produce numerous errors and problems when relying on 2D drawings and documents, significantly impacting the project's time and cost. Traditional CAD tools often produce different versions of building models for sustainability assessment to perform various performance simulations, such as cost estimates, structural analysis, building energy and daylighting performance evaluation, and more. Moreover, these assessments can only be made at the end of the design stage when it is too late for any design modifications to improve the project performance (Miettinen and Paavola, 2014; Sacks *et al.*, 2018).

The implementation of the traditional procedure to support green building assessment can be described as a complex process in its nature (Mateus and Bragança, 2011; Hwang and Tan, 2012; Doan *et al.*, 2017; Sanhudo and Martins, 2018), in addition to being segregated or unconnected process rather than integrated. Raouf and Al-Ghamdi (2019) argue that using conventional methods can bring up challenges related to increasing time and cost resulting from the complex design variables, project documentation, and the workflow implemented to improve the overall building performance. Hope and Alwan (2012) add the lack of communication between project teams, deficiencies in delivering sufficient and reliable data, and the separation between ordinary and sustainability project documentation. Moreover, the process requires high levels of collaboration between different project teams (Ahmad, Thaheem and Anwar, 2016) due to the complex design process that necessitates multi-interdependent decisions iteratively. Motawa and Carter (2013) also add the integration between the conventional tools to prevent multi-data entry and the amount of information needed to perform the sustainability analysis, considering external data sources.

Traditional CAD tools are used to prepare building models for energy, daylight, and other sustainability factors, which can be imported to other energy analysis tools such as EnergyPlus, IES-VE, and others

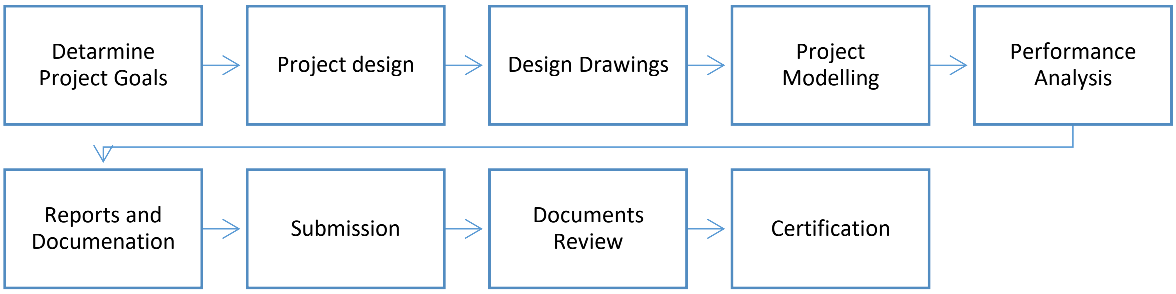


Figure 1-1 Traditional process for green building assessment

(Cho, Alaskar and Bode, 2010). However, the analysis is mainly made in the last design stages, when their components and elements have already been chosen (Jalaei and Jrade, 2014). See Figure 1-1.

1.2.2 Building performance simulation tools

Building performance simulation (BPS) programs offer the robust capability for modelling buildings in design phases to predict how a building interacts with the outdoor environment during its life cycle (Morbitzer, 2003; Maile, Fischer and Bazjanac, 2007). The development of building performance simulation tools has received much attention in the last twenty years. Many tools have been developed for various purposes. For example, EnergyPlus (US Dept. of Energy, 2019) and DesignBuilder (Design Builder Ltd, 2019) are tools that were designed to assess the energy and thermal performance of buildings, while Integrated Environment Solutions-Virtual Environment (IES-VE) (Integrated Environmental Solutions Ltd., 2013) was developed with more capabilities to simulate daylight, air quality and more.

Østergård (2016) argues that most simulation tools are evaluative, meaning they can only assess building performance in the last design stage rather than guiding the design process and influencing the design options in the concept stage. Attia (2012) states that out of 392 tools listed in the Building Energy Simulation Tools Directory (Directory, 2018), less than 1% can be used to inform a project at the briefing stage. For example, the engineer at the concept design stage is frequently asked by the architect and the owner several what-if questions regarding different design alternatives, such as the use of external shading systems, the use of passive or active cooling systems, different window-to-wall ratios, prior to any detailed design work. It is very challenging to answer these enquiries during the concept stages of the design due to various uncertainties, including the lack of design details, the rapid changes in the design, and the massive amount of time spent preparing different scenarios and obtaining the answer (Østergård, Jensen and Maagaard, 2016).

Integrating building performance evaluation tools and GBRT is limited to a few criteria in specific standards. Ansah *et al.* (2019) have reviewed some of the most commonly used tools, as cited in (Lu *et al.*, 2017), in addition to other relevant tools, and highlighted the limited availability of direct functions to assess green building criteria.

The limited integration between the BPE tools and GBRT is often argued to the complexity, bulkiness, the various number of GBRT and its constant updates, each with its distinct structure and differently tackled issues, in addition to the technical challenges, such as the interoperability between design and simulation tools and the tremendous efforts and time needed for modelling and conducting simulating results. Moreover, GBRT extensively tackles various sustainability issues such as energy demand, thermal comfort, daylighting, water use, and more. No single simulation tool can be found to tackle all these issues.

1.2.3 Building Information Modelling

One of the significant developments recently in the construction industry involves Building Information Modelling (BIM), which brings the opportunity to address some of the challenges revealed above and provide effective decision-making for design purposes at the conceptual stage of a project (Motawa and Carter, 2013), thus improving the process of green building delivery.

BIM delivers various benefits, including technical superiority, time-to-cost savings, early capture of building information, interoperability capabilities, building lifecycle, and reduced design collision risks and errors. (Harris and McCaffer, 2013; Ghaffarianhoseini et al., 2017). In addition, BIM offers a fundamental technical advancement over traditional CAD tools (Miettinen and Paavola, 2014).

Integrating BIM and green buildings has been defined as "Green BIM" (Lu *et al.*, 2017). Wong and Zhou defined green BIM as "*a model-based process of generating and managing coordinated and consistent building data during its project lifecycle that enhance building performance and facilitate the accomplishment of established sustainability goals"* (Wong and Zhou, 2015). BIM contains vast information that can potentially be used for more effective sustainable assessment (Biswas, Wang and Krishnamurti, 2013). Moreover, the development of Green BIM tools gives in a single model that integrates both the design and simulation models in one environment, the potential for multi-disciplinary information to be analysed, improving the analysis process and avoiding data management errors (Azhar *et al.*, 2011). It is also possible to use intelligent information that the BIM model creates to produce whole-building energy analysis, performance simulation, and visualised 3d images (McGraw Hill Construction, 2010). Moreover, by using BIM tools, designers can choose suitable material types in earlier designing stages and make decisions related to energy which has an enormous impact on the building life cycle (Jalaei and Jrade, 2014; Lu *et al.*, 2017).

Although BIM can ensure the optimisation of sustainable building design by performing a complex analysis of building performance (Azhar, Brown and Farooqui, 2009), the link between BIM, BPS, and GBRTs is still in its early stages. One of the barriers to adopting green BIM can be highlighted as the interoperation between different BIM and performance analysis tools (Chong, Lee and Wang, 2017; Lu *et al.*, 2017).

1.3 Problem summary

The development of BIM technology has shifted the construction industry towards more efficient practice and suggests that BIM tools can potentially eliminate the shortcomings of traditional CAD tools described earlier. In addition, the use of BIM for sustainable projects delivery can aid in more collaboration between project stakeholders through different lifecycle stages of buildings and reduce the efforts needed for sustainability assessment as early as the concept stage by integrating the design and simulation data and all the related information in one centralised model.

Despite that, some shortcomings have been identified in the literature. For example, interoperability between the simulation and design tools has only been partially addressed using open data schemas, such as gbXML or IFC. In addition, GBRTs are often described as “bulky” and “complex” and tackle many criteria that may differ significantly from one standard to another. Furthermore, the integration between performance simulation tools and GBRTs is currently very limited to a few BPS tools that could partially address a limited number of GBRT criteria for the assessment process of green buildings.

The literature review provided a vital opportunity to advance the understanding of recent developments, techniques, and approaches that others have used to address the predefined challenges regarding integrating BIM, performance simulation tools, and green and sustainability standards. The review findings show that various studies have investigated integrating BIM and GBRT to automate, improve, and facilitate green building design and certification. However, most of these studies aimed to develop BIM-based approaches for specific criteria to target energy performance in the LEED rating system.

This urges the need to develop a BIM-based tool with a holistic approach that integrates BIM authoring tools with performance simulation software alongside a generic sustainability framework that tackles further green building assessment criteria in an automated workflow to facilitate the sustainability assessment in green building projects.

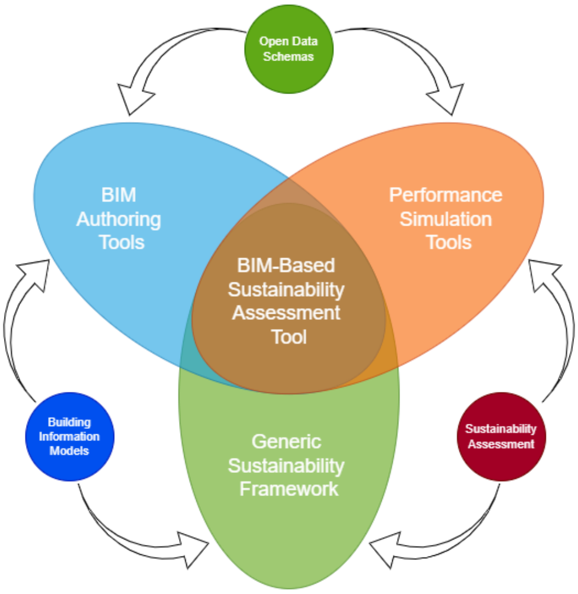


Figure 1-2 Synergy between green building rating tools, BIM, and performance simulation tools.

1.4 Research Aim and Objectives

This research hypothesises that the development of Building information modelling technology has the potential to facilitate sustainability assessment through the seamless integration of design, assessment criteria, and assessment tools.

The aim of this research is to facilitate the green building evaluation process in the early designing stages, where design decision significantly impacts the project's overall performance, by introducing a BIM-based toolkit that can assess the proposed project performance. The toolkit aims to reduce the time and effort needed in conventional evaluation workflows by integrating different tools to automate the evaluation process. At this stage, the Jordan Green Building Guide (JGBG) criteria are targeted for developing the proposed toolkit as the assessment criteria.

To correspond to the thesis aim, the following objectives are identified:

1- Review and analyse the Jordanian Green Building Guide (JGBG) requirements with other leading regional and international rating systems to understand its maturity, complexity, and comprehensiveness.
2- Investigate and identify the challenges in integrating BIM and Building Performance Simulation (BPS) tools and the concept of green BIM for the sustainability assessment of buildings.
3- Analyse and map the information available in the BIM data schema and the JGBG criteria requirements with building performance evaluation tools.

4- Develop a BIM-based toolkit that integrates BIM data schema, BPS tools, and the assessment criteria of the JGBG to automate the assessment of buildings.
5- To test and validate the proposed toolkit through certified green building case studies.

1.5 Research Questions

This thesis aims to answer the following questions:

- To what extent can BIM technology facilitate green building assessment?
- What information is required to conduct the assessment of green buildings?
- How can BIM tools integrate GBRTs with BPS tools to facilitate green building design assessment?
- Can BIM data schemas carry sufficient building information required for performance evaluation tools?

1.6 Research Motivation

This research has been motivated by three aspects related but not specific to the Jordanian construction industry. The first aspect concerns the concept of sustainable and green construction in Jordan. The second relates to the inefficient workflows illustrated by manual workflows and procedures throughout the design process and the limited adoption of BIM tools for efficient and effective workflows. And finally, the absence of knowledge and experience in working with building performance simulation tools in designing and constructing highly efficient buildings. This section discusses the issues above that have formulated the motivation to conduct the research.

The first draft of the Jordan Green Building Guide (JGBG) was issued in 2009, and the guide became available for use in 2015. Since then, very few buildings have been certified, and unfortunately, no official figures can be referenced to reflect the adoption of the JGBG. The Green Building Information Gateway (GBIG) data shows that only 12 buildings have received the LEED certificate in Jordan, indicating minimal adoption of the green building concept (Green Building Information Gateway, 2022). Tewfik and Ali (2014) stated that the financial constraints and resistance to change are reported as significant barriers to adopting the concept of green architecture in Jordan. Ali, Barakat and Sharif (2021) have also reported that the green buildings concept is still uncommon in Jordan due to the lack of awareness, explanatory projects, and benchmarks (Alkilani and Jupp,z 2013; RSS and FES, 2013). Furthermore, in a report published by the Royal Scientific Society in Amman, the lack of demand, lack of public awareness, lack of design and construction teams, lack of professionals, expertise and knowledge, and the limited number of available case studies for knowledge management, are all reported as barriers to the development of green building practices in Jordan (RSS and FES, 2013).

The JGBG has not received much attention or development since its launch and has not received any minor or major updates to its content. The JGBG assessment schema is limited to new buildings and does not have a schema to guide or assess the existing buildings. More importantly, design teams cannot use a dedicated web page or an online platform for project information management and submittal. Instead, the required documents for each criterion must be issued and submitted manually. Hence, the assessment process is described as challenging and very complex due to the number of documents and reports required for submission to assess any criteria.

The adoption of BIM in the Jordanian AEC market has emerged very lately. Matarneh and Hamed (2017) investigated the adoption of BIM in 2017 and demonstrated that many aspects challenge BIM implementation by the AEC market in Jordan. The most significant barriers reported were (1) the lack of mandatory governmental requirements and codes that endorsed the implementation of BIM, (2) the lack of knowledge about BIM's benefits to the AEC industry, and (3) the lack of client demand, and (4) the lack of BIM specialists and the resistance to change. The study has also revealed that the architects' adoption of BIM is fairly better than the contractors'. Nevertheless, the study highlights that most architectural firms still adopt a traditional workflow for project design and delivery, formulating another challenge regarding the feasibility of conducting building performance assessments.

In this regard, the AEC in Jordan has minimal interest in building performance assessments due to the lack of mandatory requirements, the absence of local codes enforcements, and building performance benchmarks. Many articles highlighted that using traditional workflows for generating performance models from 2D CAD drawings could potentially complicate the assessment process (Choi *et al.*, 2016; Beazley, Heffernan and McCarthy, 2017). For example, performance models take significant time to generate manually, and if the design does not perform as required, it will lead to redoing the modelling works until the performance satisfies clients' needs. Generating multiple versions of the performance models could lead to errors in data consistency and flow between the design and performance models, data leaks and redundant data processing, and require significant preparation time.

Most architectural practices in Jordan tend only to focus on the buildings' aesthetic, functional, and financial aspects, with a total absence of performance efficiency. Shamout, Boarin and Melis (2019) stated that insufficient expertise, technologies, awareness and implementation formulate a technical drawback for developing energy-efficient buildings in Jordan. Al-Hinti and Al-Sallami (2017) indicated that more than 77% of the residential dwellings in Jordan do not have any thermal insulation installed on the building fabric, despite being mandatory. Most of the surveyed dwellings were not constructed by the existing owners. The study stated that adherence to thermal insulation codes is still "a matter of choice" for contractors and that they are driven by the economic feasibility rather than the thermal comfort of occupants or energy savings in the long run. Therefore, if the concept of energy-efficient or green buildings is uncommon, the need for using or developing BPS tools and workflows is, as a result, uncommon. However, no published data currently highlights the adoption of building performance simulation tools in the Jordanian construction industry, which underlines another gap in the Jordanian AEC.

Despite the various benefits that a green building could deliver, such as thermal comfort, energy, materials, and water savings, the lack of awareness in the local construction sector leads to the construction of inefficient buildings by the absence of local codes and regulations enforcement. Besides, the technical challenges and resistance to change are highlighted as common factors for implementing better construction workflows, such as adopting BIM for project design and delivery. The literature review highlights that Implementing BIM for green building design and assessment can facilitate sustainability assessment by allowing for early integration with BPS tools.

The literature has concluded that existing sustainability assessment workflows are insufficient, and there is still a need to develop flexible and expandable workflows based on the users' needs. This section highlighted critical aspects that have helped formulate the motivation to develop a BIM-based assessment tool that can encourage the adoption of BIM technologies and facilitate using building performance simulation tools within the JGBG requirements.

1.7 Research Scope

This research investigated the potential of automating the sustainability assessment of green buildings that target the JGBG certificate through BIM-based tool development. This is due to Jordanian AEC's challenges regarding green construction, informed by time-consuming manual assessment workflows and limited experience utilising building performance simulation tools. Jordan Green Building Guide was selected to demonstrate the implementation of the proposed tool. The current version of the integrated sustainability assessment toolkit (iSAT) focuses on Energy Efficiency, Healthy Living Environment, and Materials and Resources categories, representing different assessment complexity levels. The tool was tested during development using a few scenario-based projects to validate the evaluation workflow and ensure accurate assessment results.

Whereas several buildings were accredited and designed using JGBG since its first edition was issued in 2012, the data of only two buildings were obtained as case studies. This was mainly due to the lockdown restrictions during Covid-19 pandemic early in 2020. The first case study is a detached residential family villa that received its JGBG certificate in 2018. The other case study building is an office building that was certified in 2015. Both cases were built in Amman and were modelled and tested using the available information provided by the architects of these buildings. The integrated sustainability assessment toolkit (iSAT) was initially developed for residential buildings assessment based on the criteria of the JGBG. However, this has been extended to cover office buildings, as both typologies share similar structures and assessment criteria in the JGBG.

The iSAT tool was tested and evaluated against the available information prepared by the architecture teams of each case, and the results of the tool evaluation will be discussed later in Chapter 8.

1.8 Thesis Structure

This thesis consists of seven chapters as follows:

- Chapter 1, Introduction, introduces the research problem, aims, objectives, scope, motivation, and scope of this research.
- Chapter 2, Sustainability Assessment of Buildings, Sustainability Assessment of Buildings, discusses the sustainability assessment of buildings by introducing the GBRTs as assessment standards, followed by a discussion about BPS tools as programs used to evaluate the performance of buildings and highlighting the existing integration between the BPS and GBRTs.
- Chapter 3, Methodology, presents the methodological approach to fill the identified research gap.
- Chapter 4, Comparison of selected green building rating systems, consists of an analysis of five green building rating tools, followed by a discussion about the complexity of the assessment requirements.
- Chapter 5, Building Information Modelling (BIM) for green building assessment, introduces the concept of BIM and its integration with GBRT through the concept of GreenBIM, reviews the state-of-the-art development of GreenBIM and discusses the interoperability issue between BIM and building performance evaluation tools.
- Chapter 6, Pilot Study: Automating Passivhaus Evaluation using BIM, presents the pilot study conducted in this research through the development of a BIM-based tool to automate the assessment of energy-efficient buildings using visual programming environment and the passive house planning package

- Chapter 7, Integrated Sustainability Assessment Tool (iSAT), demonstrates the development of the iSAT toolkit. This chapter starts by introducing the tool architecture, its core components and their functionalities and demonstrates through use cases how the tool can automate the assessment of buildings for selected criteria.
- Chapter 8, Tool validation, demonstrates, through case studies, how the iSAT toolkit can be used on real-world case study buildings. In this chapter, a comparison between the criteria assessed manually and by the iSAT was conducted to validate and highlight the benefits of using the iSAT.
- Chapter 9, Discussions and Conclusions, discusses the research findigs, and presents this research's conclusion, the research limitation, and future work.

2. Sustainability Assessment of Buildings

2.1 Introduction

The construction industry is responsible for more than 36% of the final energy, accounted for nearly 40% of CO_2 emissions in 2017 (IEA and UNEP, 2018) and consumes more than 30% of global resources (Rode, Burdett and Soares, 2011). In addition, the construction sector produces 40% of the solid waste in developed countries (Yılmaz and Bakış, 2015). To address these challenges and reduce the negative environmental impact of the building sector, the construction industry was one of the first to adopt the concept of sustainability. However, the term "sustainability", along with" sustainable development", "sustainable construction", and "green buildings", are all terms that were used interchangeably by the AEC community. The following section will introduce and distinguish between these terms.

"Sustainability" means the capacity to maintain some entity, outcome or process over time (Basiago, 1998). According to the US Environmental Protection Agency (EPA), sustainability can also be "… based on a simple principle: Everything that we need for our survival and well-being depends, directly or indirectly, on our natural environment. To pursue sustainability is to create and maintain the conditions under which humans and nature can exist in productive harmony to support present and future generations" (US EPA, 2016). From Stoddert's (2011) point of view, sustainability can be defined as the fair and effective distribution of resources across generations with socio-economic activities within the boundaries of a confined ecosystem. The United Nations Sustainable Development Goals report (UN-DESA, 2018) suggests that the fundamental objective of sustainability is to endorse the balance between society, the economy and the environment within the boundaries of the regenerative ability of Earth's life-supporting ecosystem.

As utilised in this thesis, the sustainability concept is formed by two major parts. The first part is the equal distribution of resources across generations; the other is maintaining and sustaining life within the planet's ecosystem capacity. The concept also integrates three aspects that address human challenges: social, economic, and environmental, to ensure sustainable development (Mensah, 2019).

Although various definitions for Sustainable Development (SD) have been introduced, the Brundtland Commission Report (our common future) was the most cited one (Mensah, 2019; Zimmermann *et al.*, 2019). The report defined the concept of sustainable development as **"**development that meets the needs of the current generation without compromising the ability of future generations to meet their own needs" (Keeble, 1988). It aims to address social development, environmental stability, and economic advancement**.** Since economic growth, environmental issues, and social equality are the primary issues of sustainable development, it can be argued that sustainable development relies mainly on three conceptual pillars (Mensah, 2019), namely economic sustainability, social sustainability, and environmental sustainability (Doan *et al.*, 2017; Mensah, 2019; Zimmermann *et al.*, 2019). Although sustainability and sustainable development are used synonymously and interchangeably, Diesendorf (2000) distinguishes sustainable development as a process while sustainability is one of its goals.

The global construction industry has prioritised sustainable development since the traditional way of building, operating, and demolishing a building accounts for numerous natural resources (Carvalho, Bragança and Mateus, 2019). Hence, the concept of sustainable construction emerged.

Sustainable construction is a widely used term to address buildings' economic, social, and ecological issues within their community context. Sustainable construction was first introduced at the First World Conference on Sustainable Construction by Charles Kibert in 1994 (Carvalho, Bragança and Mateus, 2019). Kibert (1994) defined sustainable construction as creating and managing a healthy building environment based on a design considering ecological principles and resource-efficient use. Thus, seven principles of sustainable construction were introduced to inform decisions made during the building's life cycle, namely:

1- Reduce: to reduce the consumption of resources.
2- Reuse: to reuse the maximum resources available.
3- Recycle: to use recyclable or renewable resources.
4- Protect nature: to protect the natural environment.
5- Eliminate Toxins: to create a non-toxic, healthy environment.
6- Life Cycle Costing.
7- Quality: to construct a built environment aiming at quality.

The principles can be applied during the construction life cycle, from planning to demolition. Moreover, the principles can be applied to the resources (land, materials, water, energy, and ecosystems) during the operation and construction of the built environment through its life cycle.

Accordingly, "sustainable buildings" and "green buildings (GB)" are all terms used to describe the social, economic and ecological impacts of buildings (Li *et al.*, 2017; Shareef and Altan, 2017). The term "green building" refers to the building structure's attributes and characteristics using sustainable construction principles and manners (Haapio and Viitaniemi, 2008; Kibert, 2016).

Correspondingly, green design, sustainable design, and environmental design are all terms that can be used to label the implementation of sustainability principles in the built environment. However, Kibert (2016) argues that proper green commercial buildings are virtually non-existent. Kibert also states that most current green buildings offer gradual improvements instead of fundamentally changing traditional construction methods.

Green buildings must respond to various considerations, including energy-efficient, water-conserving, durable and non-toxic, high-quality spaces, high-recycled content materials, and much more. However, the definitions and parameters for these factors vary enormously from standard to standard and country to country. Green buildings can potentially solve many planetary resource problems (Ali and Al Nsairat, 2009). Ries *et al.* (2006) and Vyas and Jha (2018) claim that green buildings can save up to 30% of energy consumption compared to non-green buildings, and the annual CO2 savings range from 139-6440 tons depending on the applied energy savings and renewable sources generation. Besides, green buildings can help to increase the productivity of the building's occupants by 25% (Ries *et al.*, 2006). Numerous different green building certificates, standards, and rating systems were introduced in the past 20 years (Vierra, 2016) as a step to address and cut the significant impact of the construction sector on the built and natural environment (Junnila and Horvath, 2003; Ebert, Eßig and Hauser, 2011).

2.2 Green Building Rating Tools

Fowler and Rauch (2006) define green building rating tools (GBRT) as tools that assess overall building's designed performance and translate that assessment into a comprehensive evaluation that compares one building's performance to another. Globally, many rating systems and tools measure different sustainable building design features. Different sustainable rating systems differ between countries and regions based on the diversity of cultural and climatic factors (Biswas, Wang and Krishnamurti, 2006; Say and Wood, 2008). However, there are also some common categories in these rating systems. Generally, these categories indicate that almost all sustainable rating systems consider indoor environment quality, ecological loadings, and resource use (Cole, 2005).

According to Ali and Al Nsairat (2009), two approaches have been adopted in the construction industry. The first is a multi-criteria credit system, which assigns particular credit to the specific issue within a set of categories that influence the overall building sustainability, considering the ecological, economic, and social aspects. BREEAM and LEED are examples of systems that adopt this approach. The second approach is based on tools that use Life Cycle Assessment (LCA) procedure, a more complex-scientific method to evaluate the building's environmental impact. Athens is an example of tools used for LCA (Athena Sustainable Materials Institute, 2020). However, Berardi (2012) adds a third approach, a cumulative energy demand system, which only focuses on the energy consumption of buildings, such as the Passivhaus standards (Passive House Institute, 2015). The green building rating systems based on the multi-criteria approach are the most adopted worldwide and will be referred to when using the green building rating tools (GBRTs) acronym in this thesis.

The sustainability of a building can be evaluated using various green building rating tools that are distinct from each other in terms of the calculation methods, weights, credits, and the issues considered in these standards. Various national and international green building rating systems have been developed in the last 20 years (Mattoni *et al.*, 2018). The following standards are examples of international GBRT (see also Figure 2-1):

1- Leadership in Energy and Environmental Design (LEED) in the USA. LEED was also developed into many national versions.
2- Building Research Establishment Environmental Assessment Method (BREEAM) in the United Kingdom.
3- Green Star in Australia was further developed into national versions in New Zealand and South Africa (Say and Wood, 2008; Doan *et al.*, 2017; He *et al.*, 2018; Mattoni *et al.*, 2018).

Among the national rating systems is:

1- Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) in Japan.
2- Green Building Evaluation Label (China 3-Star) rating system in China (GBIG, 2020).

Examples of rating systems in the Middle East are:

1- Jordan Green Building Guide (JGBG) in Jordan.
2- Pearl for Estidama in Abu Dhabi.

To accomplish the most effective use of GBRT, these rating systems require varying levels of knowledge in sustainable design (Fowler and Rauch, 2006). Therefore, these differences can significantly affect the final score a building can achieve using different standards (Mattoni *et al.*, 2018). It is also important to acknowledge that these green building rating systems are developed to correspond to local priorities, such as local climatic conditions and geographical attributes. Based on this, the weights of a specific rating system cannot be implemented worldwide unless adjusted to suit the needs of specific regional priorities (Ding, 2008; Alyami, Rezgui and Kwan, 2015; AbdelAzim, Ibrahim and Aboul-Zahab, 2017).

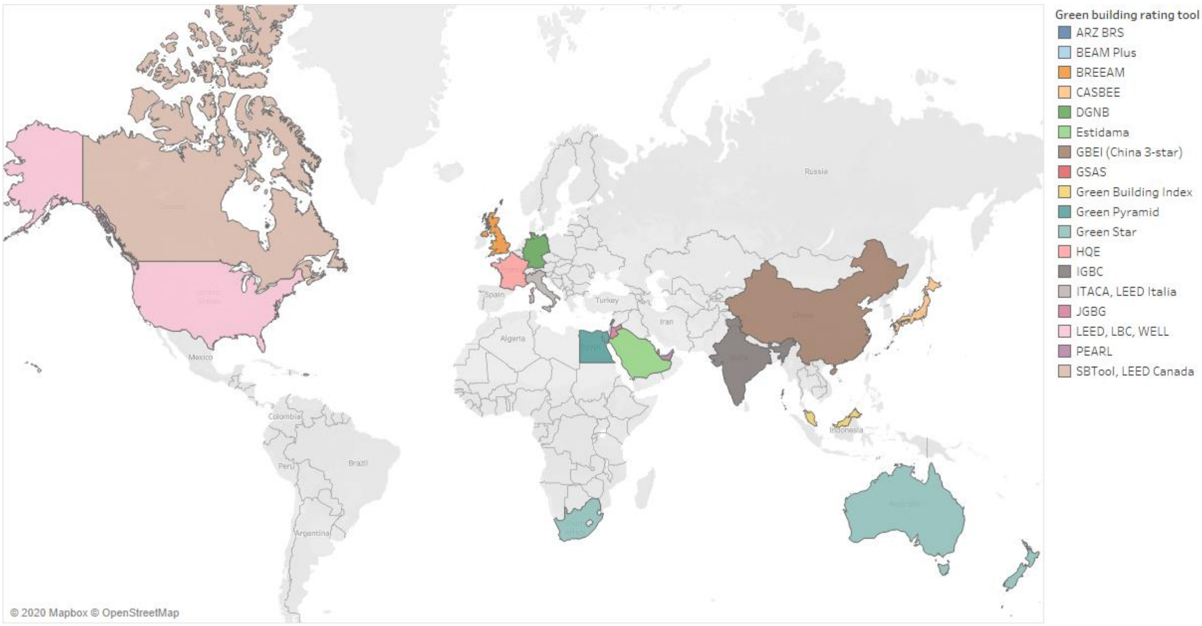


Figure 2-1 Wide spread of green building rating tools.

While these green protocols vary significantly, no common sustainability standard has been defined globally. Therefore, a green building in one country might achieve a lower certification level in another. For example, Roderick *et al.* (2009) conducted a computational simulation to evaluate the energy performance of an office building in Dubai according to the energy performance criteria in three GBRTs: LEED, Green Star, and BREEAM. The study results showed significant differences in the building's energy performance according to the chosen certification standards since these standards vary in the evaluation method and the performance benchmark. While the building achieved a high-energy rating in Green Star, the building has achieved a meagre rating according to BREEAM and failed to achieve LEED certification. Mattoni *et al.* (2018) highlight that most of the GBRTs have not yet defined substantial measures that can be used to evaluate the building envelope performance, such as materials efficiency, economic efficiency, life-cycle cost, and embodied energy. The following section will introduce some of these rating systems, followed by an overview of exemplary well-known rating systems worldwide.

2.2.1 Overview of Green Building Rating Tools

Several studies have compared local and regional green building tools to understand their differences and commonalities (Smith, 2015; Bisegna et al., 2016; Doan et al., 2017; He et al., 2018; Ismaeel, 2018; Cordero, Melgar and Márquez, 2019; Suzer, 2019a). However, most of these reviews ten to compare the first and second layers of these tools, i.e., the main category, such as the Energy and Atmosphere (EA) in LEED, and its criteria, such as "EA Prerequisite: Minimum Energy Performance". Although this level of analysis could present a good understanding of how each standard compares to the other, it could not reflect the actual level of maturity of these standards. For example, the Energy and Atmosphere category in LEED does not include criteria for passive design strategies. Nevertheless, the passive design strategies are covered under the Integrative Process requirements.

2.2.1.1 Leadership in Energy and Environmental Design (LEED)

LEED was developed by the US green building council (USGBC) and is considered the most-used green building system worldwide based on the number of countries (Doan *et al.*, 2017; Li *et al.*, 2017). LEED provides a framework that aims to ensure the development of cost-saving, highly efficient and healthy green buildings. In 2019, more than 94,000 projects were certified in over 165 countries and territories (USGBC, 2019). A set of codes and guides are included in the rating system to cover various building types, existing and new construction, interior, core and shell, and neighbourhood development. The LEED Building Design + Construction (BD+C) v4 rating system covers seven key categories: Integrative Process (IP); Location and Transportation (LT); Sustainable Site (SS); Water Efficiency (WE); Energy and Atmosphere (EA); Materials and Resources (MR); and Indoor Environment Quality (IEQ), with two different categories: Innovation (IN); and Regional Priority (RP). Table 1 shows the required points for different certificate levels (USGBC, 2019).

Table 1 The required points for LEED certification.

Level of certificate	**Platinum**	**Gold**	**Silver**	**Certified**
Required points	80 and above	60-79 points	50-59 points	40-49 points

According to Green building information gateway (2019), nine certified LEED projects and 19 others are in their certification process in Jordan. Table 2 describes the certified building types, LEED certification, and the achieved score.

Table 2 certified LEED buildings in Jordan

Project	**Project type**	**LEED certificate**	**Score**
The Edgo Atrium	Office	LEED BD+C: Core and Shell v3 - LEED 2009	Gold 61/110
World Health Organization Building	Office	LEED BD+C: New Construction v2 - LEED 2.2	Gold 42/69
Dutch Embassy in Amman, Jordan	Office	LEED BD+C: New Construction v2 - LEED 2.2	Silver 34/69
Izzat Marji Group Headquarters	Office	LEED BD+C: New Construction v3 - LEED 2009	Platinum 82/110
Aramex Warehouse	Warehouse	LEED BD+C: New Construction v3 - LEED 2009	Silver 50/110
OMNITRADE New Offices	Office	LEED BD+C: New Construction v3 - LEED 2009	Silver 57/110
Middle East Insurance Building	Office	LEED BD+C: New Construction v3 - LEED 2009	Gold 66/110
ABS Randa Kawar IB College Building	School	LEED BD+C: Schools v3 - LEED 2009	Platinum 80/110
ATG Head Quarter	Office	LEED ID+C: Commercial Interiors v3 - LEED 2009	Gold 74/110

2.2.1.2 Building Research Establishment's Environmental Assessment Method (BREEAM)

Building Research Establishment's Environmental Assessment Method, also known as (BREEAM) was the first sustainability-rating scheme in the world. BREEAM is adopted not only in the UK but also in more than 70 countries worldwide. More than 530,000 buildings are BREEAM-certified (BRE, 2019). It focuses on sustainability in different phases of the projects, building design, construction, and use. BREEAM creates higher-value buildings through its applicability of measuring and reducing the environmental impact assets. BREEAM Communities, BREEAM Refurbishment, BREEAM Infrastructure, Home Quality Mark, BREEAM New Construction, and BREEAM In-Use are different versions of BREEAM that cover all building types. The ten main categories of the BREEAM International New Construction (2016) version are Management (Man), Health and Wellbeing (Hea), Energy (Ene), Transport (Tra), Water (Wat), Material (Mat), Waste (Wst), Land Use and Ecology (Le), Pollution (Pol), and Innovation (Inn). The following table represents the levels of BREEAM certification, which can be achieved based on the collected points score (BRE, 2017). Table 3 shows the required points for different certificate levels (BRE, 2017)

Table 3 The required points for the BREEAM certificate.

Level of certificate	**outstanding**	**Excellent**	**Very good**	**Good**	**Pass**	**Unclassified**
Required points	=>85%	=>70%	=>55%	=>45%	=>30%	<30%

2.2.1.3 Living Building Challenge

Living Building Challenge (LBC) was released in 2006 as an international standard. It provides a framework that supports building design and construction for any building project in any location. The current version of LBC, V 4.0, consists of 20 imperatives in seven Petals to address different sustainability issues: Place; Water, Energy, Health + Happiness; Materials; Equity, and Beauty. Each Petal consists of one to two Core imperatives, forming ten core imperatives. The challenge is performance-based, meaning that any building can be certified after a 12-month performance period under one of the following certification paths illustrated in Table 4 (International Living Future Institute, 2019).

Table 4 Living Building Challenge certification paths with their requirements

Certification path	**Requirements**
Zero Carbon (ZC)	1. 100% of operational energy use is offset by on-or-off-site renewable energy. 2. Reduction in the primary material-related embodied carbon.
Zero Energy (ZE)	1. On-site renewables must supply 100% of the annual energy needs.
Core Green Building Certification standards	1. The project must meet all requirements of the Ten Core Imperatives. 2. Water and Energy performance must be verified over twelve months.
Petal	1. Achieve all the ten Core imperatives. 2. Achieve all the imperatives in one of the following Petals: Water, Energy, or Materials.
Living Certification	1. Achieve all the imperatives assigned to the project Typology.

2.2.1.4 Well Building Standards

The International Well Building Institute (IWBI) launched Well building standards in 2014. Well is a performance-based system that measures, certifies, and monitors building features that affect the user’s health and well-being. One of the distinct features of this standard is that it was designed to comprehensively cover different individual needs of the project occupants and simultaneously establish a common foundation to measure the wellness inside buildings. Thus, the Well building standard is developed to work harmoniously with other green building rating systems, such as LEED and Living building. The current version of Well building standards, Well v2, consists of ten main concepts: Air, Water, Nourishment, Light, Movement, Thermal Comfort, Sound, Materials, Mind and Community. Every concept contains different features that aim at a distinct health intention. These features are divided into mandatory preconditions, which must be met in all cases, and optimisations, which are optional features. A total of 110 points can be achieved in any Well-certified project. Table 5 shows different Well v2 certification levels (IWBI, 2018).

Table 5 Well certification levels

Level of certificate	**Silver**	**Gold**	**Platinum**
Required points	50	60	80

2.2.1.5 Global Sustainability Assessment System (GSAS)

The Global Sustainability Assessment System (GSAS) was the first performance-based rating system developed in the Middle East and North Africa region (MENA) for rating green buildings and infrastructure. It was introduced in 2007 based on reviewing more than 140 international green building rating systems, guidelines, and tools, with a comprehensive study for six leading international green buildings assessment systems, namely: BREEAM (UK); LEED (US); Green Globes (Canada); CEPAS (Hong Kong); CASBEE (Japan); and SBTool (International). The GSAS is developed to integrate sustainable goals and the country's needs (GORD, 2019). The GSAS consists of eight categories: Urban Connectivity (UC), Site (S), Energy (E), Water (W), Materials (M), Indoor Environment (IE), Cultural and Economic Value (CE), and Management and Operations (MO). One of the unique features of GSAS rating systems is that it contains Cultural and Economic Value as a main category, which cannot be found in other rating systems. It considers factors to preserve and maintain the heritage and cultural identity. GSAS for design and build certificate has six certification levels based on a cumulative score to measure the project's environmental impact (Alhorr, 2018). Table 6 shows the required points for different certificate levels (Alhorr, 2018)

Table 6 The required points for the GSAS certificate.

GSAS Star Rating	★★★★★★	★★★★★	★★★★	★★★	★★	★	**Certification Denied**
Cumulative score (X)	2.5<X<=3.0	2.0<X<=2.5	1.5<X<=2.0	1.0<X<=1.5	0.5<X<=1.0	0.0<X<=0.5	X<= 0

2.2.1.6 Pearl Rating System for Estidama

The Urban Planning Council (UPC) of Abu Dhabi launched the Pearl Rating System (PRS) for "Estidama" (the Arabic word for "sustainability") in 2010. Although Pearl was developed based on two leading rating systems: LEED and BREEAM, it consists of criteria that address local and regional priorities (Elgendy, 2010). It aims to assess buildings' sustainability throughout their life cycle, from design to construction and operation. Pearl provides a framework that guides the design process and evaluates the project's expected performance based on the environmental, economic, cultural and social pillars of Estidama. The PRS is divided into seven categories: Integrated Development Process, Natural Systems, Liveable Spaces, Precious Water, Resourceful Energy, Stewarding Materials, and Innovating Practice. Each category consists of required and optional credits. Table 7 shows the requirements of the three Pearl rating levels (UPC, 2016).

Table 7 Pearl rating levels

Pearl Rating Achieved	Requirement
Pearl	All required credits
Green Pearl	All required credits + 50% of the optional credits
Exemplar Pearl	All required credits + 75% of the optional credits + be a site of national significance + achieve The PRS currently comprises four documents: Pearl Community Rating System, Public Realm Rating System, Pearl Building Rating System, and Pearl Villa Rating System. Exemplar pearl status

Four rating stages have been established in PRS to cover the evolving phases of any project: Planning, Design, Construction, and Operation.

2.2.1.7 Jordan Green Building Guide (JGBG)[1]

The new Green Building Guideline and Rating System of Jordan was developed in 2009 by the Jordan National Building Council, one of the Ministry of Public Works and Housing departments. The green building guideline consists of parameters and credits that suites the Jordanian climate, resources, policies, and building techniques and strategies. Two drivers played a significant role in developing the guidelines: the limited water resources, as Jordan is considered one of few countries in the world with limited water sources (Ministry of Environment and The Hashemite Kingdom of Jordan, 2007), and energy as Jordan imports more than 90% of its energy (NEPC *et al.*, 2017); and the concern to cut pollution in the Earth's atmosphere (Awadallah *et al.*, 2011; Zawaydeh, 2018). It consists of criteria adapted to Jordan's climate, resources, legislation, policies and policies instrument, building

[1] The original text is available only in Arabic language. All the information introduced about the rating system are translated from the original text by the author of this report. See appendix (A) more information about the JGBG.

techniques and strategies (Awadallah *et al.*, 2011). The Jordan Green Building Guide (JGBG) was developed based on leading international sustainable rating systems, namely: LEED, BREEAM, QSAS (known as GSAS), and Estidama (Awadallah *et al.*, 2011). The JGBG was first issued in 2013 and is now publicly available. The adoption of the green building program in Jordan was approved in 2015 based on the JGBG (Zawaydeh, 2018).

JGBG overview

The JGBG covers Mandatory, Obligatory, and Optional requirements for architecture, construction, and mechanical and electrical works to construct green buildings. These requirements are classified as follows (MPWH, 2013):

1- Mandatory requirement: Buildings cannot be nominated for certification without complying with the mandatory requirements of the national Jordanian building codes. No points are rewarded for this compliance.
2- Obligatory requirements: no building can be nominated for the green building certification without using the scheme itself. Points can be rewarded by complying with this prerequisite.
3- Optional requirements: the project team can choose to apply for points that suit their projects and can be rewarded when these requirements are applied. These points are considered for the certification level, which is: (A), (B), (C), and (D).

JGBG has a unique system of requirements: it contains mandatory requirements, which represent the requirements of the national building codes, and complying with these requirements does not reward credits. One of the possible reasons for this is that this rating system is treated as a green building code that encourages the implementation of national building codes.

The above requirements can apply to all new building types, taking account of their functionality and the applicability of each criterion, including ministry buildings and government institutions; administrative buildings; private and public universities; schools and colleges; offices and services; enclosed commercial buildings; celebration and meeting halls and theatres; malls and shopping centres; residential buildings; hotels. However, industrial buildings, warehouses, hospitals and medical centres are all currently excluded from the list (MPWH, 2013). In contrast, GSAS, LEED, BREEAM, LBC, Pearl, and Well have schemas covering almost all building types. It is expected that the JGBG to cover all building types and include a scheme for existing buildings in the upcoming updates.

JGBG assessment criteria

The JGBG comprises six categories: Green building Management, Site Sustainability, Water Efficiency, Energy Efficiency, Healthy Indoor Environment, and Materials and Resources. Each category contains a set of Mandatory, Obligatory, and Optional requirements and the points for each criterion. Table 8 summarises each category and the additional possible points for each building type (MPWH, 2013). One of the main differences between this rating system and others, such as LEED and BREEAM, is that it does not include categories like Transportation, Urban Connectivity, Cultural Value, and Innovation. However, some of the indicators above are situated inside different categories. For example, waste is considered an indicator under the Materials and Resources category, Urban Connectivity and Transportation can be found under Site Sustainability, and Innovation is an optional indicator that can be found under sustainable site, materials and resources, energy efficiency, and water efficiency categories.

Table 8 Categories of JGBG and their allocated point.

	Residential (single)		**Residential (multi)**		**Offices/ Commercial**		**Educational**	
	With AC	Without AC	With AC	Without AC	With AC	Without AC	With AC	Without AC
Green Building Management	12	17	25	18	28	21	27	20
Site Sustainability	22	22	32	32	35	35	34	34
Water Efficiency	34	34	40	40	38	38	38	38
Energy Efficiency	72	61	84	71	89	76	85	72
Healthy Indoor Environment	15	12	22	19	24	21	22	19
Materials and Resources	35	35	36	36	36	36	36	36
Total Points	199	181	239	216	250	227	242	219
Additional Possible Points	115	111	84	84	76	76	74	74
Points to be added to the above total if a project contains one or more of the following:								
Elevators	7	7	7	7	7	7	7	7
Escalators	2	2	2	2	2	2	2	2
Green Areas	49	49	49	49	49	49	49	49
Swimming Pool	2	2	2	2	2	2	2	2
Building Reuse	4	4	4	4	4	4	4	4

Buildings that comply with the Mandatory and Obligatory requirements only will be awarded a Green Building certificate without a certification level. The certificate level can be awarded based on the percentage of the total Additional Possible Points that the building achieves. Table 9 shows the required points for different certificate levels (MPWH, 2013). For the certification process, JGBG has no online platform in which project teams submit the required documents and technical reports. Therefore, the certification process can only be conducted manually.

Table 9 Required points for JGBG certification.

Level of certificate	Grade A	Grade B	Grade C	Grade D
Total extra possible point	80% and above	70-79%	60-69%	50-59%

2.2.2 Green Building Rating Tools: good enough?

Green building rating tools were developed to reduce and mitigate the negative impact of buildings on the natural environment and resources. Although the journey to developing an environment-friendly building may be based on a particular green building guide, it must not stop there. This can be argued for many reasons, including, but not limited to, these standards are voluntary, which means that a user may not be required to improve all of the aspects of the building in order to achieve a certain certificate level. In addition, these standards aim only to mitigate or reduce the negative environmental impact of buildings rather than having a positive impact.

In this section, a literature review on GBRTs was conducted. This review aimed to assess which standard was primarily adopted in the literature, provide a critical overview and conclude the main areas of focus in the selected studies.

Recently, there has been an increasing interest in the LEED rating system review against other GBRTs, as highlighted in Table 10. The second most-reviewed rating system was BREEAM. The review indicates that LEED and BREEAM are the most developed and adopted GBRTs worldwide.

Different studies have highlighted different shortcomings of these green building rating tools. GBRTs are primarily used in the design stage of the project's life cycle. Although these tools are designed as assessment tools, they are widely used as design guidelines. Hence, Ding (2008) suggests that these tools are most valuable when implemented early in the design process. However, the project assessment is usually carried out in the final stage of the project design process (Crawley and Aho, 1999). Thus, using these tools as design guides can be challenging due to the changes possibly made in the last stages of the project design process -. Ding (2008) and Nguyen (2012) add that project teams tend to target specific criteria to promote their buildings as "green" and avoid more complex criteria, despite the overall offset in the project performance. Ade and Rehm (2020) describe such situations as "*the market of lemon*", as the project potential owners might invest in green projects expecting them to deliver high energy-efficient performance, water consumption, and indoor environment quality, while the building might have achieved the green certification by targeting different criteria.

Table 10 Studies that review and compare different GBRT since 2015

Authors	LEED	LEED India	BREEAM	GSAS	CASBEE	Estidama PEARL	JGBG	ITACA	GREEN STAR NZ	GREEN STAR AS	ASGB[2] China	GRIHA India	BEAM Plus	GBEL China	DGNB	HQE	EEWH Taiwan	BERDE Philippine	G-SEED	Green building index	ESGB[3]	Green Globes	Green Mark Singapore	GB Tool	Passive House
(Doan *et al.*, 2017)	x		x		x				x																
(He *et al.*, 2018)	x									x	x														
(Smith, 2015)		x										x													
(Suzer, 2019b)	x		x																						
(Lu *et al.*, 2019)	X												x	x											
(Cordero, Melgar and Márquez, 2019)	X		x												x	x									
(Bisegna *et al.*, 2016)	X							x																	
(Alwisy, BuHamdan and Gül, 2018)	X		x		x					x															
(Liu and Leng, 2020)					x												x								
(Culiao, Tae and Kim, 2018)	X																	x	x						
(Bansal, Biswas and Singh, 2019)	X	x	x									x													
(Awadh, 2017)	X		x	x		x																			
(Wu *et al.*, 2016)	X		x																	x	x	x			
(Zhang *et al.*, 2019)																	x				x				
(Ismaeel, 2018)	X		X		X					X			X		X	X					X		X	X	X
(Park, Yoon and Kim, 2017)																									
Frequency	12	2	7	1	4	1		1	1	3	1	2	2	1	2	2	2	1	1	1	3	1	1	1	1

[2] Assessment standard for green building, China.

[3] Evaluation standard for green building ESGB, 2006, China.

Although these GBRTs try to eliminate the negative impact of buildings on the environment by focusing on resource consumption, the indoor environment, and other related aspects, most of these standards do not consider the economic and social aspects of sustainable development (Loh *et al.*, 2020). Although a building might be promoted as green, it might be too expensive to accomplish the green building criteria (Ding, 2008). Berardi (2012) suggests that the energy performance could be well below optimal even in sustainably certified buildings. This often results in the energy-saving technique's high cost and the construction parties' lack of experience. Another aspect is the complexity and comprehensiveness of these tools (Ding, 2008; Berardi, 2012; Nguyen, 2012). Green building tools tend to be comprehensive and bulky, requiring various amounts of information to be collected, analysed and documented to assess the project's life cycle. This forms one of the barriers to adopting these tools among project stakeholders. Therefore, simplified GBRTs that balance the comprehensiveness and usability of such tools are needed for better adoption.

Stevenson (2019) and Loh *et al.* (2020) criticise green building rating systems as they do not cover the whole life cycle. Although they are designed to evaluate the predicted performance of buildings, most of these systems, such as LEED and BREEAM, do not cover the post-occupancy stage. In contrast, Living Building Challenge and Well Building Standards require a measured performance for at least twelve months as a mandatory requirement to achieve their certificate. Leading green building experts, such as (Yudelson, 2016), believe that well-known GBRTs suffer from different issues, such as the expensive certification costs. In addition, project stakeholders are driven by the score and point achievements, not by sustainability and the complicated energy modelling criteria. Yudelson (2016) adds that most of these tools are designed based on a manual workflow that reviews and issues the certification. This requires hiring green building consultants to evaluate the drawings and project information to demonstrate compliance with certain GBRT, which requires significant time and increased consultation fees. Ade and Rehm (2020) add that these tools compare the predicted building performance against an average industry benchmark or building code instead of an optimal performance goal. Yudelson and Meyer (2013) and Loh *et al.* (2020) identify this as a substantial failure of almost all GBRT. They argue that the industry needs to set a zero-energy target for all buildings instead of producing buildings with marginally less bad building performance than the industry benchmarks.

Many studies have been conducted to compare different rating systems in various ways. A study by Zimmermann *et al.* (2019) analysed ten local and international certification schemes based on the definition of sustainable buildings: (Active House, BREEAM, DGNB, Green Star, HQE, LEED, Living Building Challenge, Well, Nordic Ecolabel, and Miljobyggnad). The definition used in this study consists of Social, Environmental, and economic dimensions of sustainability. Zimmermann found that almost all the examined certification schemes target the environmental dimension. The study results show that almost all the studied certification systems highly value the environmental aspect, followed by the social aspect, while on the other hand, limited attention is paid to the economic aspect. The study found that the Well building standard was the only certificate focused on the social aspect and that only DGNB gives equal weight to the environmental, social, and economic aspects.

Mattoni *et al.* (2018) reviewed and analysed five green building rating systems CASBEE, Green Star, BREEAM, LEED and ITACA. To simplify the comparison, Mattoni and the team identified six new macro-areas, site, water, energy, comfort and safety, materials and outdoor quality, to normalise the procedure and to highlight the qualitative and quantitative differences between the above rating systems. Quantitatively, the “Energy” area was found to have the heaviest weighting in all the analysed rating systems except for CASBEE, where Comfort and Safety was the most critical aspect. In addition, the “Water” area has received the lowest impact. From the qualitative point of view, Mattoni and the team found that “Energy” and “Water” areas are shared among all the reviewed certification schemes.

Nguyen and Altan (2011) compared five well-known rating systems: LEED, BREEAM, CASBEE, GREEN STAR, and HK-BEAM. In their study, LEED and BREEAM achieved the highest score (75 out of 100) based on their proposed criteria. The study considered the following aspects: market adoption; the availability, the methodology used to process the inputs to prepare the final results, weighting system, rating level, quantitative vs qualitative criteria, the complexity and efficiency of the assessment method; data collection process, measurability and convenience, in addition to the documentation process; accuracy and verification of data inputting, processing, and outputting; user-friendliness; development; and result presentation. The results reflect that BREEAM and LEED have achieved well-maturity and development levels compared to the other GBRT.

Passive design techniques are considered one of the critical approaches to reducing the energy demand of buildings by optimising the architectural design features and efficient building envelope to reduce its energy demand. Chen, Yang and Lu (2015) compared the passive design criteria in five rating systems (BREEAM; LEED; CASBEE; BEAM Plus; GBL-ASGB). The study concludes that the passive design approach is treated differently between the chosen certificates and that these rating systems should promote passive design strategies more. The study suggests that each parameter’s allocated weight should consider the effectiveness and impact of that parameter rather than the project's performance. In addition, Chen and the team suggest that at least building layout, envelope thermal physics, building geometry, infiltration and airtightness are all aspects that must be considered in passive design strategies. Only BREEAM between the investigated tools considers this point, highlighting that more effort is required to integrate passive design concepts with GBRT.

The following section introduces the concept of building performance evaluation, programs used to perform building performance assessments, and the link between these programs and GBRTs.

2.3 Building Performance Evaluation tools

2.3.1 Introduction

Nowadays, one of the critical challenges in the building sector is its increasing energy demand, which contradicts ambitious targets for environmental design. The building sector is increasingly moving towards using environmental assessment methods as the construction industry is responsible for more than 36% of the final energy and accounted for nearly 40% of CO2 emissions in 2017 (IEA and UNEP, 2018). As a result, design teams are asked to deliver optimised, sustainable building solutions based on various criteria, as discussed earlier, including energy, daylight, materials, indoor environment, and others. One of the challenges here is balancing all design features in an optimal scenario that satisfies all the targeted factors of a GBRT. For example, optimising the window-to-wall ratio to obtain daylight and visual comfort levels can affect thermal comfort and cooling/heating energy use. Adding shading devices or installing mechanical ventilation systems might be a good solution to balance the benefits of the design features. However, it will increase energy use, capital, and operational costs (Østergård, Jensen and Maagaard, 2016).

There is a need to aid decision-making for green building design from the initial design phase, where decisions significantly impact cost and performance (Attia *et al.*, 2012; Hygh *et al.*, 2012; Kanters and Horvat, 2012). Although it is challenging to make design decisions in the initial design phase, decisions made in the later stages to optimise project performance are more difficult and expensive to apply (Santos *et al.*, 2014; Østergård, Jensen and Maagaard, 2016). See Figure 2-2.

GBRTs often require building Performance Simulation (BPS) from the early design stage due to its importance in achieving a pre-defined performance target, which requires integrating the proposed design with BPE programs that can forecast the performance of the proposed design. However, BPE programs tend to be complex and require collecting different parameter inputs that can only be known in the later design or operation stage of the project life-cycle. This chapter introduces the BPS programs and discusses some of the challenges regarding performing building simulations, in addition to integrating the BPS tools with GBRTs.

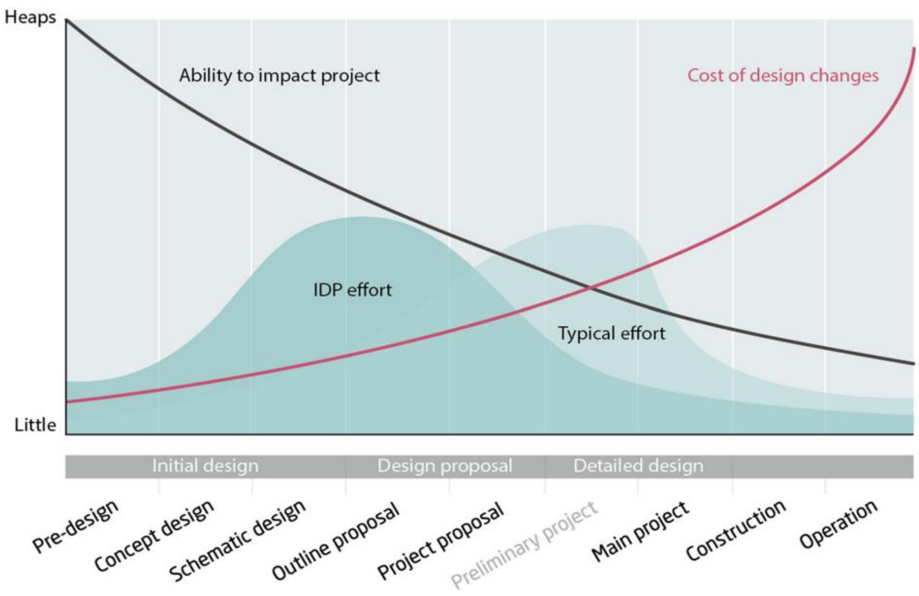


Figure 2-2 Effect of Integrated design and decisions made at different design stages on the ability to impact and project cost. Source (Landgren et al.*, 2019)*

As highlighted earlier, energy is considered the most challenging factor across all the rating systems, with the highest weight across all the compared standards. Furthermore, due to the lack of expertise in this field, the energy performance simulations' complexity is considered a critical barrier to adopting the JGBG in the Jordanian market. Therefore, this research will focus on the Energy criteria, specifically on the energy and daylight performance simulations, as the steps involved in preparing the daylight model for simulation are similar to the energy model. In the following sections, we overview building performance simulation programs, their integration with GBRTs, and the challenges of performing performance simulations in early project phases.

2.3.2 Building performance simulation programs

The development of building performance simulation has received much attention in the last twenty years. Many tools have been developed for various purposes. For example, EnergyPlus (US Dept. of Energy, 2019) and DesignBuilder (Design Builder Ltd, 2019) are tools that were designed to assess the energy and thermal performance of buildings, while Integrated Environment Solutions-Virtual Environment (IES-VE) (Integrated Environmental Solutions Ltd., 2013) was developed with more capabilities to simulate daylight, air quality and more.

Performance simulation programs offer the robust capability for creating building models in design phases to predict how a building, as designed, interacts with the outdoor environment during its life cycle (Morbitzer, 2003; Maile, Fischer and Bazjanac, 2007). One of the essential benefits of using simulation programs is the ability to compare different design alternatives to investigate energy use, thermal comfort and other issues (Maile, Fischer and Bazjanac, 2007).

Østergård (2016) described most simulation tools as "evaluative in nature", meaning they can only assess building performance in the last design stage rather than guiding the design process and influencing the design options in the concept stage. A study by Attia (2012) states that out of 392 tools listed in the building energy simulation tools (BEST) directory (IBPSA-USA, 2022), less than 1% of the listed tools can be used to inform a project at the briefing stage. For example, the engineer at the concept design stage is frequently asked by the architect and the owner several what-if questions regarding different design alternatives, such as the use of external shading systems, the use of passive or active cooling systems, different window-to-wall ratios, prior to any detailed design work. It is very challenging to answer these enquiries during the concept stages of the design due to various uncertainties, including the lack of design details, the rapid changes in the design, and the massive amount of time spent preparing different scenarios and obtaining the answer (Østergård, Jensen and Maagaard, 2016).

2.3.2.1 Overview of Building Performance Simulation Tools

The functionality of certain programs is limited to specific domains, such as energy, daylight, indoor environment quality, thermal comfort, and others. Table 11 compares some of the most commonly used programs for building performance simulation listed in the BEST directory (IBPSA-USA, 2022) with a brief description of their functionalities and use across different design stages. Most of the selected tools were cited in different studies to compare their usage in different design stages, capabilities, and flexibility in accepting different input files (Maile, Fischer and Bazjanac, 2007; Architects, 2012; Bahar *et al.*, 2013; Østergård, Jensen and Maagaard, 2016; Han *et al.*, 2018).

Table 11 Overview of different performance simulation tools

software	User		Design stage			Input file	Simulation engine	Application						Reference
	Architect	Engineer	Conceptual	Spatial	Technical design			Energy	Thermal	Daylight	Air quality	LCA	LCC	
EnergyPlus	✓	✓			✓	ASCII (text file)	Own engine	✓	✓		✓			(NREL, 2022)
Green Building Studio	✓	✓	✓	✓		GbXML, 3D-CAD	DOE-2	✓						(Autodesk, 2013)
OpenStudio		✓		✓	✓	GbXML, IFC	EnergyPlus, Radiance	✓	✓	✓	✓		✓	(NREL, 2019)
IES-VE	✓	✓	✓	✓	✓	GbXML, IFC, DXF	Own engine (Apache), SunCast, Radiance	✓	✓	✓	✓	✓	✓	(Integrated Environmental Solutions Ltd., 2019)
Sefaira systems		✓		✓			EnergyPlus, Radiance	✓	✓	✓				(Trimble, 2019)
TRNSYS		✓			✓	ASCII (text file)	Own engine	✓	✓	✓				(The University of Wisconsin, 2019)
Trace 700	✓				✓	GbXML		✓	✓	✓		✓		(Trane, 2019)
BSim		✓	✓	✓		DXF	Own engine	✓	✓	✓	✓			(BSim Engineers, 2019)
DesignBuilder	✓	✓	✓	✓	✓	GbXML, DXF, pdf	EnergyPlus, Radiance, jE+	✓	✓	✓	✓		✓	(Design Builder Ltd, 2019)
Ladybug Tools	✓	✓	✓	✓		GbXML, idf, Json, GEM, OSM	EnergyPlus, Radiance, Openfoam, Therm/Window	✓	✓	✓	✓			(Ladybug Tools, 2022)
Pollination	✓	✓	✓	✓		GbXML, idf, Json, GEM, OSM	EnergyPlus, Radiance, OpenFOAM	✓	✓	✓	✓			(Pollination, 2022)
OpenLCA		✓			✓							✓	✓	(GREENDELTA, 2022)

As seen in Table 11, most of these tools are mainly oriented to use by design engineers, while some can be used by architects in the early design stages. In addition, most of these tools can accept open data schemas, such as gbXML and IFC, as input files, which can be produced by the Building Information Modelling (BIM) authoring tools. Therefore, the modelling and assessment process can be less complex than the traditional workflow of generating energy models from text-based input files (i.e., ASCII or IDF files for EnergyPlus).

2.3.2.2 Current Challenges in Performing Early Building Performance Simulation

Traditional computer-aided design tools (CAD), such as Autodesk AutoCAD, are used to model buildings for sustainable design practice. An energy simulation tool such as EnergyPlus, Ecotect and IES Virtual Environment is then used to analyse the building performance by entering the design data, typically taking account of thermal insulation, climate response, glazing, shading, solar gain, solar penetration, airtightness, artificial lighting, natural ventilation, mechanical ventilation HVAC systems, and thermal mass (Cho, Alaskar and Bode, 2010).

Moreover, these tools consider local weather data sets and utility prices when processing thermal loads. These simulation packages produce an annual hourly thermal load in two ways, textual and graphical outputs. For example, if the simulation outputs do not meet the pre-defined performance target, the designer can modify and edit as many design features as possible, like window-wall ratio, building orientation, and other strategies. Then it is required to remodel the new design proposals to test the effect of the design modification on daylight performance, energy consumption and thermal loads.

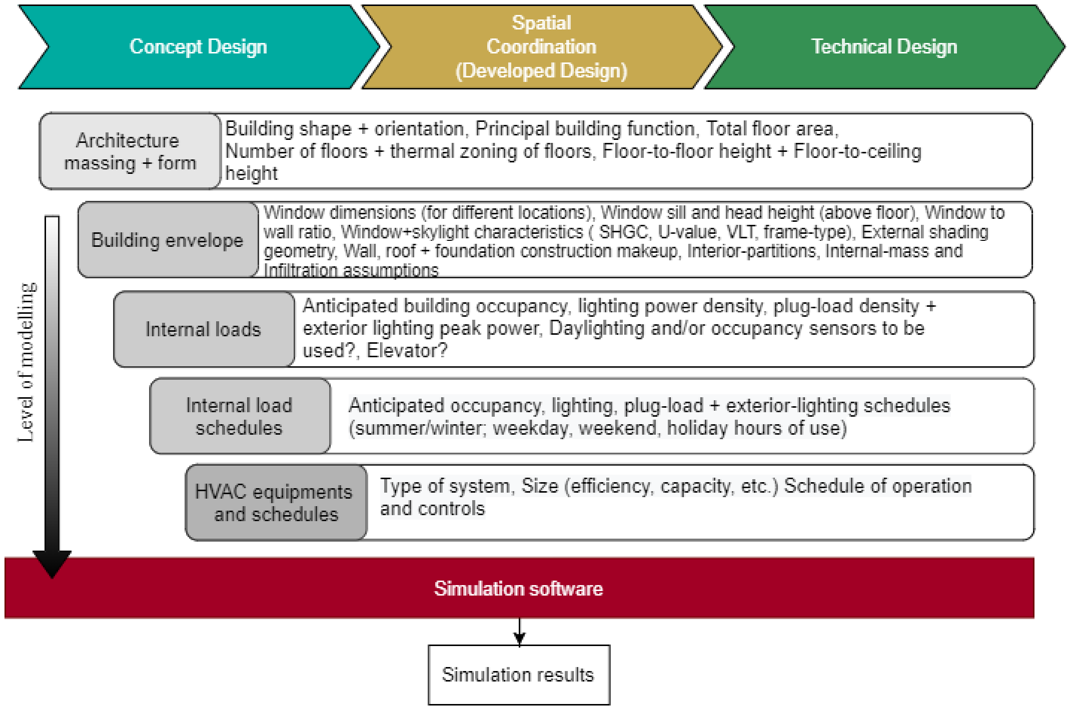


Figure 2-3 Level of details development across different design phases

Weather data is considered a critical factor that affects performance predictions. While most tools currently use past weather data, simulation results cannot be guaranteed to reflect the actual performance of buildings within the occurring climate change worldwide. Hence, it is crucial, where possible, to use prediction tools to generate reliable future weather files instead of historical weather data. In this regard, Eames, Kershaw and Coley (2011) have developed a tool to predict the UK's future weather data.

The detailed energy analysis is mainly made in the technical design stage once its components and elements are specified. Usually, the more specific the project information is, the more accurate the results. However, the downside of such a detailed simulation is the needed time and effort to prepare the simulation and obtain accurate results due to the complex information needed for the simulation process and the efforts needed to adjust and modify the energy model to reflect the design changes. For ultimate performance optimisation, designers should make decisions in the early concept design stage by identifying and analysing component-based energy consumption and choosing the most convenient design alternative which leads to energy efficiency in buildings (Jalaei and Jrade, 2014). However, it is challenging to know all the detailed specifications and the impact of decisions made at this stage due to uncertainties and the rapid design development process. Figure 2-3 represents the accumulated details needed for building performance simulations in different design phases, with the identified project information in each phase (adopted from (Maile, Fischer and Bazjanac, 2007; AIA, 2012; Bahar *et al.*, 2013)).

Furthermore, Motawa and Carter (2013) state that one of the significant problems in current practice when targeting multi-objective sustainability assessment is the integration between the design and BPE tools to prevent multiple data entries, repetitive modelling, and the consideration of building features changes during its life-cycle, resulted by the maintenance and operational needs.

Although the architect or the designer of the project might have rough information about the project's architectural design features in the conceptual phase, the detailed building design plans and their details will not be available at this moment for the energy assessment (Gervásio *et al.*, 2014; Santos *et al.*, 2014; Ferrero *et al.*, 2015). To overcome this challenge, assumptions about the missing data must be made. Several tools have already used different design templates to overcome this issue, such as DesignBuilder and Green Building Studio, which use pre-defined values and building components (Han *et al.*, 2018). Using pre-defined values by software vendors may facilitate and lead to a rapid assessment process. However, this approach cannot guarantee accurate results compared to a detailed simulation that benefits from inputting actual occupancy and operational schedules. Accurate project information can only be obtained in the last project phase when all the needed information is identified (Østergård, Jensen and Maagaard, 2016; Han *et al.*, 2018).

The accuracy of simulation results is highly dependent on the accuracy of inputs and the level of detail for the simulation as defined by the software programme parameters. The required inputs are the weather data, the external environment, building geometry and orientation, operation schedules and strategies, internal loads, fenestration properties and window-to-wall ratio (WWR), the HVAC systems, equipment loads, lighting loads, and more (Maile, Fischer and Bazjanac, 2007; Bahar *et al.*, 2013).

Conducting energy simulation is often a complex process that requires experience and knowledge in energy modelling principles and techniques. The first step in the manual procedure to conduct a building performance assessment is to prepare the design drawings in a CAD environment. The design drawings are then used to create the energy model, either textually, using a text editor or IDF file editor, or using a graphical user interface (GUI) to create the energy models, such as the OpenStudio. After creating the energy model, the energy modelling environment allows for assigning the identified project information, such as the materials, processes, equipment, and others. Once all the information needed is identified and assigned to the energy model, the assessment team performs the energy simulations. If the model performance does not meet the identified target, the assessment team must repeat the process until the identified performance targets are met. Figure 2-4 illustrates the typical workflow to create the energy assessment of a project.

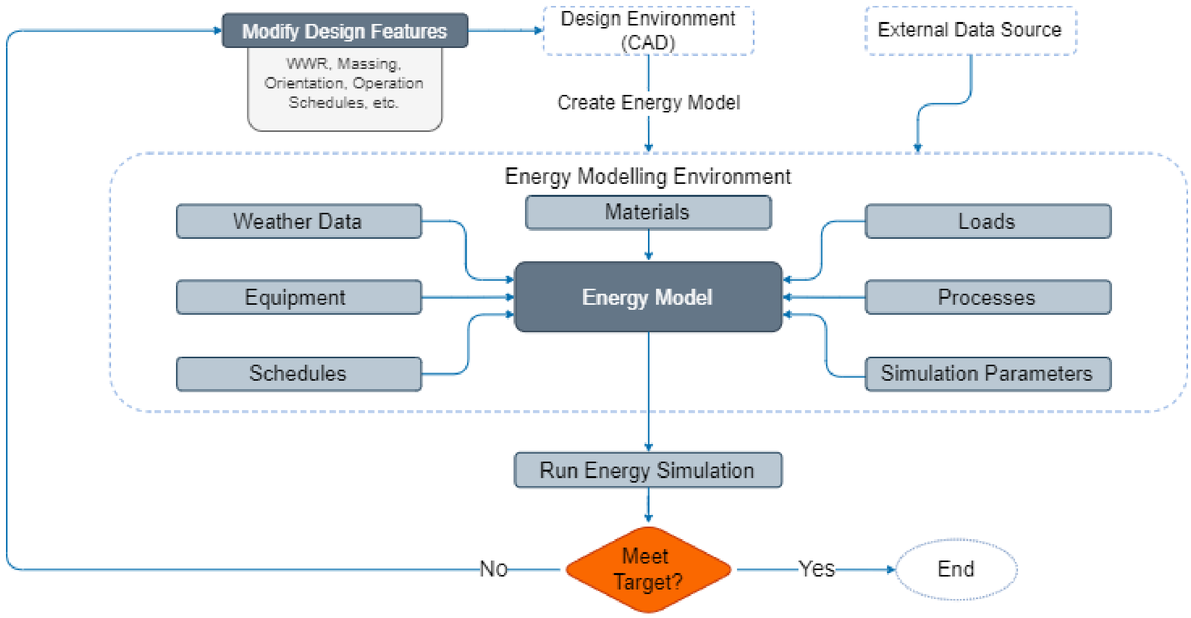


Figure 2-4 Typical energy assessment Workflow

2.4 Green Building Rating Tools and Building Performance Simulations

Building performance analysis is often required in most GBRTs for various sustainability factors, such as energy performance, daylight performance, indoor air quality, and thermal comfort. Integrating building performance evaluation tools and GBRT is limited to a few criteria in specific standards. For example, Green Building Studio (Autodesk, 2013) can only predict LEED points for Glazing factor and Water credit for projects in the United States; IES-VE can predict up to 50 points from both (1) LEED v4 from Location & Transport, Sustainable Sites, Energy & Atmosphere and Life Cycle Assessment categories, and (2) BREEAM UK NC 2018 Health and Wellbeing, Energy, Materials, and Management categories (Integrated Environmental Solutions Ltd., 2019).

Ansah *et al.* (2019) reviewed some of the most commonly used tools, as cited in (Lu *et al.*, 2017), in addition to other relevant tools and highlighted the availability of direct functions to assess green building criteria (see Table 12). The limited integration between building performance simulation programs and GBRTs is often argued that GBRTs receive constant updates, which can be described as complex, bulky, and differently structured based on local and regional priorities. Furthermore, technical challenges include the interoperability between design and simulation tools and the tremendous effort and time needed for modelling and simulating results. In addition, GBRTs extensively tackle various sustainability issues such as energy demand, thermal comfort, daylighting, water use, and more. No single simulation tool can be found to tackle all these issues. This issue adds more efforts on the design teams to develop different versions of building models further to use in different tools, and the significant time and effort needed to redo the modelling if the performance of one model does not meet the design expectation in one of the assessed aspects, which adds more obstacles to the green building assessment and simulation tools.

Table 12 Selected Tools and functions for green building criteria assessment. Source: (Ansah *et al.*, 2019).

Software	Applicable Green building criteria
AECOsim	-
ArchiCAD	-
Autodesk Green Building Studio	-
Autodesk Revit- Light Analysis tool	LEED (IEQc8.1) and LEED v4 (EQc7 opt2)
Bentley Hevacomp	-
DesignBuilder Simulation	-
DOE2	-
eQUEST	-
EnergyPlus	-
FloVENT	-
HEED	-
Integrated Environment Solutions-Virtual Environment	LEED (Thermal comfort, daylight and quality views of indoor environment quality),
	BREEAM (Management, Health and Wellbeing and Energy credits)
Navisworks	-
ODEON Room Acoustics Software	-
One-Click LCA	LEED v4 (building life-cycle impact reduction (MRc1))
	BREEAM (life-cycle impact (MAT 1))
TRANSYS	-

Different GBRTs require a different set of parameters and use different performance benchmarks. For example, Roderick *et al.* (2009) compared an office building's energy performance using the energy performance criteria of three different GBRTs: LEED, BREEAM, and Green Star. While the building achieved a high-energy rating in Green Star, the building has achieved a very low rating according to BREEAM and failed to achieve LEED certification. This issue highlights the differences across different GBRTs requirements in the energy performance factor alone, which formulates an obstacle to a broader integration between GBRTs and building performance simulation programs.

The following section will discuss the challenges in early assessment for building energy performance and integrating BPE programs with GBRTs.

2.4.1 Green Building Compliance Performance Modelling

As discussed earlier, GBRTs often assess different building performance factors, such as energy, daylight, and thermal comfort. To assess green buildings, a building performance model is prepared to assess the performance of the project following a pre-defined procedure that requires comparing the design model performance against a baseline model that can be characterised based on national or international building codes, such as ASHRAE 90.1 (ASHRAE, 2022) which is adopted in the US and many regions around the world.

For example, LEED's Energy and Atmosphere criteria "EA Prerequisite: Minimum energy performance" can be achieved using ASHRAE 90.1 pathways: "Section 11 Energy Cost Budget Method (ECB)" and the "Appendix G Performance Rating Method". Similarly, JGBG's Energy Efficiency Criteria, 10th requirement, "Perform Energy Simulation", requires preparing the design model to be compared against a baseline model, which can be identified according to the Energy Efficient Codes in Jordan (also developed based on ASHRAE standard (Awadallah *et al.*, 2009)). Table 13 highlights some differences between the baseline and the proposed design energy performance models required by the JGBG.

Table 13 Basic differences between baseline and proposed design's energy performance model characteristics

Parameters	Proposed Design scenario	Benchmark model scenarios
Weather files	Amman weather file	Amman weather file
Orientation	As designed	North, south, east, west
Window openings	As designed	30% in all elevations
Glass thermal transmittance coefficient	As designed	Energy efficient codes
Shading coefficient	As designed	Energy efficient codes
Interior lighting	As designed	As designed
Exterior lighting	As designed	As designed
Cooling	As designed	As designed
Heating	As designed	As designed
Ventilation	As designed	As designed
Fans and exhausts	As designed	As designed
Pumps	As designed	As designed
Equipment loads	As designed	As designed
Anti-freezing equipment	As designed	As designed
Elevators	As designed	As designed
Swimming pool equipment	As designed	As designed
Cooking equipment	As designed	As designed
Schedules	As designed[4]	As designed
Walls, roofs, and floors Thermal transmittance coefficient	As designed	Energy efficient codes
Cold roofs modelling	As designed[5]	Energy efficient codes
Shading devices	As designed	No shading
HVAC systems	As designed	National building codes[6]
Process energy[7]	As designed	As designed
Renewable energy sources	As designed	As designed

Most GBRTs only require performance simulations, such as the energy performance, at the design stage. Different studies highlighted that certified green buildings often suffer from a mismatch between the predicted and the actual energy performance, referred to as the "performance gap" (Carbon Trust, 2011; Dwyer, 2012; Corry *et al.*, 2015). The performance gap can be caused by many reasons, such as inaccurate inputs of simulation assumptions, geometry modelling, internal loads,

[4] Except if there are any necessary differences to simulate innovative energy efficient strategies, such as lighting and natural ventilation control, or reducing water heating loads.
[5] Solar reflectance coefficient can be used.
[6] To compare with the lowest-acceptable efficiency in the national building codes.
[7] Offices equipment, computers, elevators, escalators, cooking equipment, communication rooms, task-lighting, motors, medical equipment. All based on actual/realistic schedules.

materials specifications, and more (Tarantino, 2020). However, “model calibration” can be referred to as enhancing the accuracy of data inputs by observing data from occupied buildings to reduce the risk of performance gaps occurring and produce accurate results from the building performance simulations (Coakley, Raftery and Keane, 2014). Therefore, it is argued that rather than asking for compliance with the predicted performance of buildings, certificates must be given based on the actual performance of the building where all the simulation inputs, building components, and occupants’ behaviour are known, hence, eliminating the risk of performance gap to occur.

2.5 Discussion

Green and sustainable construction is often used as synonyms to describe a building designed to mitigate its negative environmental impact. This chapter introduced the concept of sustainable constructions and green buildings and introduced different local and international GBRTs. Various GBRTs were developed worldwide to assess and aid in the design and construction of green buildings. Most of these tools address common issues based on regional priorities, such as energy, water, indoor environment quality, site, transport, and materials and resources. However, green building rating tools have since been criticised for different reasons.

Most of the GBRTs tools are designed to assess the design stage of buildings, not the operational. Besides, these standards allow buildings to be certified based on intellectual criteria often found easy to meet by the design teams. In addition, green building rating tools aim to reduce the negative impact instead of targeting at least net-zero energy performance.

The assessment criteria in many GBRTs require using different building performance simulation tools to assess the performance of buildings. This chapter has identified critical challenges in performing building performance simulations during the design stage of green projects. These challenges can be summarised as follows: (1) lack of necessary information in the early design stages; (2) rapid changes throughout the design stages, which consumes more time in remodelling and performing repetitive tasks and simulations; (3) conducting the evaluation based on assumptions or defaulted values, which leads to performance gaps.

In addition, this chapter has highlighted the challenges that lead to the limited integration between GBRTs and BPS tools, such as (1) complexity and variety of sustainability requirements, (2) simulation programs’ capabilities and their complexity, (3) interoperability between tools, their evaluative rather than guiding nature, and (4) the challenge of design optimisation to balance the energy, daylight, thermal comfort, and other GBRT targets at once.

The recent development in BPS programs led to the introduction of parametric performance analysis tools, such as Ladybug tools (Ladybug Tools, 2022) and openstudio's Parametric Analysis Tool (PAT) (NREL, 2019). Programs with parametric analysis features allow the user to analyse different scenarios to determine the best design scenarios compared to the benchmark model, such as changing WWR, insulation specifications, orientation, and other characteristics, combined or separated. In addition, these tools can help eliminate many redundant tasks and modify and manipulate the input models to perform different performance simulations for selected sustainability factors. Furthermore, these features can aid design decisions by assessing the uncertainty of different design parameters in a process called "Uncertainty Quantification" (Burhenne *et al.*, 2013).

Parametric BPS tools can facilitate the iterative nature of assessment criteria in GBRTs. It can help produce different design proposals with minimal effort. Therefore, this research considers Ladybug tools as the simulation tool for the integration assessment workflow development due to their proven capabilities, which will be discussed further.

Building Information Modelling (BIM) has enabled the support of integrated BPE through a centralised and data-rich model that allows simultaneous project design updates. Most BIM authoring tools can share the designed model through open data schemas standards, such as Green Building Extensible Markup Language (gbXML) and Industrial Foundation Classes (IFC), allowing easier integration between the design and BPS tools. Therefore, BIM will be adopted as one of the potential solutions for the challenges mentioned above, and its integration with GBRTs and BPS programs will be discussed in Chapter 5.

3. Methodology

3.1 Introduction

The manual procedures often challenge the sustainability assessment process to generate different design models, generate different performance evaluation models, and the lack of information and digital data representation in the assessment tools. These evaluation models are often required to perform performance assessments, such as daylight, energy, life cycle impact, and more. Furthermore, the assessment requirements often vary from one GBRT to another regarding the assessment methodology, factors assessed, and performance benchmark that must be met to pass the criteria. The development of BIM technology has allowed for better integration between the GBRTs, the design and BPS tools by facilitating the generation and sharing of rich-data models. BPS programs with parametric analysis features allow users to analyse different scenarios for the best design option. Functions can be developed based on the adopted GBRT and its criteria requirements, which makes the assessment process flexible and expandable to host any rating system, considering the availability of digital data representation of buildings.

This chapter describes the methodology adopted in this research to investigate the potential capabilities of BIM technology to facilitate green building assessment. To do so, five main steps have been attained: (1) a Critical literature review of Green Building Rating Tools (GBRTs) analysing the assessment factors considered in each tool and their complexity levels, (2) a Critical literature review of Building Information Modelling (BIM) analysing integration in green building assessment, (3) Pilot study (BIM2PHPP) to examine the potential integration between BIM and sustainability assessment tools (PHPP), (4)-develop the integrated sustainability assessment tool (iSAT), a BIM-based tool that integrates BIM with GBRTs and BPS tools designed to assess buildings' performance according to specific GBRT criteria, and (5)- tool validation using two residential and office building case studies. The iSAT tool was designed to simplify and reduce the complexity of assessing buildings' designed performance and automate the sustainability assessment based on the JGBG. The main aspects considered in developing this tool are energy performance, daylight performance, and materials. The selected criteria represent different levels of complex workflows illustrated in section 4.3 as proof of the tool feasibility concept, which can be extended further to implement further criteria and GBRTs.

3.2 Methodological Approach

This research aims to facilitate the sustainability assessment of buildings by automating the assessment processes and integrating the assessment criteria with the assessment tools. The recent development of BIM technology has allowed for efficient design workflows that produce intelligent, data-rich models with capabilities to integrate with BPS tools. However, this integration requires the development of adequate data management procedures to allow for effective and automated integration between the assessment tools with the digital information models to facilitate the sustainability assessment. Hence, this research aims to utilise the capabilities of BIM technology to automate the sustainability assessment process and the integration of assessment criteria and assessment tools to facilitate flowless information integration between these tools. In this research, Deductive reasoning was adopted in this thesis, where the problem was first defined, followed by formulating the hypothesis and research questions that identified the data to be collected and analysed to test the hypothesis. The research hypothesis was formulated as *"The development of Building information modelling technology has the potential to facilitate sustainability assessment through the seamless integration of design, assessment criteria, and assessment tools."*

Accordingly, the research questions were identified to formulate a comprehensive understanding of the aspects of this research area, including tools, methods, and workflows. The research design was then formulated, and the steps for data collection and analysis required for the tool development were identified. The developed tool's performance was finally assessed using the identified case studies. As seen in Figure 3-1, research questions interlink with three main topics, which are the assessment criteria (GBRTs), assessment (BPS) tools, and BIM authoring tools (and data exchange schemas).

In this research, we questioned the ability of BIM technology to provide the necessary means to automate the assessment of GBRTs. Therefore, a comprehensive literature review was conducted in this research to explore the application of BIM in facilitating green building assessments. The literature review helped investigate the current GBRTs status through a comparative analysis of five rating systems, aimed at highlighting each tool's comprehensiveness in terms of the factors covered in the assessment criteria in each tool. A generic structure that hosts all the factors in the GBRTs was introduced based on the documents analysed. The barrier from various GBRTs categorisation strategies makes the comparison impossible. As such, a generic structure was derived based on the analysed factors to serve the evaluation framework, which re-maps individual rating systems' categories based on actual assessment criteria and factors instead of comparing their original category's structure.

Furthermore, the complexity of selected GBRTs criteria was analysed. On the other hand, the assessment (BPS) tools were also investigated, and the application of some of the well-known tools in assessing GBRTs' criteria was reviewed. The analysis has revealed that GBRTs tend to be very complex and assess many factors, which can vary significantly regarding the methodology and assessment procedure. Moreover, limited integration between BPS and GBRTs tools was identified, highlighting further obstacles in green building assessment. Hence, the second research question was identified: *"What information is required to conduct the assessment process?".*

The literature review was also conducted to review the development of BIM technologies. Various studies have adopted the concept of GreenBIM in the literature due to the capabilities of the technology and tool features. Such features consist of parametric capabilities, providing data-rich models, and integrating all design teams, allowing them to work simultaneously on one central model. BIM-based approaches were developed to automate the sustainability assessment of buildings using different techniques. Each technique was then reviewed, and its challenges and opportunities were discussed. Furthermore, a pilot study was introduced to investigate the potential of integrating BIM with BPS. It was concluded that BIM as a design tool could be integrated using open data schemas, such as IFC and gbXML, formulating the third research question, "*How can BIM tools integrate GBRTs with BPS tools to facilitate green building design assessment?".*

Finally, the last part of the literature focused on the data interoperability between the involved tools to conduct performance analysis of buildings. In this regard, the use of gbXML and IFC has been investigated in depth, and data mapping between the design tools (BIM-gbXML), assessment tools (BPS) tools, and the assessment criteria (GBRTs) to allow for a comprehensive understanding of the overall implementation proposal. gbXML was identified as the base data schema for the tool due to its acceptance as an input format in various assessment tools and since it was mainly developed to

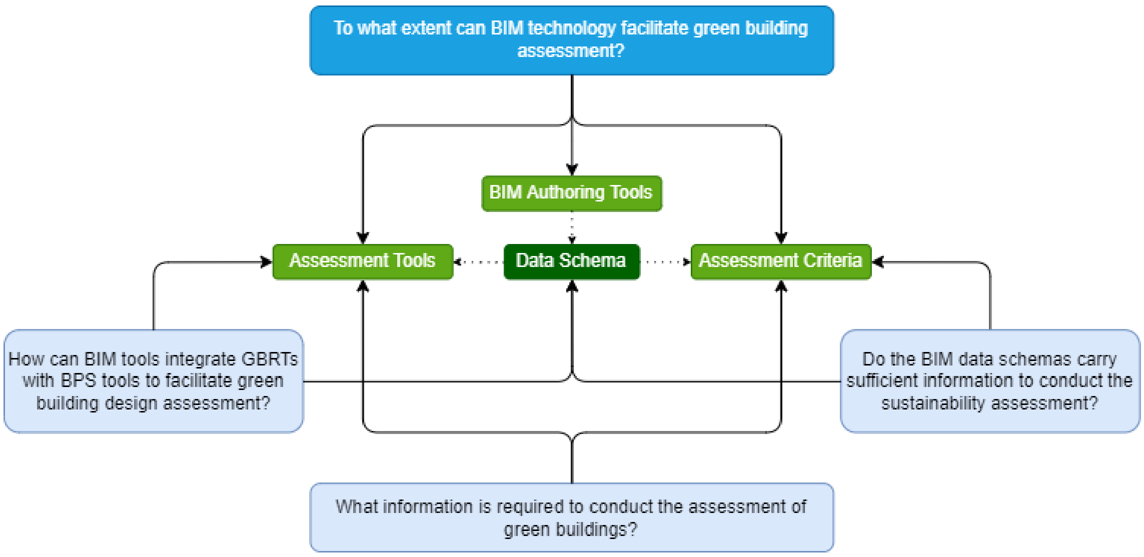


Figure 3-1 Research questions and identified topics to investigate.

conduct energy and daylight assessments. Hence, the fourth research question was asked, *"Do the BIM data schemas carry sufficient information to conduct the sustainability assessment?".*

The design of this research follows an exploratory mixed method. The information in exploratory research is used to build quantitative research based on qualitative research and exploration of the research topic (Creswell, 2014, p. 16). Document Analysis was used as a qualitative approach, formulating the primary data that contributed to exploring the research gap and identifying the needed information, processes, and possible approaches to bridge this gap. The analysis of GBRTs highlighted in Chapter 4 has provided an overview of the existing GBRTs assessment factors, exploring their complexity, highlighting the differences between distinct GBRTs for assessing specific criteria and classifying the assessment factors based on their complexity levels.

Furthermore, the review of BPS tools and their general applications in building performance assessments identified that only limited GBRTs criteria are integrated with GBRTs and identified the required information to conduct a complete assessment. The analysis of BIM integration in green building assessment in Chapter 5 has further explored the state-of-the-art development of BIM technology and how it can provide potential solutions to facilitate green building design and assessment. Visual Programming Environment (VPE) was one of the identified approaches that demonstrated the feasibility of facilitating the sustainability assessment of buildings.

Therefore, In Chapter 6, the BIM2PHPP tool was developed as a pilot study to explore the potential of VPE workflow. The BIM2PHPP tool was developed to investigate how can BIM data schema support the integration between the design (BIM) and assessment (BPS) tools while embedding the assessment criteria (GBRTs) in one integrated approach. Although the pilot study demonstrated great potential for integrating BIM with BPS, this integration was limited to particular tools, such as the adopted Visual Programming Environment (VPE) approach. The identified challenges using VPE were related to data interoperability between different design and assessment tools and the dependency on specific environments.

Chapter 7 comprehensively discusses and demonstrates the development of the Integrated Sustainability Assessment Toolkit (iSAT). The chapter presented the iSAT as a BIM-based tool to automate and streamline sustainability assessments in green building projects. Through a step-by-step explanation, the chapter has demonstrated the tool's features, including iSAT-gbXML for parsing and processing building information, the iSAT-JGBG for executing machine-readable rules based on gbXML data to assess Jordan Green Building Guide (JGBG) criteria, and the iSAT-Performance for conducting complex performance simulations.

The tool (artefact) development falls into the Information Systems (IS) research domain. Alter (2008) has defined information systems as systems that produce informational products or services that use technology, information, and other resources from activities or processes carried out by humans or machines. Kilani and Kobziev (2016) state that IS research can be categorised under subjects such as Technology, Management, Political Science and Strategy. The information systems methodologies have been developed to design computer-based systems and facilitate information systems modelling that meets the demand of users of the information (Rowley, 1993). Information systems research can aid in developing systems that handle and process information. Nunamaker, Chen and Purdin (1991) argue that system development can be seen as a “proof-by-demonstration”, as it can be accepted as evidence (artefact) that promotes a “proof” accepted as evidence that supports a hypothesis. They add that system development’s primary function is to work as a proof of concept for primary research and produce an artefact that can be focused on in continuing research.

Therefore, to comply with the requirements of developing the artefact that corresponds to the problem identified in this research, a pragmatic approach was implemented in this thesis, where the research problem was identified, and the research questions were asked. Creswell (2013) states that to answer the research questions best, researchers adopting this worldview will use multiple data collection methods, utilise different sources to collect data, focus on the functional research implications, and assert the significance of carrying out the research best addressing the research problem. Shields (1998) stated that pragmatism has an experimental way of enquiry that is fixed and focused on developing conceptual and practical tools to resolve “problematic situations. Casula, Rangarajan and Shields (2021) argue that pragmatism can adequately situate exploration and working hypothesis, which he described as *“The working hypothesis is first and foremost a hypothesis or a statement of expectation that is tested in action”; h*ence, exploration can fit comfortably within the pragmatic philosophical worldview.

The tool was developed using computer programming. Frey (2018) defined programming as “*the process of creating computer “code”—or instructions that a computer can interpret—to automate quantitative summaries of data”*. As discussed earlier, this tool aimed to facilitate the assessment of green buildings through automated processes, including data retrieval, evaluation, and complex simulations. In this regard, one of the real benefits of using programming is that it allows for highly flexible approaches and workflows to be designed and implemented, facilitating the expansion of the tool’s functionality and broader adoption. A program may consist of functions defined to perform complex tasks in an automated fashion. Functions are sub-routines that perform a specific task. A user inputs some data, and the function produces outputs based on the processes involved per the function’s design. Frey (2018) suggests that writing these functions in a simplified way is very beneficial, allowing for code reproducibility and reusability.

As Nunamaker, Chen and Purdin (1991) described, tool development involves five steps. They suggest that it starts with (1) constructing a conceptual framework, (2) developing the system (tool) architecture, (3) designing and analysing the system, (4) building the prototype, and (5) observing and evaluating the system. They suggest that the evaluation of the system developed can be conducted using case studies, field studies, lab experiments, and others. Hence, the tool was evaluated using two-certified green buildings in Jordan selected as case studies designed based on the JGBG.

Finally, Chapter 8 validated the iSAT toolkit's development and implementation. The validation process involved a rigorous and systematic evaluation of the iSAT toolkit's performance, accuracy, and reliability to ensure it aligns with its intended functions and primary objectives. The validation included extensive testing using various demo buildings, deliberately representing extreme scenarios to detect and address any encountered errors. Moreover, the iSAT toolkit's validation was reinforced by assessing two real-world case studies that successfully obtained certification from the Jordan Green Building Guide (JGBG). The iSAT toolkit's credibility and effectiveness were substantiated through this thorough validation process, concluding its potential impact on automating and enhancing sustainability assessments in green building projects.

3.3 Data Collection and Analysis

Data collection was conducted in two steps in this research. In the first instance, the information collected and analysed in chapters 2, 4, and 5 helped produce the necessary data to formulate the research problem. An extensive literature review has been conducted to explore the identified aspects. Published articles, books, reports, manuals, and websites were all primary information sources to understand the current knowledge, practices, tools, and methods used in each topic. Based on that, a conceptual framework was proposed for the tool development. The information concluded from the first step was essential to proceed with the tool development, as it helped highlight the processes, workflows, and information needed to conduct a complete assessment.

A comparative analysis was conducted in Chapter 4 to compare the GBRTs and re-map the assessment factors based on the common structure between the selected five GBRTs. The analysis results also highlighted that factors' complexity varies significantly depending on the assessed criteria requirements. The literature review conducted in Chapter 2 highlighted the challenges in current practices in assessing green buildings. The review highlighted that the integration between GBRTs and BPS tools is minimal. However, it is also revealed that parametric BPS tools carry capabilities to facilitate the assessment of green buildings. Chapter 5 highlighted through a comprehensive literature review how BIM could potentially facilitate sustainability assessment through different approaches identified by others. In addition, it discussed how it could integrate with BPS tools for various performance assessments. Table 14 highlights the implemented data collection and analysis strategy, which contributed to formulating a comprehensive understanding of the knowledge gap in this research.

Table 14 Data collection and analysis strategy.

Question	Data collection/analysis strategy		
	GBRTs	**BPS**	**BIM**
What data was collected?	GBRTs manuals	BPS tools	BIM features
	Review articles about GBRTs	GBRTs' criteria integration with BPS tools.	BIM application in green building assessment
			IFC and gbXML application in sustainability assessment.
Where was the data collected from?	The tool.		
	Published articles.		
	Manuals.		
	Online documentation.		
	Books.		
Why was data collected?	Overview and compare the selected GBRTs.	To highlight the existing challenges in using BPS tools.	To understand the capabilities and limitations of BIM for sustainability assessment.
	To re-map sustainability factors covered in GBRTs in a generic structure	To understand the capabilities and limitations of BPS tools for sustainability assessment.	To understand BIM capabilities of interoperability with BPS tools.
	Conclude the complexity of sustainability factors and assessment criteria.		To identify the workflows developed by others to conduct sustainability assessments using BIM.
How was the data analysed?	Comprehensive literature review		
	Comparative analysis.		
What was the data collection/ analysis output?	Most GBRTs do not cover the operational phase of buildings and are optional.	BPS tools are complex, requiring various inputs.	BIM offers data-rich models that all design teams can work on simultaneously.
	GBRTs are complex, bulky, and require experienced users.	BPS tools do not cover most of the GBRTs and their assessed factors.	Different approaches were identified to support sustainability assessment using BIM.
	A re-map of the reviewed GBRTs in a unified structure highlights the comprehensiveness and shortcomings between GBRTs.	Interoperability with design tools is an issue.	IFC and gbXML have partially resolved the interoperability issue between BIM and BPS tools.
	Complexity levels vary significantly from factor to factor.	Missing information is an issue, although default values can be used.	
	There is still a need to develop an integrated sustainability assessment tool that can integrate different GBRTs and is interoperable with BPS tools.		
	GbXML data schema will be used to map GBRTs requirements to BPS tools.		

3.4 Development Framework

Developing an automated building performance assessment tool requires integrating the assessment criteria with the BPS and design tools. The required information must be translated flawlessly between the design and the assessment tool. This section describes the development of the iSAT toolkit in five phases (illustrated in Figure 3-2), from data collection and analysis to developing the algorithm to perform an automated sustainability assessment for selected criteria from the JGBG.

The first phase is data collection. The assessment criteria, such as the JGBG rating system, green BIM concepts, and BPS tools, were all overviewed to reveal the research gap and highlight opportunities for developing an automated assessment tool. The overview has helped formulate the research gap, demonstrated by the complexity of the assessment process and the lack of integration between design and BPS tools, in addition to the limited support for GBRTs criteria assessment in BPS tools, which uncovered the need to facilitate the sustainability assessment by automating the performance evaluation processes of buildings.

The second phase involved further analysis of the JGBG, BIM (gbXML) model, and the required information to use as inputs for the BPS tools. The selected GBRTs were analysed and compared under one structure that hosts all the GBRTs factors. The re-mapping has helped us understand what factors are assessed in each rating system and helped to clarify the varying complexity of different criteria in the JGBG. The complexity of a criterion can be concluded by reviewing the processes and performance evaluations required to complete the assessment based on the identified methodology of a rating system. BPS tools are then reviewed, and the integration with GBRTs is evaluated, which has helped identify what information the BPS tools require to perform a specific assessment. Finally, the gbXML model was exported from the BIM authoring tool, and its quality and content were reviewed. The gbXML model plays a significant role in facilitating the assessment process as it carries the model information from the design to the assessment tool.

In phase three, the criteria from the JGBG were further analysed using an Excel spreadsheet to determine what building elements, operations, or processes (if needed)were required to complete the assessment. Furthermore, the criteria were analysed, and building elements, assessment operations, and performance benchmarks were prepared to convert its content from textual into machine-readable computational rules. GbXML data were mapped with the analysed data from the JGBG criteria, and the missing information to conduct performance assessments was identified and prepared using Json dictionaries to perform an automated assessment process.

In the fourth step, the iSAT tool was developed using Python. The iSAT tool consists of five core modules. The first module, "iSAT gbXML", is a functional library developed to analyse and extract the required information from any gbXML file. Secondly, "iSAT JGBG" is a functional library developed to host the assessment criteria in a machine-readable format. The third and fourth parts of the tool, "iSAT Energy" and "iSAT Daylight", are python modules developed using the Software Development Kit (SDK) of Ladybug tools to allow for the integration of BPS tools with BIM and GBRTs. Finally, "iSAT Materials" is a functional library developed to assess the materials information.

Finally, the tool was tested and validated using two case studies built and certified in Jordan per the JGBG requirements. The first case study is a detached residential family villa that received its JGBG certificate in 2018. The other case study building is an office building that was certified in 2015. Both cases were built in Amman and were modelled and tested using the available information provided by the architects of these buildings. Currently, no codes or regulations endorse the use of BIM authoring tools for any construction project in the Jordanian AEC industry, and therefore, it can be very challenging to find an architectural firm that adopts a BIM-based practice.

The validation of the iSAT toolkit was a crucial step in its development and implementation. The process involved systematic assessment and verification of the tool's performance, accuracy, and reliability to ensure it functions as intended and meets its primary objectives. The iSAT toolkit's performance was thoroughly tested using different demo buildings, representing extreme scenarios to identify and debug any encountered errors. Additionally, validation was carried out using two real-world case studies that achieved the Jordan Green Building Guide (JGBG) certification.

The iSAT toolkit was further validated using a multi-faceted approach to ensure accuracy and effectiveness. Firstly, it was compared against manual assessments of green building projects based on the JGBG criteria. A parallel manual assessment to the automated iSAT toolkit assessment was conducted, and the results from both methods were compared to assess the iSAT's ability to evaluate sustainability criteria accurately. The computational efficiency and resource requirements of the iSAT toolkit should be evaluated to ensure smooth and efficient operation, handling large BIM models and complex simulations effectively.

Finally, the iSAT toolkit's accuracy in achieving higher points in the JGBG assessment was examined by assessing green building projects using manual and iSAT-assisted methods. Comparing obtained scores has demonstrated the tool's potential to enhance sustainability performance and support decision-making in green building design. By conducting comprehensive validation, the iSAT toolkit could establish itself as an accurate and efficient solution for automating sustainability assessments and streamlining the green building design process.

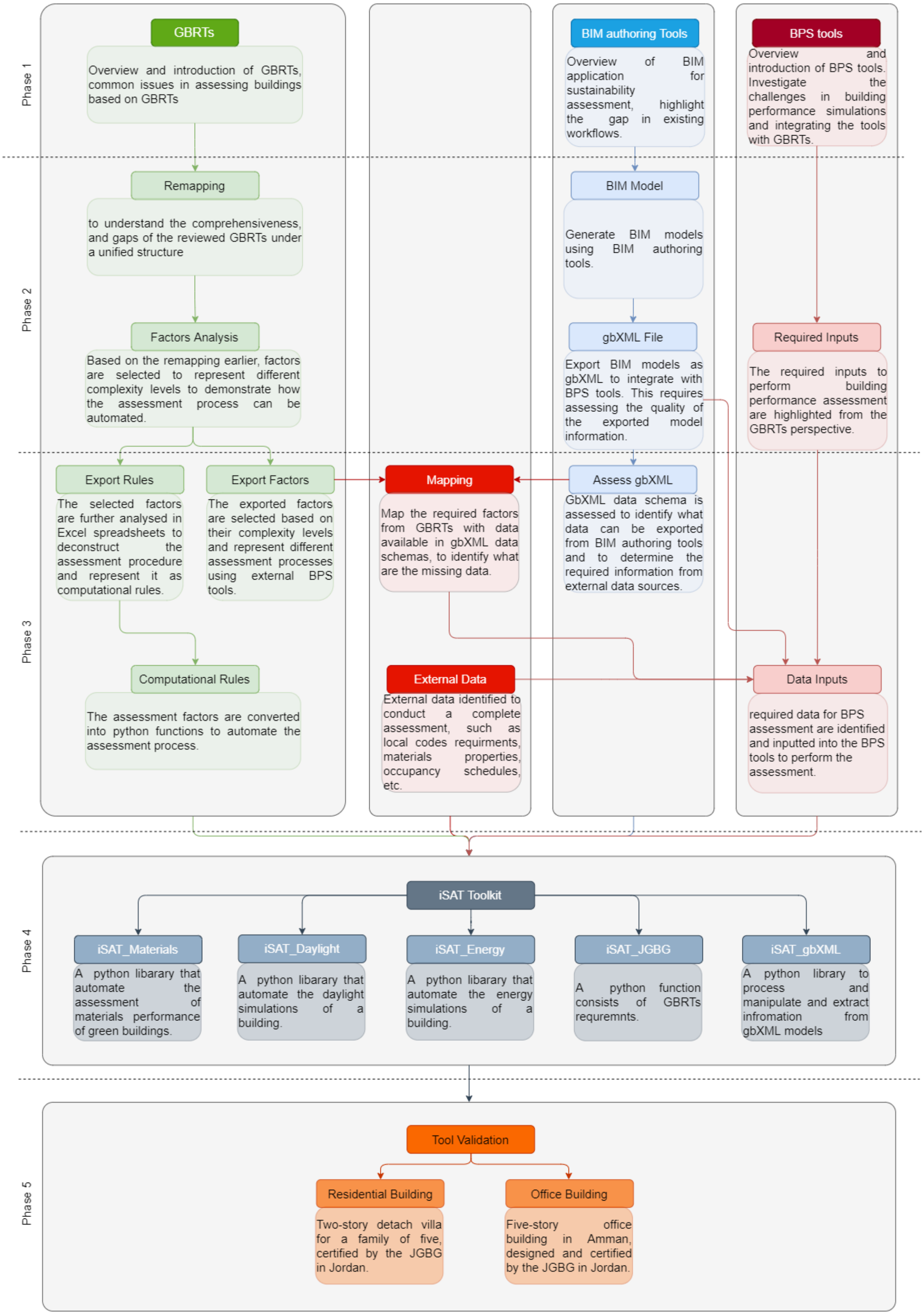


Figure 3-2 Methodology for developing the iSAT toolkit.

3.5 Conclusion

This chapter has described the research methodological framework to investigate BIM capabilities in facilitating green building assessment. Based on the analysis of GBRTs, BPS tools and BIM tools integration in green building assessment, a BIM-based sustainability performance assessment tool integrates the design and assessment tools to work flawlessly and automatically by allowing the design to be assessed according to the selected GBRT has been introduced. As a proof of concept, the JGBG, Autodesk Revit, gbXML data schema, and Ladybug Tools were chosen to develop this tool. The selected criteria from the JGBG represents different complexity levels that can be addressed by varying integration levels. The focus of this tool aims to facilitate energy performance, daylight simulations, and materials performance assessment.

The Ladybug tools were developed using Python as an open-source tool, and its software development kit (SDK) is publicly available through its website (Ladybug Tools, no date b). The ladybug tools can perform various sustainability assessments, including energy simulations and daylight assessments. The parametric capabilities of the tool can facilitate model generation and manipulation with minimal effort. Python programming language was used for the Ladybug SDK. Five Python modules were developed to facilitate the tool's information integration and data exchange to perform a complete assessment of the predefined criteria.

A programming approach to develop an open-source tool can facilitate the adoption of the tool's core parts to be further expanded. The objective is to develop customisable approaches and workflows and better integrate them with different assessment tools. Hence, the novelty of this approach lies in: first, developing an open-source Python algorithm that can be used for different performance assessments, allowing for customisable workflow developments. Second, it facilitates the integration between different performance simulation tools that can host any rating system by only converting the criteria from textual-based rules into machine-readable functions.

The key innovation of this research lies in developing the Integrated Sustainability Assessment Tool (iSAT), a BIM-based approach that automates and streamlines sustainability assessments in green building projects. By integrating assessment criteria and assessment tools within the BIM environment, the iSAT toolkit offers a flexible and efficient solution, enhancing the accuracy and comprehensiveness of sustainability evaluations. Its parametric capabilities allow for the automation of complex assessments, such as energy and daylighting simulations, enabling design teams to test different scenarios effortlessly. The iSAT toolkit's significant contribution to knowledge lies in its potential to transform green building assessment practices by bridging the gap between BIM technology, assessment criteria, and assessment tools. This research advances the field by showcasing the feasibility of automating sustainability assessments, addressing integration challenges, and improving data interoperability between various design and assessment tools.

However, the gbXML data, as discussed earlier, may not provide all the necessary information about the project to conduct performance assessments. Therefore, the tool was designed with capabilities that allow external data to be integrated easily, including different flexible approaches and data manipulation based on the user's needs. The tool development will be precisely described in Chapter 6.

4. Comparison of selected green building rating systems

Several studies have compared local and regional green building tools to understand their differences and commonalities. Li *et al.* (2017) suggest that developing a new rating system or upgrading an existing one requires analyzing its strengths and weaknesses in three different ways: (1) statistical analysis of GBRT usability based on green building practices information (Todd, Pyke and Tufts, 2013), (2) green building professionals feedback (Schweber, 2013), and (3) by comparing the existing rating systems and standards through the comparative analysis method (Shamseldin, 2018).

In this regard, Li *et al.* (2017) have reviewed 57 articles on green building assessment methods through comparative analysis. According to their study, GBRTs are compared under four levels: (1) general, which looks into the developer, tool history, certification levels, and schemes available, (2) category, in which researchers compare the main categories, their weighting and the available score. Although this level of analysis could present a fair understanding of how each standard compares to others in specific categories, it could not reflect the actual level of detail required for the assessment by the standard. (3) Criteria, where individual criterion and their weighting points are considered, in addition to re-categorisation and mandatory criteria of each standard. Although the level of comparison could provide more details than the categories comparison, it does not fully represent which sustainability indicators (factors) are considered for the evaluation by the GBRT. And (4) indicator comparison represents the required parameters in each criterion. According to the study, criteria and indicators are less often used to compare GBRTs to general and category comparisons. Figure 4-1 below illustrates the four-level structure using JGBG.

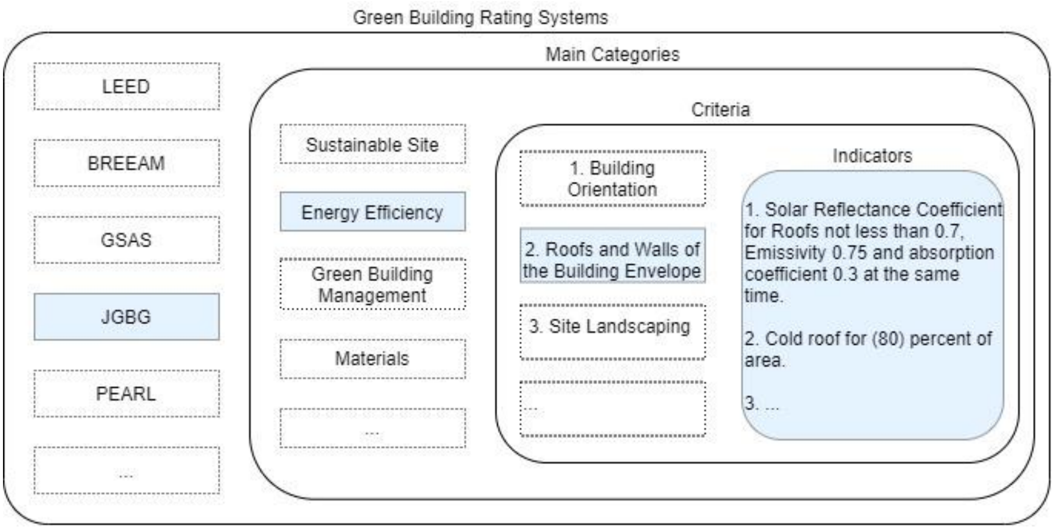


Figure 4-1 Green Building Rating Systems structure- Example of JGBG criteria

4.1 Remapping Green Building Rating Tools

To date, numerous GBRTs have been published worldwide. In 2013, the Jordan Green Building Guide was first introduced, and since then, it has not received any minor or major updates. Only a few studies have considered reviewing the JGBG (Shareef and Altan, 2017; Elnaklah, Walker and Natarajan, 2021). Based on this, the following section compares the JGBG with four leading rating systems, i.e., LEED and BREEAM, two of the most adopted and well-developed international GBRT, and GSAS and PEARL for Estidama in the middle east as two leading regional standards. This analysis aims to:

1- Present a robust understanding of the maturity and comprehensiveness of the JGBG against leading international and regional standards.
2- Highlight the most and least considered factors across the GBRT.
3- Provide a better representation of all the assessment factors investigated among the GBRTs, which will be later used as a guiding framework to aid in developing the iSAT assessment tool.
4- Develop a generic framework for building sustainability assessment facilitate green building performance evaluation.

To correspond to the GBRT analysis aims, LEED, BREEAM, GSAS, and Pearl were selected for the analysis against the JGBG, which was developed based on these tools. LEED and BREEAM are cited in the literature as the most developed and adopted worldwide, in addition to Pearl and GSAS, considered the region's most developed and mature local green building rating tools. Comparing JGBG with international (BREEAM and LEED) and regional (GSAS and Pearl) would demonstrate how each standard addresses the regional priorities differently, prove the maturity level, and would, in the case of JGBG, reflect on how significant the local priorities affect the development of the JGBG as it was developed based on these standards.

The initiative behind the factors analysis was to better neutralise all the rating system factors in the first instance to understand the targeted issues within each rating system and compare them to each other, thus understanding comprehensiveness and shortcomings and highlighting the differences among the studied rating system.

The information and documents used in this section were obtained directly from the officially published documents and the rating system website to conduct an objective analysis. Critical review and comparative analysis of the available documents were conducted as a bottom-up approach to analyse and compare the selected GBRT, focusing on the indicators (factors) between the selected standards. Sustainability factors in GBRT vary between systems regarding availability, weight, hierarchical structure of different categories, and compulsion level. Therefore, assessing the similarities and differences between different standards without considering these aspects regarding the sustainability factors may lead to misleading assessment results.

Hence, we proposed eight generic sustainability categories based on the analysis outcomes. Some factors in each category, requirement, and criterion can intercorrelate with other categories within the same standard. For example, *LEED* Credit: *Integrative Process: Energy-Related Systems: (site conditions, massing and orientation, building envelope attributes)* are all indicators that could significantly affect the Energy Efficiency of the building and, at the same time, must be considered in the EA Prerequisite: Minimum Energy Performance.

The proposed generic categories were proposed based on categorising all the reviewed factors into their end goal of sustainability, as illustrated in Table 15:

Table 15 description of the new macro-areas

Category	Criteria
Site	Site Assessment, Site Selection, Ecology Protection and Development, Urban Heat Island, Light Pollution, Sound Pollution, Outdoor Thermal Comfort, Heritage and Cultural Identity.
Water	Indoor Water Use, Outdoor Water Use, Water Reuse, Stormwater Management, Water Metering, and Water Quality.
Energy	Passive Design Strategies, Energy Performance Assessment, Energy Metering, Renewable Energy, Greenhouse Gas Emissions, Energy-Efficient Equipment, Lighting, Grid Harmonization, and Energy-Efficient Transport System.
Indoor Environment Quality	Indoor Air Quality, Contamination Control, Ventilation, Thermal Comfort, Tobacco Smoke Control, Lighting, Visual Comfort, and Acoustics Performance.
Materials	Life Cycle Assessment, Existing Structure Reuse, Materials Reuse, Local Materials, Responsibly Sourced Materials, Materials Content, Environmental Product Declaration, Certified Wood, Low-Emitting Materials, Construction Waste Management, Operational Waste Management, and Materials Efficiency.
Management	Integrative Process, General Safety on Site, Life Cycle Cost and Service Life Planning, Construction Environmental Management, Commissioning and Handover, Facility Management, Leak Detection and Prevention, Workers Accommodation, Support of National Economy, Adaptation to Climate Change, Regional Priority
Transport	Public Transport, Surrounding Density, Proximity to Amenities, Accessibility, Carshare, Shuttle Bus, Cycling Facilities, EV, Parking, Load on Local Traffic, Mixed Use, Travel Plan
Innovation	Energy-Efficient Innovative Design, Water-Efficient Innovative Design, Sustainable Site Innovative Design, Indoor Environment Innovative Design, Materials Innovative Design.

4.2 Results

In this section, we compare five rating systems to highlight the similarities and differences between these systems. JGBG for offices and commercial buildings was compared with two leading rating systems in the region, namely, GSAS, and PEARL, in addition to two leading international rating systems: LEED and BREEAM, recognized for their widespread maturity and acceptance worldwide. The original structure and allocated points of the above rating systems vary significantly depending on the priorities and the issues each rating system tackles, which are formed by the characteristics of the local climatic conditions and geographical attributes (Ding, 2008; Mattoni *et al.*, 2018). For example, Energy, Water, Materials, Site Sustainability, and Indoor Environment Quality appears to be shared categories among these standards. On the other hand, Transport, Management, Integrative Process, Innovation, Pollution, Waste, and Regional Priorities are distinct to the rating system to address specific issues that challenge the built environment in the targeted region. Figure 4-2 presents the original structure of the compared GBRTs by presenting all of their main categories with the allocated point weights.

The figure below shows that energy is the most crucial sustainability aspect in all the reviewed rating systems. JGBG is uniquely weighting this category by around 40% of the overall score. On the other hand, water is allocated 17% of the overall score in JGBG, making it the second-highest priority of this standard. This highlights that JGBG criteria are driven by Energy and Water as the focus and most important issues, as they are allocated 57% combined from the overall achievable score. Furthermore, Pollution and Waste are two categories uniquely forming part of the BREEAM tool. Other categories that are unique to specific systems are Cultural and Economic (GSAS), Regional Priority (LEED), and Integrative Process (LEED and PEARL).

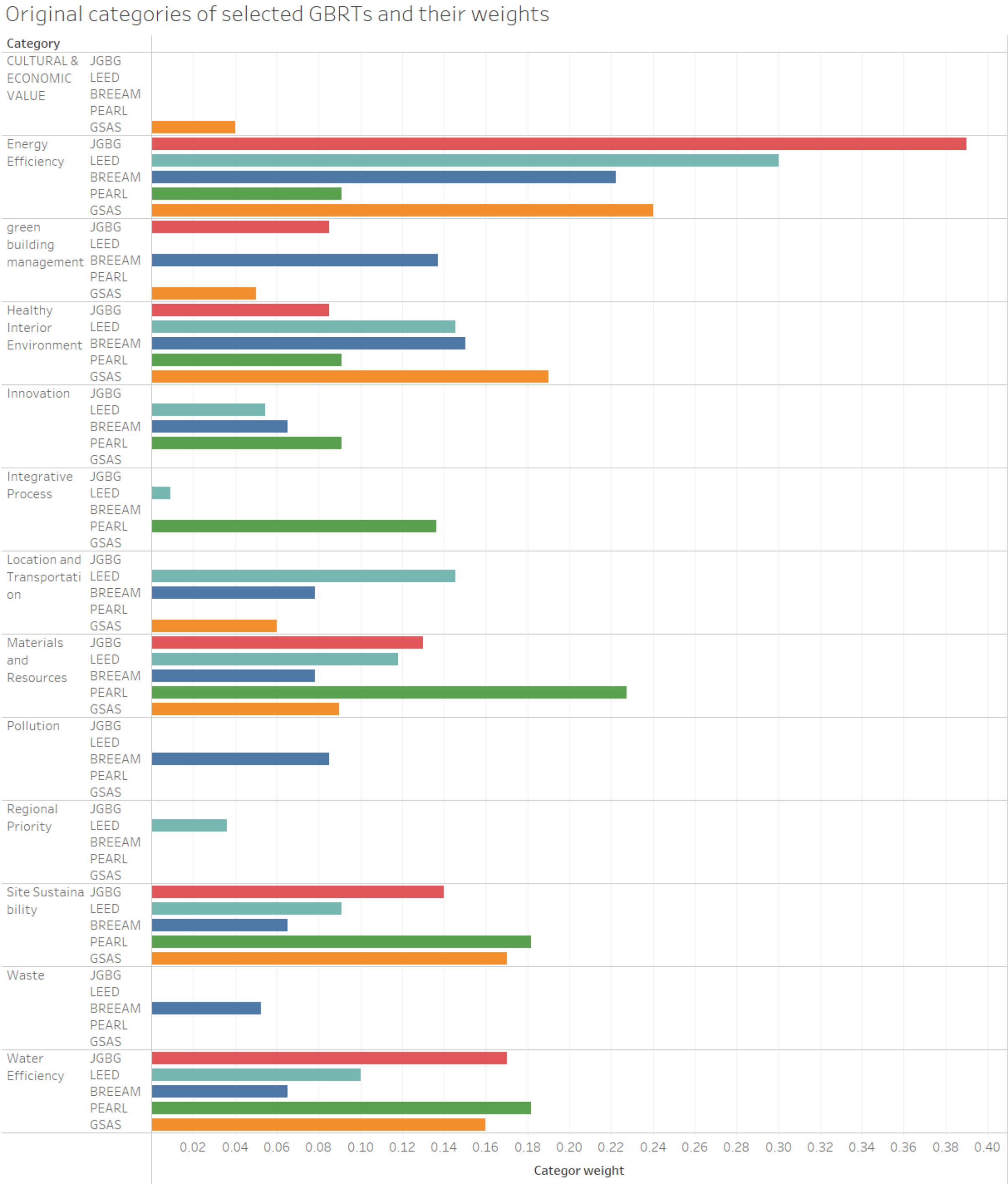


Figure 4-2 GBRT categories and their weights

As discussed earlier, the barrier from various categorisation strategies makes the comparison impossible. As such, a generic structure was derived based on the analysed factors to serve the evaluation framework, which re-maps individual rating systems' categories based on actual assessment criteria and factors instead of comparing their original category's structure. For example, although Innovation -as a category- cannot be found in JGBG, it is included under different categories as an optional requirement. This is also the case for Transportation. Therefore, a generic structure was introduced and re-categorised the chosen standards into eight macro-areas: Site, Water, Energy, Indoor Environment Quality, Materials, Management, Transport, and Innovation. For the demonstration, JGBG factors re-mapping is illustrated in Figure 4-3 Remapping JGBG Criteria based on factors analysis, which highlights the original structure as follows: (1) original categories (left column), (2) original criteria (second-left column), (3) assessed factors (middle column), (4) proposed criteria (second-right column), and finally (5) the proposed new macro areas (right column). The proposed macro-areas were selected to represent the principal categories most standards use. See Appendix B for the remaining GBRT's re-mapping representation. The mapping process was based on the level of the factors that resulted from the critical review and comparative analysis of the selected GBRT to represent each system better.

The following sections present a detailed review of the new macro-areas and how they are tackled in each rating system. The overview covers the main criteria in each category and highlights if the rating system requires minimum standards as prerequisites. For this comparison, the score points of presented GBRTs were eliminated, as the allocated score for one criterion can vary significantly and might be addressed in different levels of detail in each rating system, in addition to being out of the scope of this research. For example, Passive design strategies in JGBG were addressed by tackling eight separate criteria and allocated 29 points, while in BREEAM, Passive design strategies were only tackled in one criterion, with up to 3 achievable points.

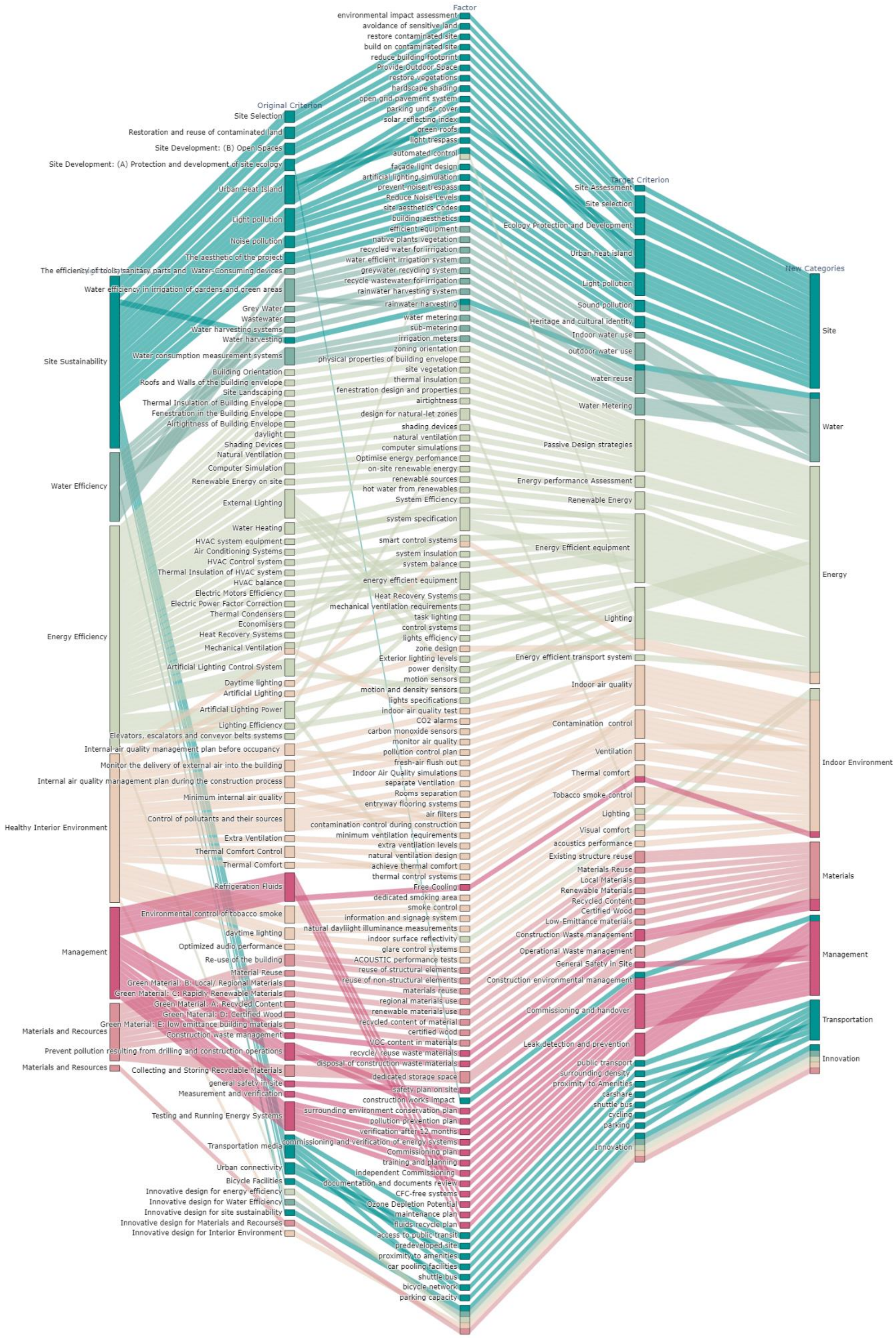


Figure 4-3 Remapping JGBG Criteria based on factors analysis

4.2.1 Site

Site macro-area is a common category among the original structure of the selected rating systems. Here, we evaluate the project's impact on the site to limit its negative impact. Table 16 below highlights the main evaluation factors and how each rating system tackles these issues. Most criteria evaluate environmental-related aspects, which are well covered in all the rating systems. Pearl and GSAS, on the other hand, uniquely evaluate how projects address outdoor thermal comfort through defined measures in their manuals for the project users, which we consider one of the measures to assess social sustainability. This might be important to GSAS and PEARL because of the harsh weather characteristics in summer. The project's cultural and heritage identity is another social-related aspect that measures how the architectural project features correspond to the local architecture, which GSAS and JGBG only measure.

Table 16 Site category and identified factors in different rating systems

Site Criteria	Factors	JGBG	LEED	BREEAM	PEARL	GSAS
Site Assessment	Site assessment	○	○	○	●	
	Hazard assessment			○		
Site selection	Sensitive land	●	○			
	Disadvantaged communities		○			
	Community benefits		○			
	Include affordable housing		○			
	Best site		○			
	Restore contaminated land	○	○		○	○
	Use of Contaminated land	○	○	○		
Ecology Protection and Development	Soil preservations					○
	Habitats protection				○	○
	Protection of ecological features			○		○
	Landscape and habitat management			○	●	○
	Restore habitats				○	○
	Protection of ecological features		○		●	○
	Increase ecological value			○	○	
	Mitigation and compensation				●	
	Previously Developed site		○	○	○	○
	Building footprint	○				○
	Outdoor space	○	○		●	
	Outdoor activities				○	
	Vegetation	○	○		○	○
Urban heat island	Nonroof shading	○	○			○
	Pavement Systems	○	○			○
	Parking Under Cover	○	○			○
	Solar reflection index	○	○			○
	Green roof	○	○			○
	Effective design					○
Light pollution	Light trespass	○	○			○
	Automated control	●		○	●	○
	Lighting design	○		○		○
	Lighting simulation	○				
	Uplight		○			○
	Illuminance levels		○	○	●	○
	Motion sensors				●	○
	High-performance fixtures					○
Sound pollution	Noise trespass	○				○
	External noise Reduction					○
	Site layout and zoning			●		○
	Maximum noise levels	●		○		
	Noise source control			○		○

	Noise impact assessment					
Outdoor thermal comfort	Outdoor thermal comfort					
	Outdoor shading areas					
Heritage and cultural identity	Site aesthetics					
	Building aesthetics					
		20/46	20/46	14/46	17/46	31/46
Legend	Mandatory Factors	Voluntary Factors	Not Available			

4.2.2 Water

The macro-area addresses environmental-related issues such as indoor and outdoor water use efficiency, water reuse (greywater, wastewater), water harvesting systems (rainwater), and water quality. JGBG is the only GBRT that does not assess water quality. The JGBG scored the lowest in the comparison in terms of tackled factors, even though Jordan is one of the world's poorest countries in terms of water resources. See the Table 17.

Table 17 Water category and identified factors in different rating systems

Water Criteria	Factors	JGBG	LEED	BREEAM	PEARL	GSAS
Indoor water use	Efficient equipment's					
	Process water					
outdoor water use	Efficient irrigation					
	Water features					
	Education and Awareness					
water reuse	Greywater recycling					
	Wastewater recycling					
	Rainwater harvesting					
	Recycled Process water					
Stormwater Management	Runoff volume					
	Flood risk assessment					
Water Metering	Metering					
	Sub-metering					
	Irrigation meters					
	Monitoring					
Water quality	Water quality					
	Minimise water Pollution					
	Water treatment					
		8/18	10/18	11/18	10/18	15/18
Legend	Mandatory Factors	Voluntary Factors	Not Available			

4.2.3 Energy

The energy macro-area consists of criteria that evaluate and measure the overall energy use of buildings, carbon emissions, renewable energy, the efficiency of building equipment, and architectural features corresponding to passive design strategies. As seen in Figure 4-2, energy is considered the most critical issue among all GBRT. GSAS treats most of the criteria in this category as mandatory requirements that must not achieve a negative score. Although Energy performance is required in all these standards, it is often achieved through energy performance simulations that predict the design performance and not the actual energy consumption. The compared standards here do not highlight any criteria for green buildings' operational stage energy performance. In this regard, Lu *et al.* (2017)

highlight that this is one of the gaps that need to be addressed by requiring actual performance data rather than the predicted design stage. Furthermore, Newsham, Mancini and Birt (2009) highlight that 28-35% of LEED-certified buildings consume more energy than ordinary buildings. This urges the need to develop more comprehensive criteria to assess whole lifecycle energy performance.

The original structure for energy efficiency in JGBG consists of 29 mandatory and optional criteria, each consisting of at least one indicator, making this rating system more complex and challenging to use than others, such as LEED. Although carbon emission is considered one of the critical challenges these rating systems try to mitigate, PEARL and JGBG are the only tools that do not consist of criteria to assess the reduction of carbon and NOx emissions. This point has received much critique, as highlighted earlier in Chapter 2. Another critical aspect to highlight is that despite the reasonable efforts to reduce the negative impact of green buildings on the environment, it is not enough to ask for reduced energy use or carbon emissions production. Instead, GBRT needs to target net-zero energy buildings as their optimal criteria. The Living Building Challenge, as introduced in Chapter 2, is one of the few standards that address the highlighted issues here. See Table 18.

Energy Criteria	Factors	JGBG	LEED	BREEAM	PEARL	GSAS
Passive Design Strategies	Orientation					
	Massing					
	Materials properties					
	Site Condition and Landscape					
	Building envelope					
	Fenestration					
	Airtightness					
	Daylight					
	Shading					
	Ventilation					
Energy performance assessment	Computer simulation					
	Performance cost index					
	Energy positive building					
	Optimised energy performance					
Energy Metering	Building metering					
	Processes metering					
Renewable Energy	On-site renewables					
	Off-site renewables					
	External lighting					
	Hot water					
Greenhouse Gas Emissions	Co2 emissions					
	NOx Emissions					
	Greenhouse gas emissions					
Energy Efficient equipment	Heating & Cooling systems					
	Equipment efficiency					
	Hot water					
	Mechanical ventilation					
Lighting	Task lighting					
	Control systems					
	Smart Light Control					
	Automated control					
	Lighting efficiency					
	Zone design					
	External lighting levels					
	Light density					
	Outdoor motion sensors					
	Indoor motion sensors					
	Light specifications					
	Demand response					
	Load flexibility					
Energy efficient transport system	Systems analysis					
	Energy efficient system					
	Disabilities requirements					
		30/43	26/43	28/43	12/43	26/43
Legend	Mandatory Factors	Voluntary Factors	Not Available			

Table 18 Energy category and identified factors in different rating systems

Energy Criteria	Factors	JGBG	LEED	BREEAM	PEARL	GSAS
Passive Design Strategies	Orientation	Voluntary	Voluntary	Voluntary		Mandatory
	Massing		Voluntary	Voluntary		
	Materials properties	Voluntary	Voluntary	Voluntary	Mandatory	Mandatory
	Site Condition and Landscape	Voluntary	Voluntary	Voluntary		Mandatory
	Building envelope	Mandatory	Voluntary	Voluntary	Mandatory	Mandatory
	Fenestration	Mandatory	Voluntary	Voluntary	Mandatory	Mandatory
	Airtightness	Mandatory			Mandatory	Mandatory
	Daylight	Voluntary	Voluntary	Voluntary		Mandatory
	Shading	Mandatory	Voluntary			Mandatory
	Ventilation	Mandatory	Voluntary	Voluntary		Mandatory
Energy performance assessment	Computer simulation	Voluntary	Mandatory	Mandatory		Voluntary
	Performance cost index		Mandatory			
	Energy positive building			Voluntary		
	Optimised energy performance	Voluntary	Voluntary	Mandatory	Voluntary	Mandatory
Energy Metering	Building metering		Mandatory	Mandatory	Mandatory	Voluntary
	Processes metering		Voluntary	Voluntary	Mandatory	Voluntary
Renewable Energy	On-site renewables	Voluntary	Voluntary	Voluntary	Voluntary	Voluntary
	Off-site renewables		Voluntary			
	External lighting	Voluntary				
	Hot water	Voluntary			Voluntary	
Greenhouse Gas Emissions	Co2 emissions			Voluntary		Mandatory
	NOx Emissions			Voluntary		
	Greenhouse gas emissions		Mandatory	Voluntary		
Energy Efficient equipment	Heating & Cooling systems[8]	Mandatory	Voluntary	Voluntary		Mandatory
	Equipment efficiency[9]	Mandatory	Voluntary	Voluntary	Mandatory	Mandatory
	Hot water	Mandatory	Voluntary			
	Mechanical ventilation	Mandatory				
Lighting	Task lighting	Mandatory		Voluntary		Voluntary
	Control systems	Mandatory	Voluntary	Voluntary		Voluntary
	Smart Light Control	Mandatory				
	Automated control	Mandatory	Voluntary	Voluntary	Voluntary	Voluntary
	Lighting efficiency	Voluntary	Voluntary	Voluntary	Voluntary	Voluntary
	Zone design	Mandatory		Voluntary		
	External lighting levels	Mandatory		Voluntary		Voluntary
	Light density	Mandatory				
	Outdoor motion sensors	Voluntary				Voluntary
	Indoor motion sensors	Mandatory				
	Light specifications	Mandatory		Mandatory		
	Demand response		Voluntary			
	Load flexibility		Voluntary			
Energy efficient transport system	Systems analysis			Voluntary		Voluntary
	Energy efficient system	Mandatory		Voluntary		Voluntary
	Disabilities requirements					Voluntary
		30/43	26/43	28/43	12/43	26/43
Legend	Mandatory Factors	Voluntary Factors	Not Available			

4.2.4 Indoor Environment Quality

In contrast with the Energy category, Indoor Environment Quality criteria measure the social sustainability issues affecting the building occupants' quality and experience, such as thermal comfort, daylighting, and air quality. GSAS does not define any minimum standards in this category. It is also

[8] **System Design, System Control**

[9] **Certified Systems, Efficiency, Specifications, Internal Loads, BMS Control**

notable that PEARL has no criteria in this category except for Tobacco smoke control. See Table 19 below.

Table 19 Indoor Environment Quality category and identified factors in different rating systems

Indoor Environment Criteria	Factors	JGBG	LEED	BREEAM	PEARL	GSAS
Indoor air quality	IAQ testing	Voluntary	Voluntary	Voluntary		
	CO2 monitoring	Voluntary	Mandatory	Voluntary		Voluntary
	Airflow monitoring	Voluntary	Mandatory	Voluntary		
	IAQ monitoring	Voluntary		Voluntary		Voluntary
	IAQ assessment During construction	Voluntary	Voluntary	Voluntary		
	Pre-Occupancy Air flush out.	Voluntary	Voluntary	Voluntary		
	IAQ simulation	Voluntary				
Contamination control	Separate ventilation	Voluntary	Voluntary			Voluntary
	Physical isolation	Voluntary				Voluntary
	Entryway systems	Voluntary	Voluntary	Voluntary		Voluntary
	Air filtration	Voluntary	Voluntary	Voluntary		Voluntary
	Contamination source control	Mandatory	Voluntary	Voluntary		
	Appropriate materials					Voluntary
	Laboratories containments			Mandatory		
Ventilation	Minimum ventilation	Mandatory	Mandatory			Voluntary
	Extra ventilation	Voluntary	Voluntary			
	Operable windows		Voluntary			Voluntary
	Natural ventilation	Voluntary	Voluntary	Voluntary		Voluntary
Thermal comfort	Achieve thermal comfort	Mandatory	Voluntary	Voluntary		Voluntary
	Thermal comfort Control	Voluntary	Voluntary	Voluntary		Voluntary
	Thermal modelling and assessment			Voluntary		Voluntary
	Free cooling	Voluntary		Voluntary		
Tobacco smoke control	Dedicated smoking area	Mandatory	Mandatory	Voluntary	Mandatory	
	Smoking control	Voluntary	Mandatory	Voluntary	Mandatory	
	Information and signage systems	Mandatory			Mandatory	
Lighting	Indoor lighting levels			Voluntary		Voluntary
	Natural daylight levels	Voluntary	Voluntary			Voluntary
	Daylighting simulation	Voluntary	Voluntary	Voluntary		Voluntary
	Lighting simulation					Voluntary
	Uniformity of illuminance			Voluntary		Voluntary
	Design for natural lighting	Voluntary		Voluntary		
Visual Comfort	Colour rendering index		Voluntary			
	Surface reflectance	Voluntary	Voluntary			
	Quality views		Voluntary	Voluntary		Voluntary
	Glare control	Voluntary	Voluntary	Voluntary		Voluntary
	Glare simulation					Voluntary
acoustics performance	External noise			Mandatory		Voluntary
	Acoustics performance	Voluntary		Mandatory		Voluntary
	Noise levels		Voluntary	Voluntary		Voluntary
	Building services noise		Voluntary			Voluntary
	Sound insulation			Voluntary		Voluntary
	Special hearing and communication needs			Mandatory		
	Location of Noise-Sensitive Areas			Voluntary		Voluntary
	Reverberation times		Voluntary	Voluntary		
		27/44	26/44	30/44	3/44	27/44

Legend	Mandatory Factors	Voluntary Factors	Not Available

4.2.5 Materials

In the Materials category, we find that PEARL covers most of the criteria as mandatory requirements for the certification. Most of the GBRT define criteria that assess the materials' greenness by looking at different aspects, like their source location, recycled content, renewable sources, and toxicity.

Studies show that materials embodied in carbon and energy are significant challenges in the built environment that we need to eliminate as it accounts for more than 20% of the total energy use in buildings in their full lifecycle use (Ramesh, Prakash and Shukla, 2010; Crawford and Stephan, 2013). This issue highlights another shortcoming in these standards, as LEED, BREEAM, and GSAS are the only systems in this review that require Life cycle Impact evaluation that investigates the embodied carbon and energy for the materials used in green projects. The JGBG indirectly address this issue by encouraging the reuse of existing structures and functional adaptability criteria. See Table 20 below.

Table 20 Materials category and identified criteria in different rating systems

Materials Criteria	Factors	JGBG	LEED	BREEAM	PEARL	GSAS
Life cycle impact	Life cycle assessment		Voluntary	Voluntary		Voluntary
	Embodied carbon assessment		Voluntary			Voluntary
Existing structure reuse	Reuse of Structural elements	Voluntary	Voluntary	Voluntary		Voluntary
	Reuse of Non-Structural elements	Voluntary	Voluntary	Voluntary		Voluntary
Materials Reuse	Materials reuse	Voluntary	Voluntary		Mandatory	Voluntary
Local Materials	Regional materials	Voluntary			Voluntary	Voluntary
Responsibly sourced Materials	Responsibly sourced Materials		Voluntary	Voluntary		Voluntary
Renewable Materials	Renewable materials	Voluntary			Mandatory	
Recycled Content	Recycled content	Voluntary	Voluntary	Voluntary	Voluntary	Voluntary
Environmental Product Declaration	Environmental product declaration		Voluntary	Voluntary		Voluntary
Certified Wood	Certified wood	Voluntary	Voluntary	Mandatory	Mandatory	
Low-Emittance materials	Low-emitting materials	Voluntary	Voluntary	Voluntary	Mandatory	Voluntary
	Ingredient reporting		Voluntary			
	Ingredients optimisation		Voluntary		Mandatory	
	Asbestos-free materials			Mandatory	Mandatory	
Construction Waste management	Reduce/reuse construction waste.	Voluntary	Voluntary	Mandatory	Voluntary	
	Disposal of construction waste	Voluntary		Mandatory	Mandatory	
Operational Waste management	Collection facilities	Mandatory	Mandatory	Mandatory	Mandatory	Voluntary
	Processing and Treatment Facilities			Mandatory	Voluntary	Voluntary
	Waste management plan				Mandatory	Voluntary
	Landscape waste				Mandatory	
	Hazardous waste management	Mandatory	Mandatory			Voluntary
	Biomass energy					Voluntary
	Information and Policies			Mandatory	Voluntary	
Materials Efficiency	Efficient use of materials			Voluntary	Mandatory	
	Durable materials			Voluntary	Mandatory	
	Design for disassembling					Voluntary
	Speculative finishes			Voluntary		
	Materials information				Voluntary	
		12/29	15/29	17/29	18/29	16/29
Legend	Mandatory Factors	Voluntary Factors	Not Available			

4.2.6 Management

Unlike the other categories, management evaluates issues related to all the defined sustainability pillars. Most compared standards here define at least one issue as a prerequisite except GSAS. Management area consists of criteria that assess social-related aspects such as safety on the site, workers' accommodation, environmental issues such as environmental construction management, water and refrigerant leak detection and prevention, and economic aspects such as national economy support and life cycle cost. Commissioning and handover are some of the most important aspects of green building management and are considered a procedural dimension here (Awadh, 2017). LEED uniquely rewards green projects with some credits to address regional priorities such as water or energy-related issues. GSAS, on the other hand, is the only standard that rewards projects that support the national economy. See Table 21 below.

Table 21 Management category and identified criteria in different rating systems

Management Criteria	Factors	JGBG	LEED	BREEAM	PEARL	GSAS
Integrative Process	Integrative process					
	Project Brief and Design					
General Safety on Site	Safety on-site					
Life cycle Cost and service life planning	Life cycle cost					
Construction environmental management	Construction impact on site					
	Environmental management					
	Considerate construction					
Commissioning and handover	Post occupancy evaluation					
	Post occupancy verification					
	Building fabric commissioning					
	MEP commissioning					
	Refrigerant system Commissioning					
	Commissioning plan					
	Training and support					
	Independent Commissioning					
	Documentation and user guides					
Facility management	BFM systems					
Leak detection and prevention	CFC/HCFC-Free systems					
	Ozone Impact of Refrigerants					
	Refrigerants Impact assessment					
	Refrigerants leak detection and prevention					
	Water leak detection and prevention					
	Refrigerants fluid recycling					
Worker's accommodation	Workers accommodation plan					
Support for the national economy	National economy					
	Adaptation to climate change					
Regional Priority	Regional priority					
		14/24	11/24	18/24	8/24	7/24
Legend	Mandatory Factors	Voluntary Factors	Not Available			

4.2.7 Transportation

GSAS is the most mature system that covers all the criteria in this category, while PEARL and JGBG cover very few aspects. As seen in the table below, all the standards do not require minimum criteria for Transportation except PEARL, which has only one criterion. This indicates that these standards tackle sustainability issues at the building level only. See Table 22 below.

Table 22 Transportation category and identified criteria in different rating systems

Transportation Criteria	Factors	JGBG	LEED	BREEAM	PEARL	GSAS
	Access to Public Transit					

public transport	Increase in local Bus service			V		
	Dedicated Bus service			V		
surrounding density	Surrounding density	V	V			V
proximity to Amenities	Proximity to Amenities	V	V	V	M	V
Accessibility	Accessible entrances & pathways			V	M	V
	Safe access			V	M	V
	Light and visibility			V		V
	Delivery Routes and Parking			V		
	Signage and street marking			V		V
	Inclusive and accessible design			V		V
	Access to open spaces				M	V
carshare	Carshare	V	V	V		
shuttle bus	Shuttle bus	V	V		V	V
cycling	Cycling network	V	V	V		V
	Cyclists' facilities	V	V	V	M	V
EV	EV		V	V		V
parking	Adequate Capacity	V		V		
	Visibility					V
	Shading					V
	Reduced parking		V			V
	Unbundling parking		V			
	Shared parking					V
	Parking design and safety					V
	Space-saving mechanism					V
Load on local traffic conditions	Access					V
	Parking capacity and layout					V
	Improve road network capacity					V
Mixed-use	Major uses					V
	Impact on Traffic					V
	Facilities					V
Travel Plan	Travel plan			V		
	Travel Assessment			V		
	Sustainable models of transport			V	V	V
	Occupants' involvement			V		
		8/35	10/35	19/35	8/35	26/35
Legend	Mandatory Factors	Voluntary Factors		Not Available		

4.3 The Complexity of GBRTs Requirements for an Automated Sustainability Assessment

Five GBRTs were selected and analysed in the previous section to inform how these tools vary significantly in their structure and the tackled sustainability factors. The analysis has introduced a generic structure that hosts GBRTs, highlighting all the measured factors among all the analysed tools. Many factors are shared across all the rating systems, as highlighted in Table 16-Table 22. For example, in *the Energy* category, *Energy Performance Assessment* criterion, the *Computer Simulation* factor requires conducting computer simulations for the predicted energy performance, which is considered in JGBG, LEED, BREEAM, and GSAS. Similarly, the *Renewable Energy* criterion, the *On-Site Renewables* factor, assesses the installation of on-site renewable energy technologies, such as PV panels, shared among all the reviewed GBRTs. However, the methodology adopted in one GBRT may have slight variations and require achieving different benchmarks in other GBRTs for the same factor.

This research aims to facilitate building sustainability assessment by developing a tool that automates the sustainability assessment workflow. In this regard, GBRTs, and their factors were analysed and re-categorised based on a generic mapping considering the assessed factor instead of the criterion. The analysis helped better understand how each GBRT tackles particular criteria and what factors are assessed. Furthermore, the analysis output highlighted varying processes that involve factors' assessment complexity levels, where some requirements can be directly assessed while others require complex calculations and integration with different assessment tools. Hence, these requirements were classified into four levels based on their readiness for automation and complexity level to achieve a fully or semi-automated workflow. These levels are (1) *unapplicable*, (2) *directly assessable*, (3) *semi-complex*, and (4) *complex* factors, as discussed below. In this research, JGBG is chosen to represent the GBRTs, and factors that represent the levels above will be selected to demonstrate the proposed tool's workflow and development.

First, the *unapplicable factors* represent machine-independent factors, which cannot be automated due to their nature requiring human involvement. These factors, such as BIM, cannot be represented in digital modelling environments but involve a relevant specialist or professional body to conduct the assessment. These requirements are generally found in *Green Building Management* categories in most GBRTs. For example, the first criterion in JGBG consists of nine requirements, as highlighted in Table 23, which require assigning a commissioning team for the project's commissioning and handover of the Energy systems, Preparing a report on the field examination and operation process, developing testing and operation plans, and post-occupancy commissioning and verification after one year of building occupation. Similar factors can also be found in other GBRTs categories, such as *LEED's EA*

Prerequisite: Fundamental Commissioning and Verification criteria. See Figure 4-4*,* quoted from the LEED manual (U.S. Green Building Council, 2021).

Table 23 An example of unapplicable factors in the Green Building Management category in the JGBG

	1st criterion: Testing and Operating Energy Systems	
Obligatory Requirements	1st requirement	Assign a commissioning team & prepare a handling & commissioning plan
	2nd requirement	Ensure the installation and performance of the central systems.
	3rd requirement	Prepare a report on the examination and operation process.
	4th requirement	Provide an operational and maintenance manual.
Voluntary Requirements	1st requirement	Review design documents and project requirements
	2nd requirement	Develop extensive testing and operation plans.
	3rd requirement	Ensure the installation and operation of other systems.
	4th requirement	Preparing a training manual to train the operating staff
	5th requirement	Prepare an extensive report on the examination and operation process.
	6th requirement	Re-examination and operation after one year of occupancy

Commissioning Authority Qualifications
By the end of the design development phase, engage a commissioning authority with the following qualifications.

- The CxA must have documented commissioning process experience on at least two building projects with a similar scope of work. The experience must extend from early design phase through at least 10 months of occupancy;
- The CxA may be a qualified employee of the owner, an independent consultant, or an employee of the design or construction firm who is not part of the project's design or construction team, or a disinterested subcontractor of the design or construction team.
  - For projects smaller than 20,000 square feet (1 860 square meters), the CxA may be a qualified member of the design or construction team. In all cases, the CxA must report his or her findings directly to the owner.

Figure 4-4 An example of unapplicable factors in EA PREREQUISITE: Fundamental Commissioning and Verification in LEED rating system

As discussed earlier, the automated evaluation of these factors is impossible because of the assessment nature, processes, and methodology involving professional bodies and in-situ processes.

Directly assessable factors do not require performing complex processes or calculations nor integrating external building performance simulation tools. The automation of assessing such factors relies on the data available in digital design and modelling environments. In this regard, Building Information Modelling (BIM) is one of the most advanced tools that can facilitate the design process and integrate the building components and their information into one digital model that all the design teams can work on simultaneously, producing centralised intelligent data-rich models. BIM models can produce, process, and extract the necessary project information, thus facilitating green building assessment. For example, the JGBG's Energy Efficiency 4th criterion assesses the U-value of the building envelope (see Table 24). The U-value of most (if not all) building envelope components can be directly retrieved using BIM authoring tools, such as Autodesk Revit. See Figure 4-5, which illustrates (1) the wall element highlighted in blue as one of the exterior building walls and (2) the analytical properties of the wall type in a BIM modelling environment (Revit).

Table 24 An example of directly assessable factors in the Energy Efficiency category in the JGBG.

4th criterion: Thermal Insulation of Building Envelope		
Mandatory Requirements	3rd requirement	U-value of Opaque walls- 0.57 w/m2. k
	4th requirement	U-value of Exposed Roofs- 0.55 w/m2. k
	5th requirement	U-value of Exposed Floors- 0.80 w/m2. k
	6th requirement	U-value of Separating walls- 2.00 w/m2. k
	7th requirement	U-value of Separating roof, floor- 1.20 w/m2. k
	8th requirement	Total U-value of walls- 1.60 w/m2. k
	9th requirement	Total U-value of Exposed roof, floor <1.60 w/m2. k

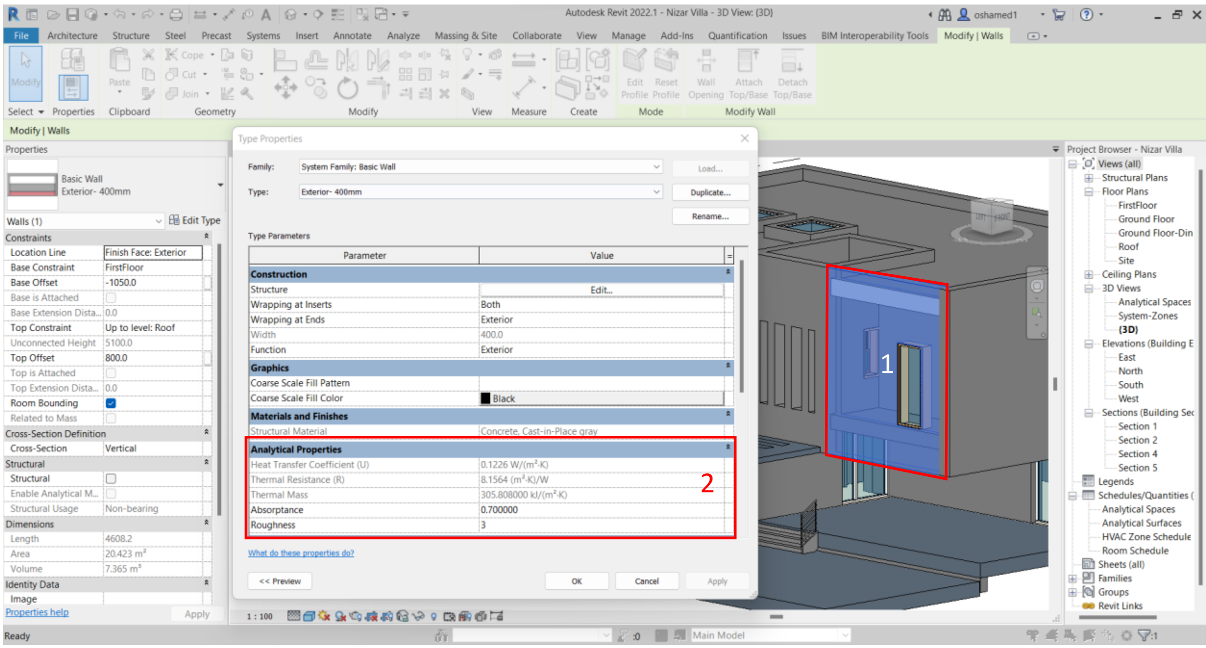


Figure 4-5 Screen shot from BIM authoring tool Revit illustrating the availability of components information

Semi-complex Factors require relatively complex processes and augment different inputs and information despite being available in the digital modelling environment. For example, windows specifications depend highly on the total percentage of window-to-wall ratio (WWR), as seen in Table 25, which describes the Energy Efficiency 5th criterion in the JGBG.

Table 25 An example of semi-complex factors in the Energy Efficiency category in the JGBG.

5th criterion: Fenestration in the Building Envelope		
Mandatory Requirements	1st requirement	if the window-to-wall ratio WWR is 10%-40%, the glass U-value should be less than 3.30 w/m2. k
	2nd requirement	if the window-to-wall ratio WWR is between 40-70%, the glass U-value should be less than 2.00 w/m2. k. if the WWA ratio is more than 70%, U-value should be less than 1.6 w/m2.k

Similarly, the 5th criterion in the Materials and Resources in the JGBG assesses the total percentage of local material use and awards points based on the percentage of extracted, collected, treated or manufactured materials within a specified radius from the project (see Table 26). In this case, the total project materials cost used in the project must be calculated, which involves sorting the local and non-local materials based on their source distance from the project, calculating each sorted list cost, and performing further calculations to assess the percentage of used local materials cost from the total materials cost.

Table 26 An example of semi-complex factors in the Materials and Resources category in the JGBG.

5th criterion: Green Material: B: Local/ Regional Materials		
Voluntary Requirements	1st requirement	Use building materials extracted, collected, treated, or manufactured within a 450 km radius the project centre. Used materials should equal at least 30% of the total materials cost.

Complex factors require complex processes or integration with external tools or data sources. Despite the availability of necessary information in the digital design environment to conduct a particular task, the design software or authoring tool may not be capable of conducting the specified task due to the nature of the task requiring specific simulation engines, such as EnergyPlus (NREL, 2022) for energy simulations, Radiance (Ward, 2022) for daylight simulations, and OpenLCA (GREENDELTA, 2022) for life cycle assessment. For example, Table 27 highlights the 10th criterion of the JGBG's Energy Efficiency category, which requires assessing the energy performance analysis of the project, and Table 28 highlights the 5th criterion of the JGBG's Healthy Indoor Environment, addressing daylight requirements. The methodology adopted in the JGBG to conduct the computer simulation requires comparing the design model performance to a benchmark model characterised by the Jordanian Energy Efficient Code (Awadallah *et al.*, 2009) requirements. These requirements consist of predefined WWR, building envelope characteristics, simulating different orientations, and further information to compare the proposed design performance against the benchmark model performance and, thus, conclude the percentage of energy performance optimisation.

Table 27 An example of complex factors in the Energy Efficiency category in the JGBG.

10th criterion: Computer Simulation		
Voluntary Requirements	1st requirement	Conduct computer simulation for energy performance analysis

Table 28 An example of complex factors in the Healthy Indoor Environment category in the JGBG

5th criterion: Daytime lighting		
Voluntary Requirements	1st requirement	Glazing factor => 2% or achieve a lighting level of more than 270 lux, or Computer Simulation to prove that the lighting level is more than 270 lux.

Most of the required information to conduct energy simulations, such as geometry, internal and external loads, lighting, equipment, occupancy schedules, processes, and materials specifications, can be found in a well-drafted BIM model. Similarly, such models can include the required information to conduct daylighting performance assessments, such as geometry, weather data, and materials specifications. However, the required information must be inputted into a simulation engine to assess the required building performance. Traditionally, this process requires generating different versions of building models, such as the daylight and energy models, which requires significant time and effort and may produce inaccurate simulation results as multiple models may lead to data loss and errors in data management. Hence, the data-rich BIM model can improve the assessment workflow by facilitating integration and interoperability with different performance simulation tools. This issue will be discussed further in Chapter 5.

As highlighted earlier, assessing GBRTs factors can vary significantly regarding difficulties and required processes involving integrating internal and external data sources, building performance simulation programs, and data processing to output the performance result. Figure 4-6 illustrates different workflows that can be adopted to assess different factors based on their automation complexity level, with examples of tools that can be used to facilitate the design and assessment of green buildings. Using suitable tools that facilitate the integration between the design and performance evaluation tools in the early designing stages is necessary to streamline the assessment process and cringe the complexity of factors assessment, information management, and performance evaluation.

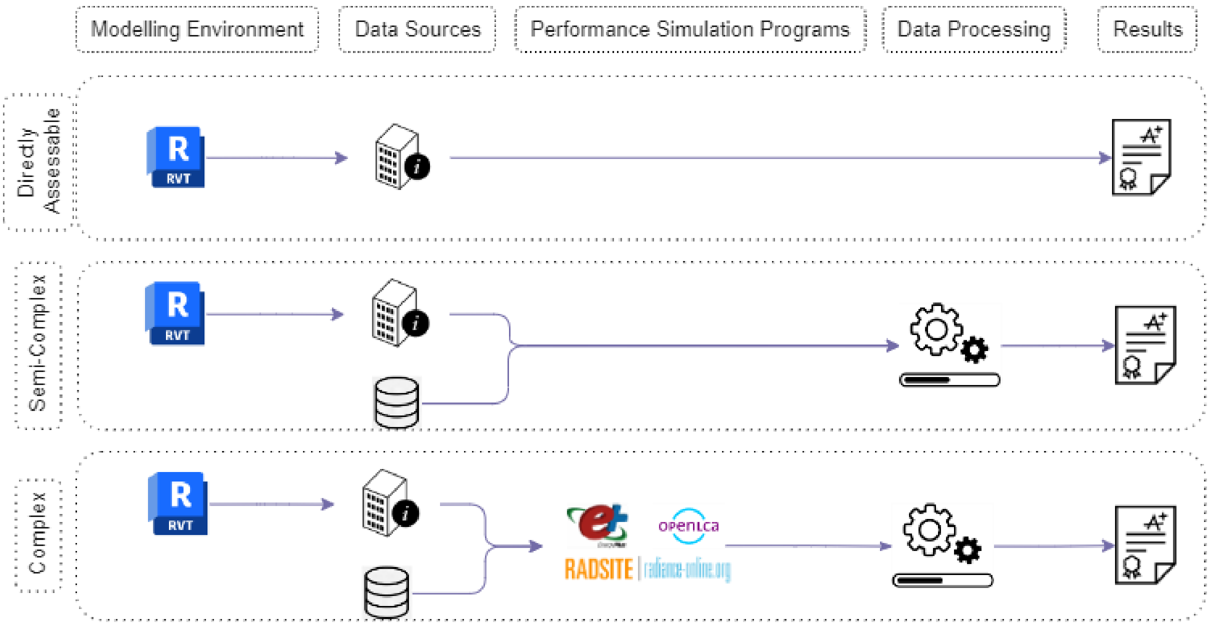


Figure 4-6 Different levels of complexity in evaluating building performance.

4.4 Summary

Green and sustainable construction is often used as synonyms to describe a building designed to mitigate its negative environmental impact. This chapter used a comparative analysis approach to compare different GBRTs to identify what sustainability factors are tackled in each GBRT. Different factors of the compared GBRTs have classified based on their complexity level and readiness for automation to facilitate the sustainability assessment process.

Various GBRTs were developed worldwide to assess and aid in the design and construction of green buildings. Most of these tools address common issues based on regional priorities, such as energy, water, indoor environment quality, site, transport, and materials and resources. However, green building rating tools have since been criticised for different reasons. As highlighted earlier, most of these tools are designed to assess the design stage of buildings, not the operational. Besides, these standards allow buildings to be certified based on intellectual criteria often found easy to meet by the design teams. In addition, green building rating tools aim to reduce the negative impact instead of targeting at least net-zero energy performance.

Five GBRTs were selected and analysed to inform how these tools vary significantly in their structure and tackle sustainability factors. The analysis has introduced a generic structure that hosts GBRTs, highlighting all the measured factors among all the analysed tools. The factors of GBRTs were analysed and re-categorised based on a generic mapping considering the assessed factor instead of the criterion. The analysis helped better understand how each GBRT tackles particular criteria and what factors are assessed. Furthermore, many GBRTS have been developed worldwide, with different versions consisting of several requirements that vary in complexity and the assessment methodology followed from tool to tool. The analysis output highlighted varying processes symbolising different complexity levels for assessment automation.

As discussed earlier, GBRTs assess various factors in different areas. Many assessed factors make a rating system complex and complicate the assessment process, data management and project information tracking. Design teams are often challenged to achieve the sustainability of buildings, as discussed earlier, and this urges the need to develop tools that can facilitate the assessment process, increase productivity, and contribute to delivering green and sustainable buildings effectively and efficiently. In this regard, the recent developments of Computer-Aided Design (CAD) tools have shifted the traditional practice toward new technologies and workflows, such as Building Information Modelling (BIM). Utilising BIM technology from the early design stage of a project can ensure producing a centralised data-rich model that can be used to facilitate enquiring project information for sustainability assessment, offering the opportunity for more effective, time-saving and error-free drawings and much more.

Similar assessment factors were identified among the analyzed rating systems, and their differences were captured within a generic structure. For instance, all the analyzed GBRTs require energy performance assessment, but each tool may slightly vary in assessment methodology and performance targets. This finding underscores the challenge of implementing a fully automated assessment using a generic structure. However, this challenge can be overcome through a flexible approach that empowers users to customize the assessment criteria to suit their needs. Due to the identified challenges, the JGBG was chosen as a proof-of-concept as the primary assessment criteria to develop a BIM-based tool to automate the sustainability assessment. Achieving specific sustainability factors may contradict others, such as optimising daylight and quality views and reducing energy performance. Therefore, it became necessary to integrate the building performance simulation tools with design and modelling environments, to validate all design decisions and achieve a balanced performance among all the tackled factors. In this regard, chapter 2 introduced building performance simulation tools and discussed their capabilities, limitations, and challenges in integration with GBRTs.

Although this chapter adopts the JGBG to be demonstrated in the tool development, this chapter formulates a vital foundation for future research that aims to develop a generic framework that can facilitate the assessment of buildings. Chapter 5 introduces the concept of BIM and discusses the integration between BIM, GBRTs, and BPS tools.

5. Building Information Modelling (BIM) for green building assessment

5.1 Introduction

Sustainability assessment requires various sets of information to carry out performance assessments throughout a project lifecycle. Traditional design tools, such as Autodesk AutoCAD, have been utilised to draft 2d and 3d graphs and annotations about the project design. However, these drafts could not communicate further information about the project, such as the materials' physical and thermal properties and cost. Using traditional tools to produce the required design drawings demands considerable time and effort. Any design feature changes will not automatically update the entire project plans. Therefore, design teams are challenged when preparing design drawings and information sheets due to the complexity of the required information and processes to prepare a final version of the design information. As seen in Chapters 2 and 4, sustainability assessment is very complex due to the massive number of sustainability criteria and the required data to assess the proposed project performance. Therefore, there was a need to adopt a more feasible and flexible approach to overcome the challenges mentioned above.

Building Information Modelling (BIM), as a verb, describes the process of producing data-rich models that integrates the design drawings and all the related information, during the project's lifecycle, from the initial design phases to operation, management, and maintenance. BIM facilitates information exchange through open data schemas, enabling seamless communication between design and building performance simulation programs. Hence, BIM offers excellent capabilities to facilitate the sustainable design of projects by providing data-rich models that can be extracted to provide the necessary information required for GBRTs assessment.

The feasibility of integrating BIM with building performance simulations (BPS) for tasks like building energy modelling (BEM) has been examined in various studies attempting to automate LEED, BREEAM, and other GBRTs assessments. However, integrating BPS and BIM has been challenged by data interoperability between the design and assessment programs and the highly complex set of GBRTs criteria and requirements. Interoperability can be described as the ability to communicate the necessary information between tools to perform specific tasks. Different data schemas were introduced to overcome this challenge, such as Green Building Extensible Markup Language (gbXML) and Industrial Foundation Classes (IFC), each focusing on a specific domain and application. Despite the developments and improvements in BIM platforms and BPS tools, recent studies highlight that the interoperability between BIM and BPS tools still exists (Bahar *et al.*, 2013; Ayman, Alwan and McIntyre, 2019; Raouf and Al-Ghamdi, 2019; Carvalho *et al.*, 2021; Porsani *et al.*, 2021).

This chapter introduces the concept of BIM, its features and capabilities, and its superiority over traditional CAD tools, followed by a discussion about BIM interoperability with BPS tools. It discusses the potential for BIM integration with BPS tools, hence facilitating GBRTs assessment.

5.2 What is BIM?

Autodesk (2019) define BIM as *an intelligent 3D model-based process that gives architecture, engineering, and construction (AEC) professionals the insight and tools to more efficiently plan, design, construct and manage buildings and infrastructure.* Sacks *et al.* (2018) define BIM as a technology for modelling and a set of processes to produce, deliver, and analyse building models. NIBS (2015) describe BIM as *"a digital representation of physical and functional characteristics of a facility. It serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onward."* NBS (2016) describes BIM as creating and managing information on a construction project across its lifecycle.

By offering intelligent capabilities and more interoperability, BIM has shown a fundamental technical advancement over traditional CAD tools (Miettinen and Paavola, 2014). For example, BIM can ensure early, consistent and accurate visualisations of the designed 3D model that facilitate the generation of multiple 2D views with accurate and consistent dimensions. This can significantly reduce the time needed to manually draft needed views and the number of potential errors. In addition, BIM facilitates early collaboration between different design teams (Harris and McCaffer, 2013; Ghaffarianhoseini *et al.*, 2017).

BIM tools can capture comprehensive building information alongside the design process. This includes information such as the building location, attributes of building components and materials, spatial organisation and geometrical information (Ghaffarianhoseini *et al.*, 2017). In turn, these features present the chance for designers to keep maintaining the relationships between building components and their construction-maintenance data (Ghaffarianhoseini *et al.*, 2017) and offer the opportunity to improve project sustainability by improving project sustainability by linking the BIM model with different analysis tools in its early design phase.

One of the superior features of BIM over traditional 2D CAD objects is the concept of parametric BIM objects (Sacks *et al.*, 2018). Parametric BIM objects offer the following benefits:

1. Contain a definition of geometric and related rules and data.
2. Non-redundant geometry integration for consistent data representation.
3. Automatic modification and updates for objects based on their parametric rules.

A change in one object in the building model will directly be updated to the related objects. For example, changing the height or thickness of any wall element will constantly be updated. Moreover, users can add, modify, and export objects attribute for various analysis purposes, such as carbon or cost estimations.

Utilising the capabilities above, BIM can facilitate sustainable project delivery by helping design teams evaluate different design alternatives in the early design phase, and for various purposes, such as structural analysis, energy, daylight, acoustics, the materials' environmental impact, and more. By using BIM tools, designers can also choose suitable material types in earlier designing stages and make decisions related to energy which has an enormous impact on the building life cycle (Jalaei and Jrade, 2014).

One of the most common BIM applications is the performance evaluation and analysis for sustainable projects (Beazley, Heffernan and McCarthy, 2017). Using parametric objects in BIM models allows easier design changes and interoperability between BIM authoring and performance analysis tools. Although various studies focused on integrating BIM with GBRTs to facilitate sustainable project delivery, recent studies highlight that interoperability is still a technical challenge between these tools, which forms a significant barrier to adopting BIM for sustainability assessment (Carvalho *et al.*, 2021; Porsani *et al.*, 2021). The following section discusses the potential of integrating BIM and GBRTs, state of the art in BIM-based sustainability assessment methods, and a discussion about the interoperability with an overview of the most common data schemas for sustainable design.

5.3 Integrating BIM with green building assessment (Green BIM)

BIM can theoretically facilitate building performance evaluation within the highlighted capabilities above by integrating BIM models with BPS tools (Azhar, Brown and Farooqui, 2009). The link between BIM and GBRTs is still in its early stages. In this section, we introduce the concept of Green BIM and review the existing BIM-based methods for sustainability assessments.

Integrating BIM and green building assessment has been defined as "Green BIM" (Lu *et al.*, 2017). Wong and Zhou have further defined green BIM as using BIM models and processes to generate, manage, and coordinate building data during the project lifecycle to enhance and facilitate the accomplishment of sustainability goals (Wong and Zhou, 2015). Building information modelling contains vast information that can potentially be used for more effective sustainable assessment (Biswas, Wang and Krishnamurti, 2013). However, Krygiel and Nies (2008) state that although BIM models offer a rich information set, external data sources are still needed.

The development of Green BIM tools investigates a single model that integrates the design model and the simulation to facilitate analysis and avoid errors in data management (Azhar *et al.*, 2011). It is also possible to use intelligent information models, which enable whole-building energy analysis and performance simulation (McGraw Hill Construction, 2010). As a result, building designers are provided with instant feedback for evaluating the design and can potentially upgrade the performance of the building at an early conceptual stage for the duration of its lifecycle (Motawa and Carter, 2013).

BIM provides an excellent opportunity to assess buildings' sustainability within an iterative design process. For instance, a wealth of information carried by a BIM model can generate the required documents for acquiring LEED credits or alternative rating systems (Biswas, Wang and Krishnamurti, 2006, 2013; Azhar *et al.*, 2011). The feasibility of using various GBRT and BIM for semi-automated evaluation has been illustrated in current research (Wu and Issa, 2012; Jalaei and Jrade, 2015; Ryu and Park, 2016; Sanhudo and Martins, 2018). In these studies, additional information was added for the required sustainability assessment, either by augmenting the existing model or linking to external databases (Biswas, Wang and Krishnamurti, 2013). However, the concept of green BIM has been challenged by many barriers, such as the interoperability and integration between different design and simulation tools, with the various versions of GBRTs available worldwide (Chong, Lee and Wang, 2017; Lu *et al.*, 2017). Therefore, we aim to investigate the feasibility of utilising BIM as a design and authoring tool to facilitate the integration with BPS integration tools and, thus, to better support sustainability assessments in GBRTs.

In the following sections, we overview the most commonly used building performance simulation tools highlighting the adoption barriers for sustainability assessment and reviewing the state-of-the-art solutions in this field.

5.3.1 BIM-based methods for sustainable design support

Various studies have integrated BIM with GBRTs and BPS programs. Twenty-nine studies have investigated proposing different methods to integrate green building rating tools with BIM to examine further the potentials and limitations of current developments of integrating GBRTs with the design and performance simulation programs. Kota *et al.* (2014) and Kim *et al.* (2015) aimed to integrate general sustainability goals without targeting specific green building rating tools. Reinhardt and Matthews (2017) have developed a workflow to automate the local compliance checking process. Solla, Ismail and Yunus (2016) and Seghier *et al.* (2017) have attempted to automate the sustainability assessment of more than one GBRT, focusing on LEED, Beam Plsus, Green Star, and Energy in Green Mark, and Green Re, respectively.

Nevertheless, most of the remaining studies have investigated LEED GBRT integration with BIM for various sustainability factors assessments reflecting its wider adoption worldwide. See Figure 5-1 and Figure 5-2.

Looking at the assessed sustainability targets, site sustainability, materials, water, indoor environment quality, innovation, location and transport, and daylight were all targeted in different studies, while energy was the most category looked at in most GBRTs. This illustrates the efforts made to address the sustainability targets and cut the carbon emissions from the building sector. Besides, the EA category accounts for 33 points in LEED, 18 of which can be achieved by one criterion: Optimise energy performance, reflecting that attempts to address energy are mainly due to its high credit score compared to all other sustainability targets. Sustainable Site (SS), Materials and Resources (MR), in addition to Indoor Environment Quality (IEQ), were found to be the second-most studied assessment criteria.

Table 29 Review of identified approaches to associate BIM with green building design and assessment

No.	Authors	Rating system	Sustainability/GBRT category targets	Research contribution	Programs	Used method	File schema
1	(Kim *et al.*, 2015)	-	Energy	Link BIM with energy modelling.	Revit API, Modelica	BIM plugin	Modelica
2	(Kota *et al.*, 2014)	-	Daylight	Develop a prototype to integrate Revit with daylight simulation tools.	Revit API, Radiance, DAYSIM	BIM plugin	Native BIM model
3	(Azhar *et al.*, 2011)	LEED	Water Efficiency, Energy and Atmosphere, IEQ	Developed a BIM-based tool to automate the calculation and documentation of 17 LEED credits.	Revit, IES-VE	Data exchange	gbXML
4	(Bergonzoni *et al.*, 2016)	LEED	IEQ	Develop a plugin using Visual programming Environment (Dynamo) to automate IEQ P1 and C2 calculations.	Revit, Dynamo, Excel	VPE	Native BIM model
5	(Biswas, Wang and Krishnamurti, 2006)	LEED	Embodied Carbon, Energy	Developed a BIM-based prototype to facilitate LEED calculations, Embodied Carbon, and Energy Analysis	Revit, EnergyPlus	BIM plugin	-
6	(Ilhan and Yaman, 2016)	BREEAM	Materials	Develop an IFC-based green building assessment tool to aid BREEAM's materials category calculations and documentation.	Excel, ArchiCAD, Visual Studio, C#.	BIM plugin + Data exchange	IFC
7	(Jalaei and Jrade, 2014)	LEED	Energy and Atmosphere, Materials and Resources, IEQ	Proposed a tool that integrates BIM, energy analysis and cost-estimating tools with LEED	Revit API, Ecotect, C#, .NET	BIM plugin + Data exchange	gbXML
8	(Nguyen, Toroghi and Jacobs, 2016)	LEED	Sustainable Site	Develop a Revit plugin to automate LEED SS criteria calculations.	Revit API	BIM plugin	-
9	(Reinhardt and Matthews, 2017)	-	Local compliance checking	Develop a Revit plugin using Dynamo to automate compliance checking.	Revit, Dynamo, Excel	VPE	Native BIM model
10	(Sanhudo and Martins, 2018)	LEED	Sustainable Site	Develop a Revit plugin using Dynamo to automate LEED site stormwater runoff calculation.	Revit, Dynamo, Python, Dyno	VPE	Native BIM model
11	(Seghier *et al.*, 2017)	Green Mark, GreenRE	Energy Efficiency	Develop a Revit plugin using Dynamo to automate building envelope design and assessment.	Revit, Dynamo, Excel	VPE	Native BIM model
12	(Shadram and Mukkavaara, 2018)	Near-Zero Energy Building (nZEB)	Embodied & operational energy	Develop a multi-objective optimisation tool to solve the trade-off problem between embodied and operational energy using BIM tools.	Revit, Dynamo, Grasshopper, Slingshot, Archsim, MySQL	VPE	Native BIM model
13	(Solla, Ismail and Yunus, 2016)	LEED, BEAM Plus, Green Star	N/A	Examined the potential of BIM tools to achieve green building rating tools score directly.	-	N/A	-
14	(Wen and Siao, 2017)	Green Building Measure-Taiwan	Energy Efficiency	Develop a BIM-based workflow to extract data from the BIM authoring tool to Excel for GBM assessment.	ArchiCAD, Excel	Data exchange	IFC
15	(Han *et al.*, 2017)	LEED	Sustainable Site	Develop a BIM-based tool to automate selected LEED credit calculations in an early project phase.	Revit API	BIM plugin	IFC
16	(Jalaei and Jrade, 2015)	LEED	Materials and Resources Energy and Atmosphere	Develop a plugin that links Revit with LEED to facilitate LEED scores in selected credits.	Revit API, Google Maps API	BIM plugin	

17	(Jrade and Jalaei, 2013)	LEED	Sustainable Site Energy and Atmosphere Materials and Recourses IEQ Innovation in Design Regional Priority	Develop a tool that integrates BIM with LEED to assess the project LCA. The authors claim that the tool can calculate up to 57 points from the BIM model.	Revit, ATHENA Impact Estimator	Data exchange	ODBC
18	(Wu and Issa, 2012)	LEED	Energy and Atmosphere	The study proposed a Cloud BIM-based solution for LEED automation and calculation using Cloud BIM technology.	BIM servers	Cloud BIM	-
19	(Jalaei, Jalaei and Mohammadi, 2020)	LEED	Location and Transport Sustainable Site Energy and Atmosphere Materials and Recourses IEQ Innovation in Design Regional Priority	Develop a plugin to calculate LEED credits at an early stage. The authors claim that the tool can process almost the entire LEED system.	Data Mining, Machine Learning, Revit, GBRT, Google Maps	BIM plugin + Machine learning	GbXML, IFC, Native BIM model
20	(Akcay and Arditi, 2017)	LEED	Energy and Atmosphere	Integrating BIM with energy analysis programs with a tool can help optimise design decisions while reducing cost.	Revit, Sefaira, Excel	N/A	-
21	(Alwan, Greenwood and Gledson, 2015)	LEED	Energy and Atmosphere IEQ	Developed a rapid-LEED assessment tool that can calculate up to 14 LEED credits	Revit, IES-VE, VASARI	Data Exchange	GbXML
22	(Biswas and Krishnamurti, 2012)	LEED	Sustainable Site	Develop a prototype to automate the assessment and generation of LEED documents.	Revit, BIM server	Data exchange	IFC COBIE
23	(Chen and Nguyen, 2017)	LEED	Location and Transportation	Develop a plugin to integrate LEED SS assessment with BIM authoring tool Revit.	Revit API, Google Maps API	BIM plugin	Native BIM model
24	(Nguyen, Shehab and Gao, 2010)	LEED	N/A	Developed a framework to extract data from the BIM model for LEED assessment and documentation	Revit API	BIM plugin	-
25	(Raffee *et al.*, 2016)	Green Building Index (Malaysia)	N/A	Develop a prototype to extract sustainability information from BIM tools for Green Building Index assessment and documentation.	Revit API	BIM plugin	IFC
26	(Wong and Kuan, 2014)	BEAM Plus (Hong Kong)	Site, Materials, Energy Use, Water	Develop BIM-BEAM Plus workflow to integrate BIM with green building assessment. The authors claim that the workflow can automate up to 26 credits of calculation and documentation.	Revit, Revit Schedules	N/A	-
27	(Wu and Issa, 2011)	LEED	N/A	Propose a web-based workflow to integrate BIM with LEED for sustainable project assessment and documentation.	Revit,	Data exchange	ODBC IFC
28	(Zhang and Chen, 2015)	LEED	N/A	Propose a rule-based system to conduct project life cycle assessment during different phases.	Revit API, C#.NET	BIM plugin	-
29	(Hamed and Wang, 2019)	Passivhaus	-	Develop a VPE approach to automate data extraction from Revit to PHPP spreadsheets.	Revit, Dynamo	VPE	Native BIM model

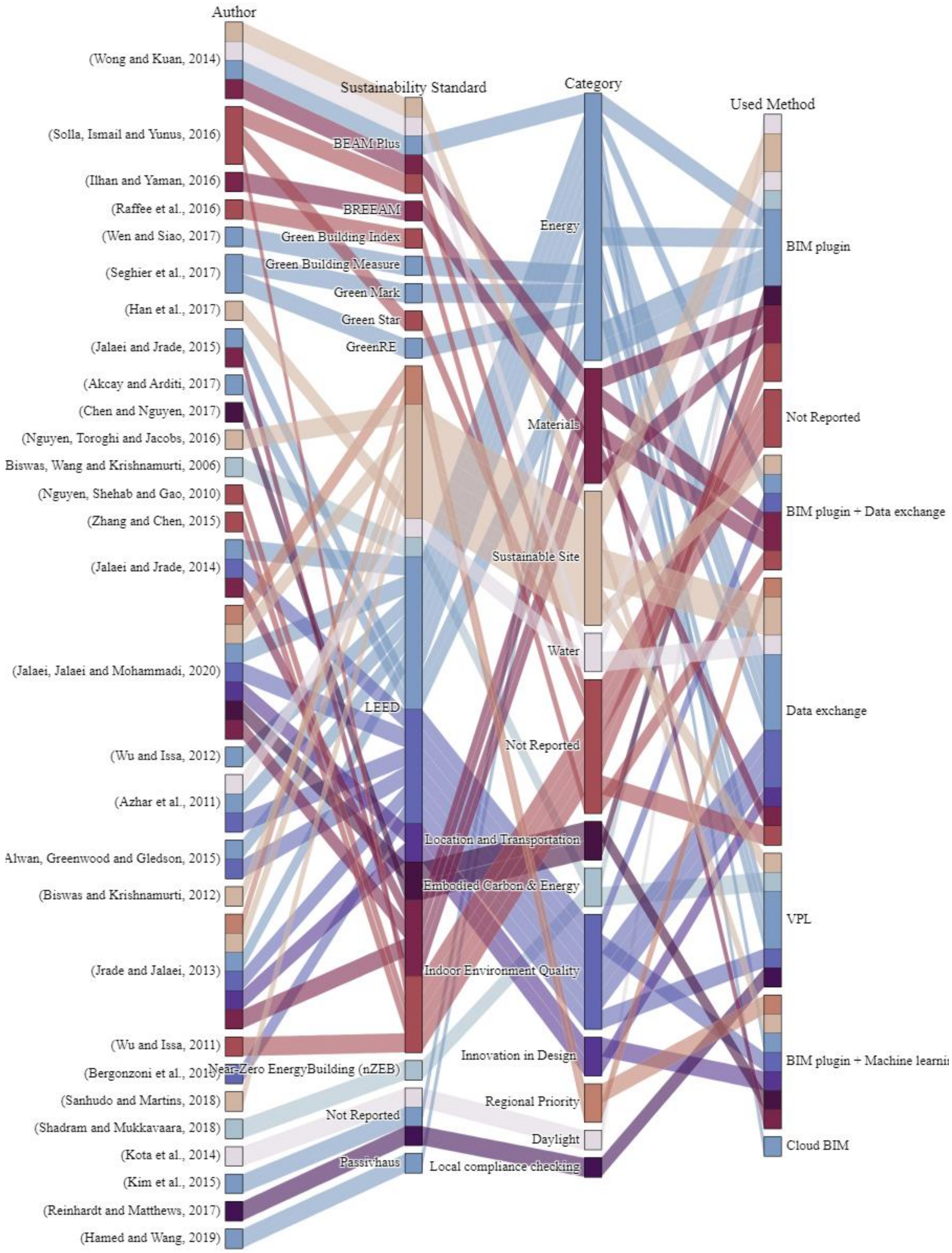


Figure 5-1 representation of targeted GBRTs and major categories associated with BIM

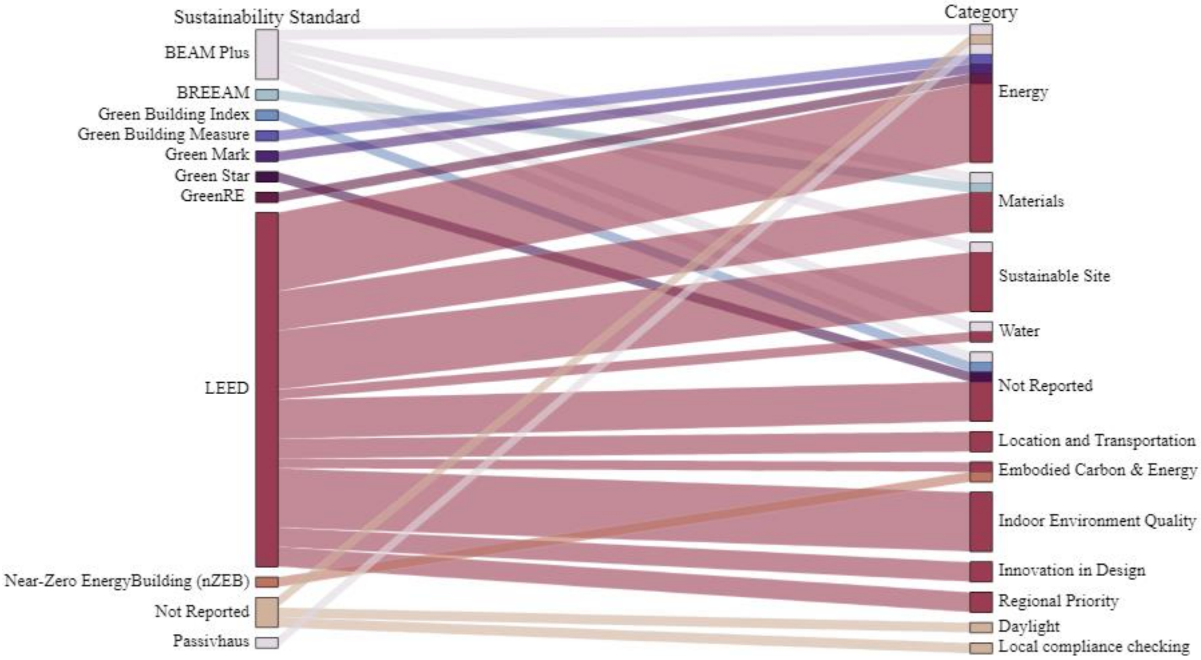


Figure 5-2 Targeted GBRTs and factors

Among these studies, only Jrade and Jalaei (2013) and Jalaei, Jalaei and Mohammadi (2020) investigated the feasibility of integrating all LEED categories with BIM. Jalaei, Jalaei and Mohammadi (2020) introduced a new approach to calculating and predicting the whole LEED system using BIM-based plugins using data mining to predict the credit score in the absence of the project information. Figure 5-2 represents the most targeted GBRT alongside the targeted category.

The review also highlights that different approaches have been used to automate the green building assessment process using BIM technologies (see Figure 5-3). Visual Programming Environments (VPE), such as Dynamo for Revit and Grasshopper for Rhino, are tools that help design teams use a node-based environment with a user-friendly graphical user interface to customise functions for task automation. VPE works directly inside BIM tools, such as Dynamo, allowing easy manipulation and customised workflows to be created using visual or script nodes. VPE plugins can be developed to automate different tasks and performance calculations.

Furthermore, these tools inherit parametric capabilities, allowing for manipulating different project scenarios and design features. Hamed and Wang (2019) have developed a VPE plugin approach to automate energy model generation and data extraction between Revit and Passive House Planning Package (PHPP) for Passivhaus certification assessment. Reinhardt and Matthews (2017) have also developed a VPE plugin to automate local code-compliance checking through BIM environments. Typically, VPE approaches depend on the native BIM model as the data and processing source and lack interoperability capabilities with other performance simulation engines.

The concept of Cloud BIM is one of the uncommon methods for automating sustainability assessment. Wu and Issa (2012) have considered this green building assessment technique by using the BIM server to process the BIM model information and automate the LEED assessment process. Tang *et al.* (2019) have conducted a comprehensive review of the application of cloud BIM in building sustainability assessments. Tang concluded that cloud BIM is mainly oriented toward certain domains, such as Facility Management, Construction Logistics and Management, and Construction operation and Monitoring. This highlights that such a method can be powerful when assessing construction and operational projects' lifecycle.

Using an Application Programming Interface (API) to develop BIM plugins was noted as the most adopted approach in this study. Autodesk Revit's API is a powerful tool often used to develop new workflows and extend application functionalities by collecting, extracting, processing and exporting model information between tools. Jalaei, Jalaei and Mohammadi (2020) have developed a Revit plugin that integrates the native BIM model with machine learning to automate LEED sustainability assessment. Han *et al.* (2017) have also developed a Revit plugin to automate LEED's Sustainable Site assessment. Despite the various benefits of such an approach, one of the shortcomings of following this approach is the dependency on proprietary software. If a plugin was developed for Revit, it could only work with Revit. Therefore, other studies have integrated this method with different data exchange schemas, such as IFC, gbXML, and ODBC, to export and augment the necessary information for sustainability assessment to different simulation tools, such as openstudio, Ecotect and IES-VE.

Most BIM authoring tools can produce data exchange files that support open data schemas. Data exchange methods extract the BIM model information for various applications. For example, Ilhan and Yaman (2016) have developed an IFC-based approach to automate BREEAM's Materials assessment, and Biswas and Krishnamurti (2012) developed an IFC-based approach to automate LEED's Sustainable Site assessment. Azhar *et al.* (2011) have developed a gbXML-based approach to automate LEED's Water efficiency, Indoor Environment Quality, and Energy and Atmosphere assessment. Alwan, Greenwood and Gledson (2015) developed a gbXML-based approach to rapidly assess LEED's Indoor Environment Quality and Energy and Atmosphere criteria. As highlighted earlier, both gbXML and IFC data schemas can support certain domains of the project, and therefore, using one of these schemas solely can only facilitate limited sustainability assessment targets. In this regard, Jalaei, Jalaei and Mohammadi (2020) have developed an integrated solution that utilises gbXML to represent the project's energy, daylight, and indoor environment quality models IFC for materials and other criteria, attempting to cover most of the LEED criteria.

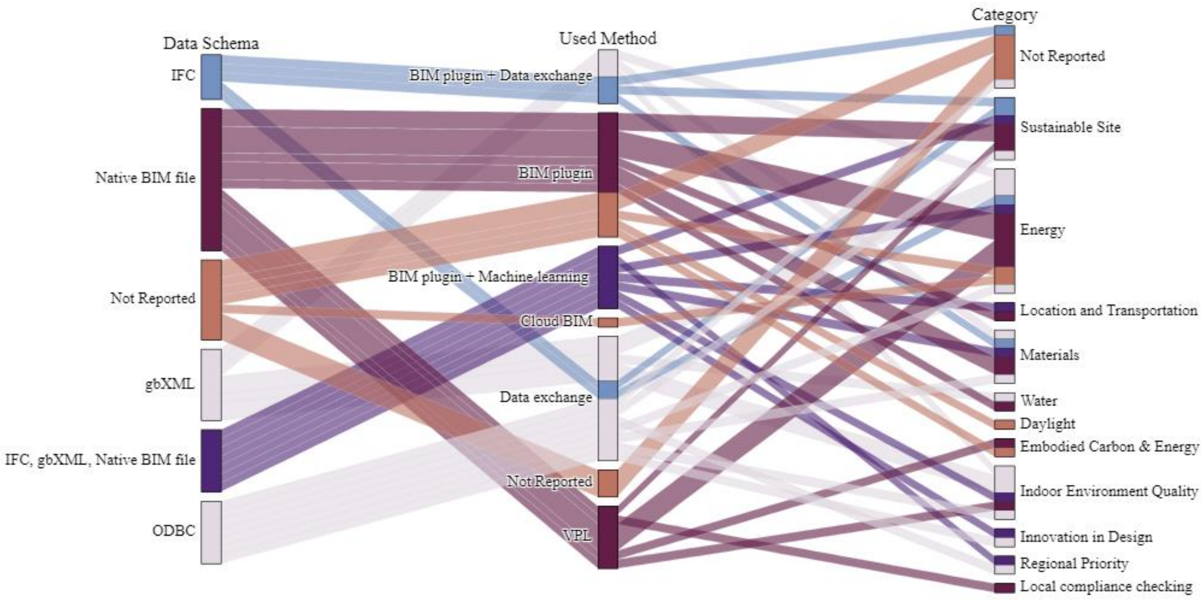


Figure 5-3 Identified approaches to integrate BIM with green buildings

Based on this, it can be concluded that sustainability assessment is a process partially addressed using various approaches, each with specific limitations and capabilities. Among these approaches, BIM data schema tools are often used to automate building performance simulation model generation. While we aim to facilitate the assessment of Energy, Daylight, and Materials criteria from the JGBG rating system, Autodesk Revit will be used as a BIM authoring tool to generate and export BIM models to the proposed BIM-based toolkit to automate the assessment of selected criteria from the JGBG as one of the GBRTs.

Integrating building performance simulation tools, such as the Ladybug toolkit and BIM authoring tools, can be addressed using open data schemas, such as IFC and gbXML. This integration can facilitate information exchange and performance simulation model generation. Hence, facilitating GBRTs sustainability assessment. The next section of this chapter discusses the interoperability of BIM and BPS tools to facilitate GBRTs assessment.

5.4 BIM for Information Exchange

As discussed earlier, sustainability assessment is a complex process requiring different tools to generate, design, model, and prepare the project's information and finally prepare for the assessment process. BIM platforms can support integrating different domains. For example, (1) architectural elements in the project represent the architectural BIM model, (2) structural elements and behaviour represent the structural BIM model, and (3) mechanical and electrical components represent the MEP BIM model. The coordination between these models can produce a centralised BIM model, which all the design teams can work on simultaneously and interoperably.

Interoperability can be defined as the ability to exchange data between two different software programs or systems. Seamless data exchange between different software tools is essential to eliminate the need for manual data entry reproduction, which is time-consuming and prone to errors. As such, the ability to exchange data interoperably is preferred. Autodesk Revit is a widely adopted BIM platform that facilitates project coordination and interoperability between different design domains within a centralised BIM model. However, automating data exchange effectively and meaningfully between BIM authoring tools and external performance simulation programs remains a critical challenge due to increasingly available model formats and categorisations. Further research is required to afford a fluid data exchange flow through which the information change in one program should be simultaneously propagated to the other without extra effort (Kumar, 2008).

Interoperability is considered a critical challenge in the architecture, engineering, construction (AEC), and facility management (FM) industry (Bahar *et al.*, 2013; Ayman, Alwan and McIntyre, 2019; Raouf and Al-Ghamdi, 2019; Carvalho *et al.*, 2021; Porsani *et al.*, 2021).

Different tools and methods are considered throughout the design, construction, and operation stages for green building assessment. GBRTs require assessing building performance on different factors, as highlighted in Chapter 4, including energy performance, daylight, thermal comfort, and more. However, BIM authoring tools, such as Revit, require additional plugins to communicate with external applications, hence, integration with other software and programs that carry capabilities to perform the required task. Therefore, open data schemas were introduced to guarantee seamless integration between different tools. Using open data standards to communicate building information can facilitate consistent information interoperation throughout the building lifecycle.

Industry Foundation Class (IFC) and Green Building Extensible Markup Language (gbXML) are considered the most common and developed formats used to export data from BIM applications (Dong *et al.*, 2007; Bahar *et al.*, 2013; Motawa and Carter, 2013; Biswas, 2015; Farzaneh, Monfet and Forgues, 2019; Kamel and Ali M. Memari, 2019). These data exchange standards were introduced to facilitate consistent data exchange for different BIM applications, such as assessing building operational energy use, daylight analysis, and facility management (Dong *et al.*, 2007; Motawa and Carter, 2013). IFC represents the entire project information by adopting a comprehensive and generic approach that covers different domains from building construction to operation. On the other hand, gbXML is only supporting energy and daylight simulation. The following sections will introduce IFC and gbXML data schemas, highlighting their key features and differences.

5.4.1 Industrial Foundation Classes (IFC)

Industry Foundation Classes (IFC) is an open data standard to exchange, describe and share construction and facilities management information. It describes how a hierarchical data structure represents civil structures and buildings. It includes physical components, mechanical and electrical systems, energy analysis models, work schedules, manufactured products, and structural analysis models. IFC allows sharing of all the information between all participants, regardless of using different software throughout any project lifecycle. At the moment, more than 150 software applications support IFC. IFC data can be managed in databases, imported/exported files, and transmitted over web services. It can be encoded in different formats, such as JSON, STEP, and XML (NBS, 2019; buildingSmart, 2022).

The latest version of the IFC data schema is IFC 4, which was released and became ISO certified in 2013, and since, IFC 4 data schema has received multiple updates. The IFC4 data schema architecture is divided into four layers, as seen in Figure 5-4. The Domain Layer consists of a domain-specific data schema. Other layers cannot reference entities defined in the domain layer as these entities are self-contained. The Interoperability layer (shared elements data schema) consists of entities that can be referenced and specialised above in the hierarchy and provides more specialised objects and relationships shared by multiple domains. The core layer, consisting of the IFCKernel schema, defines the most abstract part of the specification. It specifies the fundamental relationships and attributes, such as a product's relative location in space. In addition, the core layer consists of a Product Extension to represent the concepts of a physical product, a Process Extension which captures ideas about mapping processes in a logical sequence, and a Control Extension schema to declare basic classes for control objects and assignments. The Resource Layer consists of supporting data structures that only exist if referenced by other entities.

IFC describes how individual components are connected, how they interact with other components,

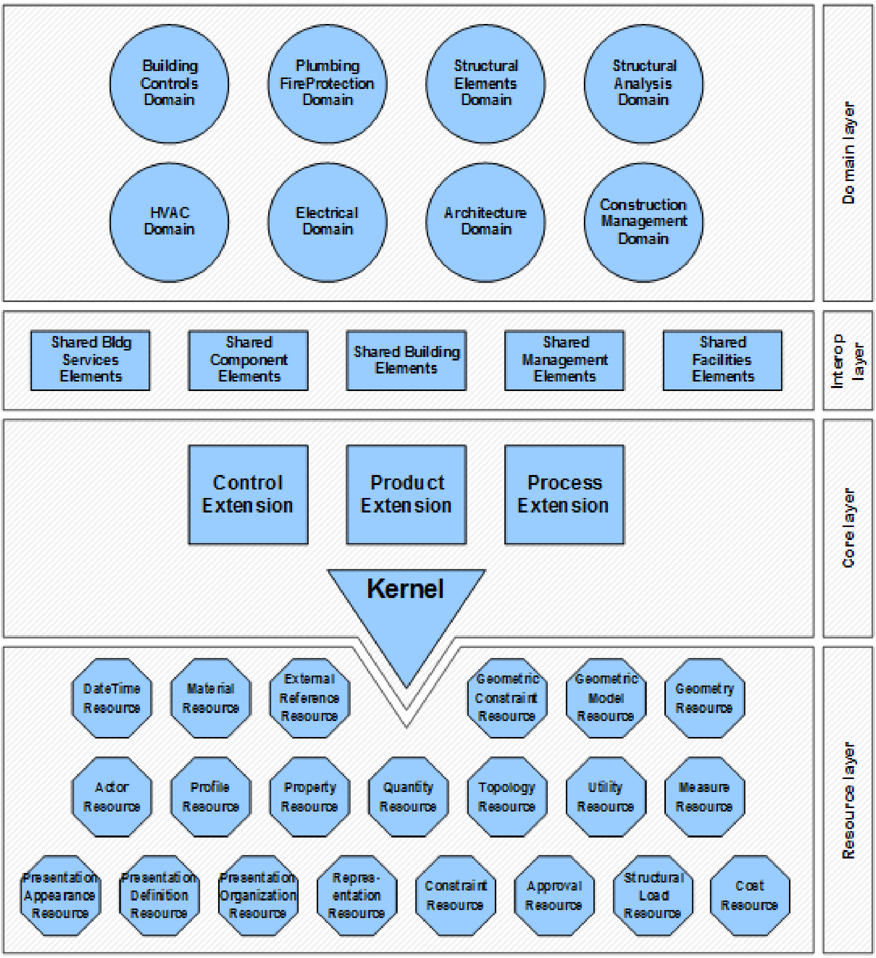
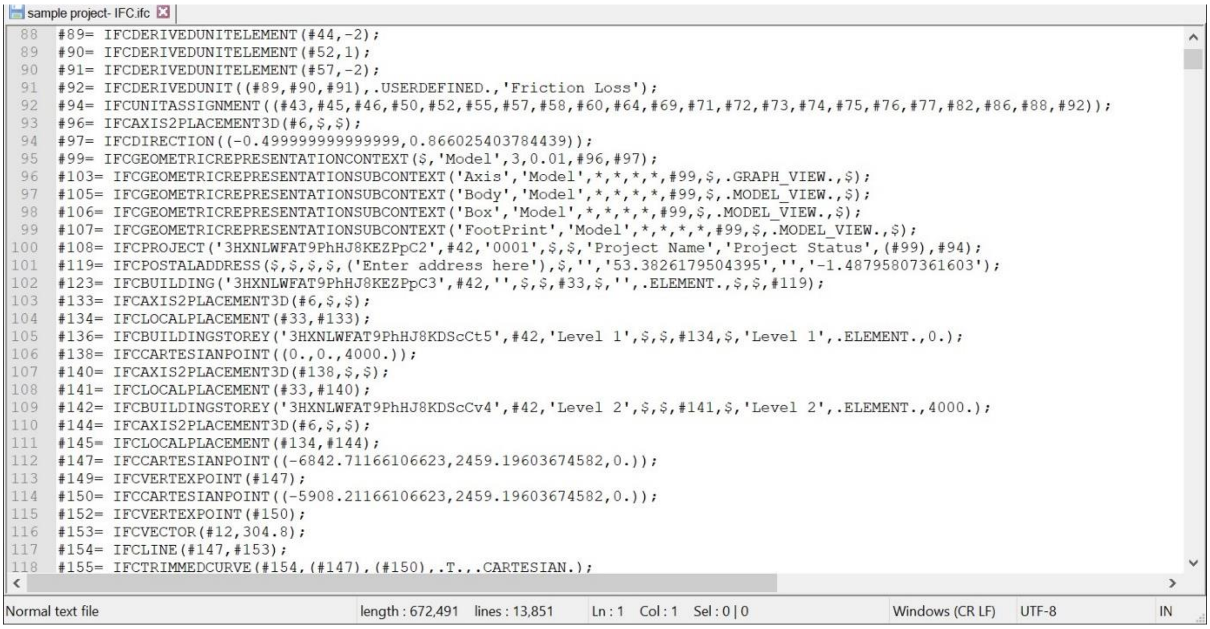


Figure 5-4 IFC data schema architecture. Source: (buildingSMART, 2022)

how they enclose the space, how they are embedded, and much more. Additional information not defined in IFC can be augmented by defining custom attributes for uncategorised objects, customised geometries, references to external libraries, and document attachments (buildingSmart, 2022). However, this highlights interoperability as an issue in green BIM between design and simulation tools. Figure 5-5 shows a sample of the IFC data schema in a textual (STEP) format.




```
#89= IFCDERIVEDUNITELEMENT(#44,-2);
#90= IFCDERIVEDUNITELEMENT(#52,1);
#91= IFCDERIVEDUNITELEMENT(#57,-2);
#92= IFCDERIVEDUNIT((#89,#90,#91),.USERDEFINED.,'Friction Loss');
#94= IFCUNITASSIGNMENT((#43,#45,#46,#50,#52,#55,#57,#58,#60,#64,#69,#71,#72,#73,#74,#75,#76,#77,#82,#86,#88,#92));
#96= IFCAXIS2PLACEMENT3D(#6,$,$);
#97= IFCDIRECTION((-0.499999999999999,0.866025403784439));
#99= IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,0.01,#96,#97);
#103= IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Axis','Model',*,*,*,*,#99,$,.GRAPH_VIEW.,$);
#105= IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Body','Model',*,*,*,*,#99,$,.MODEL_VIEW.,$);
#106= IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Box','Model',*,*,*,*,#99,$,.MODEL_VIEW.,$);
#107= IFCGEOMETRICREPRESENTATIONSUBCONTEXT('FootPrint','Model',*,*,*,*,#99,$,.MODEL_VIEW.,$);
#108= IFCPROJECT('3HXNLWFAT9PhHJ8KEZPpC2',#42,'0001',$,$,'Project Name','Project Status',(#99),#94);
#119= IFCPOSTALADDRESS($,$,$,$,('Enter address here'),$,'','53.3826179504395','','-1.48795807361603');
#123= IFCBUILDING('3HXNLWFAT9PhHJ8KEZPpC3',#42,'',$,$,#33,$,'',.ELEMENT.,$,$,#119);
#133= IFCAXIS2PLACEMENT3D(#6,$,$);
#134= IFCLOCALPLACEMENT(#33,#133);
#136= IFCBUILDINGSTOREY('3HXNLWFAT9PhHJ8KDScCt5',#42,'Level 1',$,$,#134,$,'Level 1',.ELEMENT.,0.);
#138= IFCCARTESIANPOINT((0.,0.,4000.));
#140= IFCAXIS2PLACEMENT3D(#138,$,$);
#141= IFCLOCALPLACEMENT(#33,#140);
#142= IFCBUILDINGSTOREY('3HXNLWFAT9PhHJ8KDScCv4',#42,'Level 2',$,$,#141,$,'Level 2',.ELEMENT.,4000.);
#144= IFCAXIS2PLACEMENT3D(#6,$,$);
#145= IFCLOCALPLACEMENT(#134,#144);
#147= IFCCARTESIANPOINT((-6842.71166106623,2459.19603674582,0.));
#149= IFCVERTEXPOINT(#147);
#150= IFCCARTESIANPOINT((-5908.21166106623,2459.19603674582,0.));
#152= IFCVERTEXPOINT(#150);
#153= IFCVECTOR(#12,304.8);
#154= IFCLINE(#147,#153);
#155= IFCTRIMMEDCURVE(#154,(#147),(#150),.T.,.CARTESIAN.);
```


Figure 5-5 Sample of IFC data schema

IFC data schema has been used in different approaches to automating the sustainability assessment of buildings, as highlighted in section 5.3.1. Zhang and Issa (2014) highlight that although the IFC data schema was designed to store and exchange all the building information throughout its lifecycle, the schema is far too complex for use, even for experienced developers.

The use of IFC schema as an input for building performance simulation tools is not straightforward and, thus, is identified as one of the challenges to adopting IFC for BPS tools (Katsigarakis *et al.*, 2019). Nevertheless, studies suggest that the exported IFC file's quality is far from perfect for BPS programs, despite its wide adoption and support from different BIM platforms. The identified gaps regarding IFC compatibility with BPS tools and the complexity and experience required to prepare and create necessary BIM models, tools or plugins, IFC data schema cannot be considered for GBRTs criteria analysis, especially for workflows that aim to integrate performance simulation criteria with BPS tools.

5.4.2 Green Building XML

The Green Building XML (gbXML) schema was introduced by Green Building Studio in 2000 (GbXML, 2019) to facilitate data interoperation between engineering analysis software and building design tools. It aims to help engineers, architects, and energy modellers design better energy-efficient buildings (GbXML, 2019). The industry and leading BIM vendors such as Graphisoft, Trimble, Bentley, and Autodesk support and adopt gbXML. With a developed import and export capability in more than 50 modelling analysis and engineering tools, gbXML has become an actual industry-standard schema. Using gbXML can organise building information transfer between engineering and architectural models, eliminating the time-consuming take-off plans, thus removing a significant cost barrier to designing energy-efficient and sustainable buildings. (GbXML, 2019). Figure 5-7 shows a sample of the gbXML data schema in a textual (XML) format.

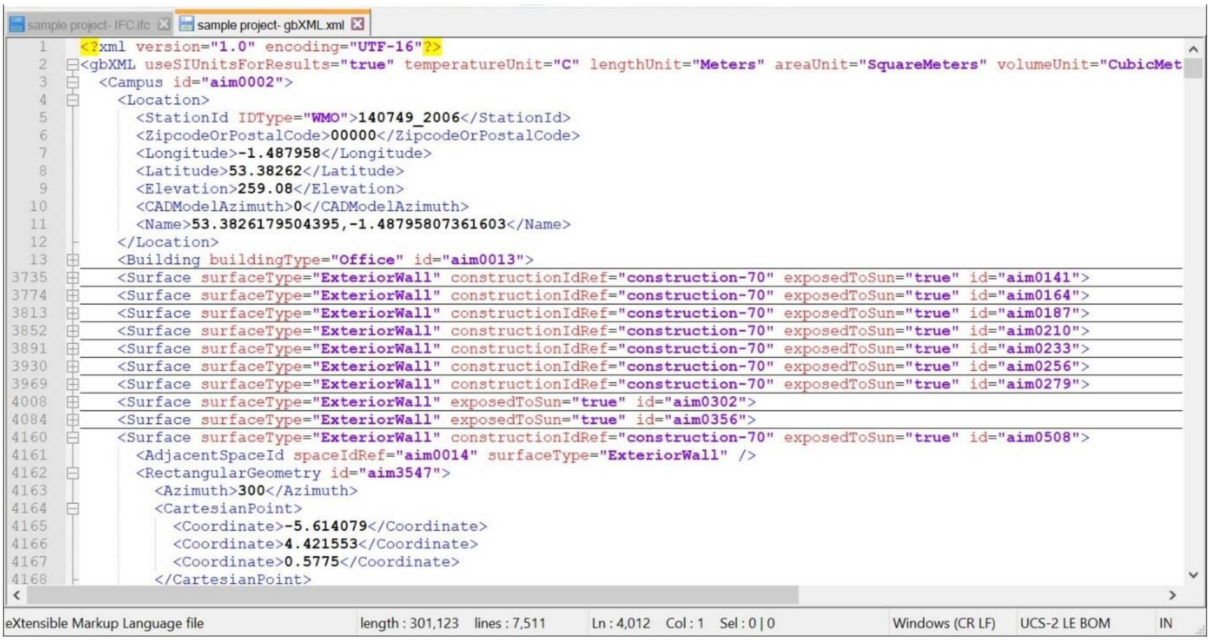


Figure 5-7 Sample of gbXML data schema

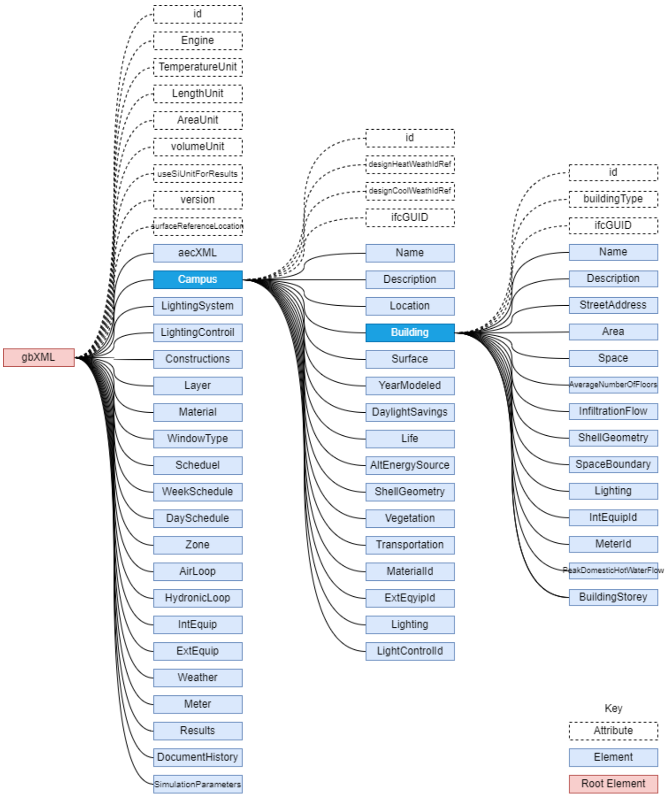


Figure 5-6 Sample of the gbXML schema heirarchial structure

The gbXML schema consists of the root element (gbXML) and a set of sub-elements and attributes, as represented in Figure 5-6, which makes it easily readable and user-friendly. The gbXML schema comprises over 500 elements and attributes that provide comprehensive building descriptions. As identified in section 5.3.1, the gbXML schema was adopted in different studies for energy, thermal comfort, daylight, and materials performance simulations, highlighting its efficiency in resolving the interoperability issues between BIM authoring tools and BPS software.

Both gbXML (GbXML, 2019) and IFC (buildingSmart, 2022) are the leading and most common informational infrastructures in the industry field. IFC aims to provide a global base for information sharing and process development in facility management and construction sectors. GbXML was developed by green building studio to support and facilitate the informational exchange between CAD and energy performance software (Dong *et al.*, 2007). While IFC represents the entire project information by adopting a comprehensive approach covering different domains from building construction to operation, gbXML only supports the energy and daylight simulation domain. In addition, IFC is a well-organised but more complex data schema that represents large data files and uses a top-down data representation approach.

In contrast, gbXML uses a straightforward, more flexible bottom-up approach (Bahar *et al.*, 2013). For the demonstration, Table 30 highlights the main differences between IFC and gbXML (Dong *et al.*, 2007; Bahar *et al.*, 2013; Ivanova, Kiesel and Mahdavi, 2015; Kamel and Ali M Memari, 2019). While gbXML is optimised for energy simulation, IFC can be used to cover and represent more information about the project in different stages. The following section discusses the shortcomings and opportunities regarding integrating BPS and BIM authoring tools to support GBRTs assessment through IFC and gbXML schemas.

Table 30 The main differences between IFC and gbXML

	IFC	**gbXML**
Data representation	Comprehensive representation through different project phases	It mainly supports energy simulation
Geometry representation	Any Shape (free-form, i.e. curves)	Only planner shapes
Data representation approach	Top-down	Bottom-up
Data representation complexity	Complex	Relatively straightforward
Schema flexibility	Less flexible than gbXML	More flexible than IFC
Support among performance simulation tools	Widely supported	Widely supported
"Thermal zone" definition capability	Yes	yes
HVAC information	Limited	limited

5.4.3 Interoperability with BPS tools.

As discussed earlier in this chapter, IFC and gbXML were adopted in different workflows to support building sustainability assessments. Section 5.3.1 highlighted that different workflows were adopted to perform different building performance evaluations. GBRTs, as highlighted in section 4.2, consist of many factors that tackle different sustainability issues. In addition, section 4.3 highlighted that these factors vary in complexity, requiring various forms of processing and integration with different BPS tools and external data sources. In this regard, section 2.4 has reviewed the existing integration between BPS tools and GBRTs, highlighting that software vendors tackle a minimal number of factors in a minimal number of GBRTs. For the scope of this research, the JGBG's specific criteria from the Energy, Healthy Living Environment, and Materials and Resources categories were chosen to illustrate the development of the proposed tool to automate the assessment process. These criteria highly depend on the BPS tools and external data sources to conduct energy and daylight simulations and materials performance calculations and will be further illustrated in Chapter 7. Hence, the integration between BPS tools and open data schemas is discussed below.

BPS tools can accept different input file types directly, as in the case of gbXML in OpenStudio, and indirectly, in the case of IFC, where the BIMSERVER is required to process the IFC file into the OpenStudio model (.OSM). This integration can facilitate building performance assessment by allowing data-rich models generated from BIM environments to integrate with BPS tools easily.

Different studies have explored the feasibility of using IFC and gbXML as input files for BPS tools. Ivanova, Kiesel and Mahdavi (2015) have compared IFC and gbXML data schemas' performance to produce a valid geometry for BPS tools by testing ten different scenarios, modelled and exported using Autodesk Revit and Graphisoft ArchiCAD. The study suggests that both IFC and gbXML require pre-processing building energy modelling (BEM) model to investigate the exported model's geometry integrity and assign missing information to complete the desired BPS successfully. Furthermore, it is concluded that the quality of any building model is highly dependent on the generated model from any BIM authoring tool. Similarly, Porsani *et al.* (2021) have evaluated the utilisation of IFC and gbXML in an automated or semi-automated workflow to support the BIM-to-building energy modelling (BEM) workflow. The study has tested two case studies that vary in complexity levels, modelled in Autodesk Revit and exported as IFC and gbXML for energy simulation programs. The study concluded that although a semi-automated workflow between BIM and BEM exists, errors in data transfer and translations still exist. Furthermore, the project's complexity can be a significant drawback in exporting a valid BIM model for performance analysis.

As discussed in sections 5.4.1 and 5.4.2, integrating gbXML with BPS tools is more feasible than the IFC schema due to its complexity and the limited support from BPS tools compared to the gbXML, as highlighted in Table 11. Only a few studies have attempted to develop IFC-to-BEM conversion tools. Space Boundary Tool (SBT-1) was first developed by (Rose and Bazjanac, 2013) to convert IFC files to valid IDF files. However, since its launch in 2014, SPT-1 has not received any updates or further development, and therefore, the current version can only support the IFC2x3 schema. Although the SPT-1 can calculate the space boundaries and convert the geometry into valid IDF data, it does not convert the physical materials' properties from the original IFC file. Instead, the tool remaps the materials from another IDF file. Visschers (2016) has also developed an algorithm to convert the IFC files into a gbXML format to support a BIM-based whole-building energy analysis. Like the SBT-1, the algorithm can only support the IFC2x3 schema. Nevertheless, such algorithms can facilitate data interoperability between different BPS and evaluation tools.

Based on this, a successful BIM-to-BPS workflow depends on the generated BIM model and export settings in the first instance. It is also highlighted that errors regarding missing models' geometrical and non-geometrical information can significantly impact the model performance and, in some cases, may not guarantee a valid energy model to perform the simulation. While many BPS programs highly depend on default values, it will result in inaccurate simulation results if used to replace necessary information (i.e., construction sets and U-value of building components). This highlights that inspecting the exported BIM model, whether an IFC or gbXML, is highly recommended before being used as a BPS input model. In this regard, Kamel and Ali M. Memari (2019) have developed a middleware tool to automatically check and fix the exported gbXML file from a BIM tool to reduce the efforts in pre-processing the gbXML file inside the BPS tools.

As discussed earlier, the gbXML schema is reported by different researchers as superior to the IFC to integrate with BPS tools to assess the selected GBRTs criteria and, therefore, will be adopted in this research as the base of the BIM-based sustainability assessment tool.

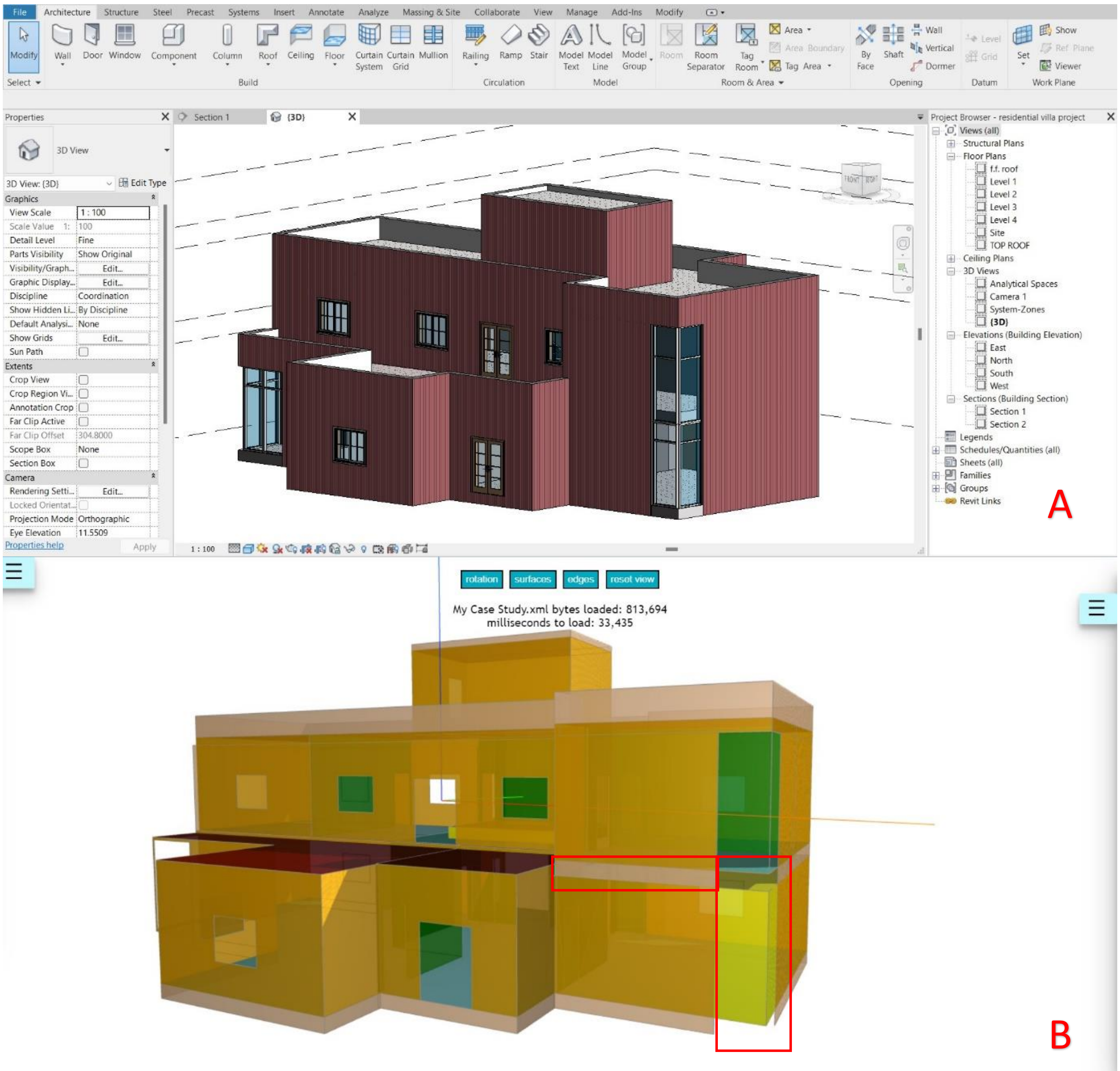
5.5 Supported information from Revit to exchange using gbXML

Interoperability between tools can be achieved once they can exchange all the required data from the design to the assessment tool to perform specific tasks, such as assessing the sustainability of a building. The available information from the source (design) tool required to be exchanged with the target (assessment) tool depends on the task's nature. For example, assessing the energy performance of a building requires transferring its geometry, location, weather data, materials' physical and thermal properties, loads, operations schedules, and more.

Autodesk Revit is one of the BIM authoring tools that can generate gbXML models, which carries necessary information that can be used as input files in BPS tools. Based on the gbXML schema documentation (GbXML, 2017), the schema can transfer more than 500 building elements and attributes that target energy and daylight simulations. However, technical challenges arise when exporting the gbXML models from the BIM authoring tools, which affect the quality and abundance of the generated gbXML data.

Although the developers of the gbXML schema provide an online validation tool that software developers can use to validate their exported gbXML files, only the OpenStudio (NREL, 2019) software has passed the validation and is officially verified as building analysis software. No BIM authoring tool has passed the validation requirements (GbXML, 2017).

It has been noted that, in many cases, it is challenging to export clean analytical models using Autodesk Revit. See Figure 5-8, which demonstrates an example of an exported gbXML model from Revit. In this example, wrong surface attributes were assigned to the highlighted parts of the model. Furthermore,



the exported spaces were not fully enclosed, meaning that the model could fail or produce inaccurate

Figure 5-8 Screenshots for a detached residential villa (A) in Revit modellig environment, (B) in a web-based gbXML viewer.

results in the energy and daylight simulations, in addition to giving false materials-related estimations such as cost, quantity take-off, and embodied energy.

Although the latest gbXML schema v 6.01 was published in 2017, Autodesk's website states that Revit currently supports exporting gbXML models based on the v 0.37 of the schema (Autodesk, 2022). Furthermore, only a limited number of building elements can be exported from Autodesk Revit using the gbXML schema. See Table 31 for an overview of what gbXML elements can be exported using Revit.

Table 31 Supported gbXML elements in Revit.

Supported gbXML Elements by Revit
Campus, LightingSystem, Construction, Layer, Material, Window Type, Schedule, WeekSchedule, DaySchedule, Zone, DocumentHistory, Location, Building, Space, Lighting, ShellGeometry, SpaceBoundary, Surface, Opening.

Although BIM models can be described as data-rich models, not all the available information in a BIM model authored in Revit can be exported using gbXML. For the demonstration, the required information for the materials' project assessment based on the JGBG was analysed in Table 32. For a comprehensive overview, Appendix C consists of the analysis of the required project information for Jordan's Green Building Guide (JGBG) assessment, gbXML schema support for such information, and whether it can be exported from the BIM authoring tool "Revit" in a gbXML format.

The analysis highlights that although the gbXML data schema seems comprehensive, only a few elements can transfer the required information. Such issues are justified by the limitation of the BIM authoring tool of utilising the full capabilities of BIM data schema. This information was then mapped with the information that can be exported using Autodesk Revit and the gbXML data schema. Only a limited number of and the project attributes are included when exporting using gbXML from Autodesk Revit BIM authoring tool.

Such limitations can formulate obstacles for workflows that implement the gbXML data schema to support the sustainability assessment of buildings. The previous example concluded that materials' attributes, such as *Solar Reflectance Coefficient, Roughness,* and *Transmittance*, can be found in native Revit models. The gbXML data schema can also host the attributes as sub-elements for the Material element. However, this information cannot be exported using the built-in Revit gbXML exporter. Other information, such as the *origin* and *renewable* attributes, are not supported in Revit or gbXML schema. The availability of such information is critical to assess, for example, the total cost of renewable or local materials used in the project.

The gbXML files can be used to perform energy performance assessments. As discussed earlier, it is not guaranteed that Revit can export clean geometry that accurately describes the model. The analytical model's purity depends on the Revit gbXML exporter and how these projects are modelled in the first instance. When considering the gbXML data schema, it is critical to acknowledge its full capabilities and limitation in supporting fully automated assessment workflows.

Table 32 Analysis of supported materials information in gbXML data schema, Autodesk Revit, which are required for JGBG assessment.

Material Element	gbXML data schema	Available in Revit?	Exported gbXML from Revit	Information required for assessment
GbXML Attribute	id	-	Id	-
	DOELibIdRef	-	-	-
GbXML child elements	Name	Yes	Name	-
	Description	Yes	-	-
	Absorptance	Yes	-	Absorptance Coefficient
	Roughness	Yes	-	Roughness
	Albedo	-	-	-
	Reflectance	Yes	-	Solar Reflectance Coefficient
	Transmittance	Yes	-	Transmittance
	Emittance	Yes	-	Emissivity
	ImageTexture	-	-	-
	R-value	Yes	R-value	-
	Thickness	Yes	Thickness	Thickness
	Conductivity	Yes	Conductivity	-
	Density	Yes	Density	Density
	specific heat	Yes	specific heat	-
	Permeance	Yes	-	-
	Porosity	Yes	-	-
	recycled content	-	-	recycled content
	Fire	-	-	-
	Cost	Yes	-	cost
	indoor air quality	-	-	-
	CADMaterialId	-	-	-
	Reference	-	-	-
	-	-	-	Origin
	-	-	-	renewable
	-	-	-	volume
	-	-	-	weight

The gbXML capabilities of transferring the model information to perform energy and daylight simulations are shown in Table 33 below, as discussed on Pollination's Github page (Pollination, 2022). The table highlights that not all model elements can currently be transferred from the BIM authoring tool using the gbXML to the analysis tools. Therefore, the missing elements essential to perform specific tasks must be provided through different approaches. Some of these challenges are discussed in Chapter 7, and an approach to overcome such challenges is presented.

Table 33 GbXML model capabilities for building performance simulations. Source (Pollination, 2022).

Model Element	gbXML
Geometry	Supported
Spaces / Zoning	Supported
Boundary Conditions	Supported
Face Types (e.g., Air Boundary)	Supported
Opaque Constructions	Supported
Window Constructions	Supported
Schedules	Work in progress
Loads	Work in progress
Thermostats + Outdoor Air Req.	Work in progress
Program Types	-
HVAC Systems	-

SHW Systems	-
Natural Ventilation	-

The following chapter presents a pilot study to automate the sustainability assessment of the Passivhaus building using the Visual Programming Environment (VPE) approach.

6. Pilot Study: Automating Passivhaus Evaluation using BIM

Declaration

This chapter presents the pilot study developed as part of this research to explore the feasibility of automating the sustainability assessment of buildings using visual programming tools. This work was published at the International Building Performance Simulation Association Conference (IBPSA-2019). The publisher retains the copyright, but I retain permission to use the materials in this thesis.

Hamed, O. S. and Wang, T. H. (2019) ‘BIM2PHPP: A new BIM-based tool for passivhaus design with PHPP’, in *Building Simulation Conference Proceedings*, pp. 100–105. doi: 10.26868/25222708.2019.210330.

6.1 Introduction

This chapter introduces a pilot study to automate the sustainability assessment. The pilot study was designed to experiment with one of the commonly used workflows to integrate Building Information Modelling (BIM) with building sustainability assessment and code compliance as a potential workflow to correspond to the aims of this thesis (Reinhardt and Matthews, 2017; Seghier *et al.*, 2017; Sanhudo and Martins, 2018; Shadram and Mukkavaara, 2018). The pilot study was designed to automate the assessment of Passivhaus buildings by integrating Autodesk Revit as a BIM authoring tool and the Passive House Planning Package (PHPP) using Visual Programming Environment (VPE) Dynamo for Revit.

In common practice, the PHPP tool tests and certifies Passivhaus buildings. The required building information can be manually inputted directly into the PHPP spreadsheet, such as the building geometry information and material properties. Alternatively, an energy model can be created by the users through a conventional 3D CAD environment with an add-on tool, such as the designPH tool—a plugin designed for Sketchup tool support the need to associate required physical attributes with raw geometric data such as surfaces, components’ thermal properties, and more. However, the integration between the PHPP spreadsheets and BIM tools is currently limited (Cemesova, Hopfe and McLeod, 2015).

The tool was proposed to enable direct information interoperation Between the BIM model and the PHPP spreadsheets. The main objective is to reduce significant time and effort for Passivhaus design through the automation of data exchange. For the demonstration, Dynamo for Autodesk Revit tool was deployed to illustrate how building elements and their related information, such as the geometry of the component, their U-values, orientation, and others, are collected, calculated, and extracted to the PHPP sheets for Passivhaus design assessment.

6.2 Tool development

Feist *et al.* (2013) state that the external dimensions of every thermal element are used to calculate the thermal envelope of a building. Therefore, all the thermal elements that function as external areas must be defined and extracted. For example, all windows, roofs, and walls that form the thermal envelope need to be extracted and defined in the PHPP spreadsheets with their material, orientation, and other physical attributes, as these are essential information for the assessment.

Although the BIM model consists of various building information, such as building components and their areas, dimensions, and thermal attributes, many related building components information cannot be directly extracted, requiring further steps to be extracted from BIM models. For example, no parameters host the component's orientation from the True North in Revit elements. To resolve such an issue, a custom node was developed for the designed BIM2PHPP toolkit to automatically measure the exterior wall and ceiling surface(s) orientation.

Defining the role of each component in the thermal envelope requires extra information to be inserted into the PHPP spreadsheets. For example, the Group Number of each element is an essential input for each component to define its function, such as ambient or a ground-exterior wall, roof/ceiling, or floor slab. To overcome this issue, a custom node was designed to define new Revit parameters for wall components (Exterior Wall) to filter exterior walls. Similarly, (Is Ground Wall) is another Revit parameter categorising the wall group. A summary of the required information in the PHPP spreadsheets, their availability in the BIM authoring tool, and the development of the missing parameters in the BIM2PHPP toolkit are presented in Table 34.

Table 34 PHPP requirements, availability in Revit, and the development of the BIM2PHPP toolkit. Source (Hamed and Wang, 2019).

Component	PHPP Requirement	Availability in Revit	BIM2PHPP toolkit
Walls & Roofs	area	yes	yes
	Group number	-	yes (user input)
	Thermal properties	yes	yes
	Deviation from North	-	yes
	The angle of inclination from the horizontal	-	yes
	Reduction shading factor	-	yes (defaulted)
	Exterior absorptivity	yes	yes
	Exterior emissivity	-	yes (defaulted)
Windows	dimensions	yes	yes
	Hosting component	-	yes
	Component information (glazing and frame types)	yes	yes
	Thermal properties (U-value, G-value)	yes	yes

	orientation	-	yes
	Shading calculations	-	-
Window frame	Glazing edge thermal bridge	-	yes (defaulted)
	Installation thermal bridge	-	yes (defaulted)

6.3 BIM2PHPP computational workflow

Three main phases formulate the BIM2PHPP toolkit workflow: (1) information modelling and preparation, (2) information processing and calculations, and (3) Data mapping and transfer, as illustrated in **Error! Reference source not found.**. To begin with the evaluation process, the availability of the required parameters in the proposed design must be checked using one of the BIM2PHPP components. If the required parameter is missing, a new one will be defined. The user fills in the new parameter or defaults in an automated process predefined by the tool. The next step is processing the obtained model information and performing the necessary PHPP calculation. Finally, the obtained model information can be mapped and exported to the PHPP tool.

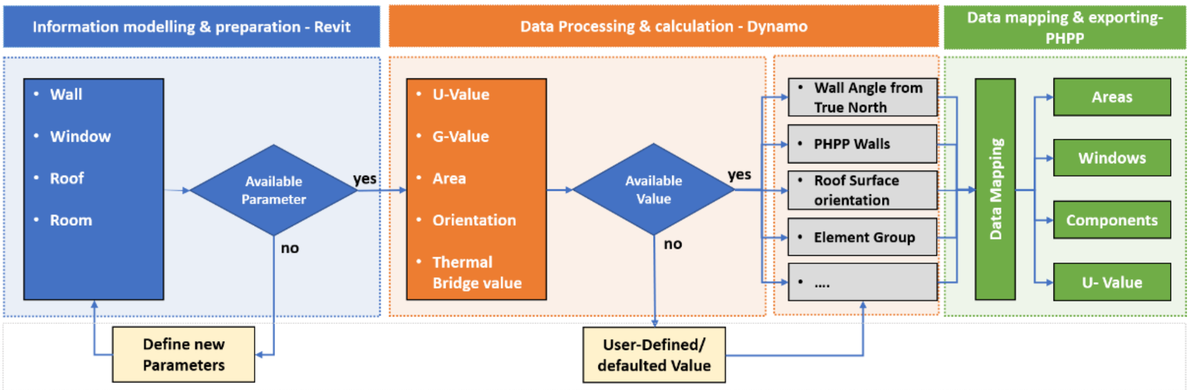


Figure 6-1 BIM2PHPP workflow. Source (Hamed and Wang, 2019)

6.4 Tool demonstration

In the proposed workflow, three tools are integrated as follows: (1) Autodesk Revit: a BIM authoring tool to generate the proposed BIM model and define parameters; (2) Dynamo: to define the values of the missing parameters, collect the BIM model information, and export it to the PHPP analysis tool, and (3) PHPP spreadsheets, for design analysis. For the demonstration, the total Treated Floor Area (TFA), representing the space's functional area, must be inputted in the Areas sheet in PHPP. As Revit components do not directly contain such information, a new instance parameter will be defined for Room components to help the user assign the necessary information.

However, to calculate the (Room TFA) the new parameter (TFA Percentage) requires user input based on the use of each space. Feist *et al.* (2013) state that the areas are weighted by (100% or 60%) based on their use. The Dynamo script will automatically calculate all the project TFA once all rooms' TFA values are provided. The data mapping is then performed to export the TFA of the Project to the Areas sheet inside the PHPP tool. **Error! Reference source not found.** demonstrates part of the tool components to process, map, and export information into the PHPP Areas sheet.

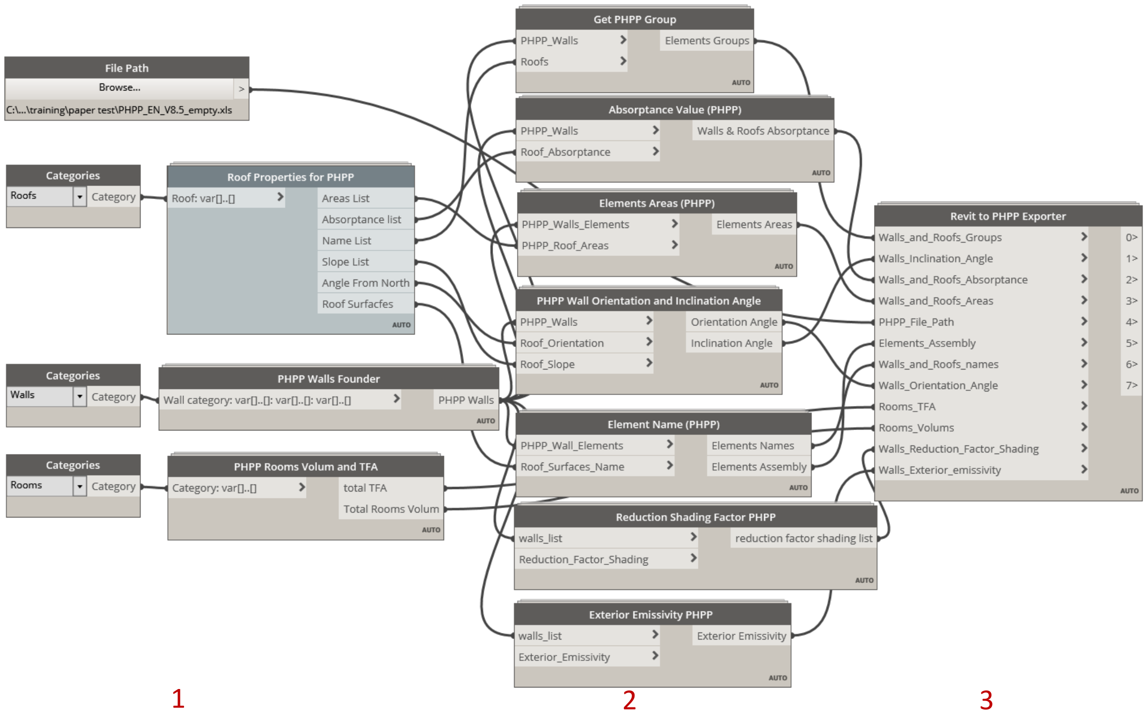


Figure 6-2 BIM2PHPP script for Areas sheet. (Hamed and Wang, 2019)

Figure 6-3 shows the interaction between the tools and their roles. For further demonstration, the following steps describe the overall workflow process.

1- Create the model using Revit.
2- Run a custom node in the BIM2PHPP tool to define the missing parameters.
3- Some defined parameters need user inputs to fulfil the data required in PHPP spreadsheets.
4- After collecting all the required information, the data mapping process is completed within the tool workflow.
5- Finally, the model performance can be analysed by exporting the collected information to the PHPP tool.

To allow for instant feedback, the users of the BIM2PHPP tool can read the PHPP analysis results dynamo using the tool. If the proposed design does not meet the targeted criteria, the user can apply different design solutions and update the PHPP spreadsheets using the proposed tool until the targeted criteria meet a satisfactory level.

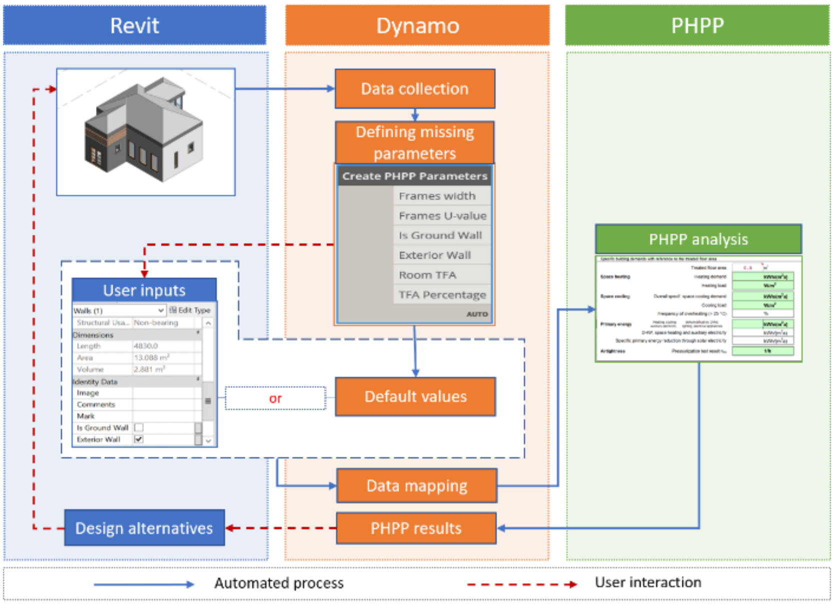


Figure 6-3 BIM2PHPP tool demonstration. Source (Hamed and Wang, 2019).

6.5 Discussions

the aim of developing the BIM2PHPP toolkit was to support the sustainable design assessment by automating data extraction from a BIM authoring tool to the PHPP spreadsheets. Three automation levels are featured by the tool: (1) Fully-automated process in which the tool allows for automatic data collection, calculation, mapping and extraction of the available data from the BIM model to the PHPP tool, such as detecting a component orientation; (2) Semi-automated process, where user inputs or defaulted-values for the missing parameters in the BIM model are required, such as TFA percentage. In this case, the process can be automated once the missing values are filled; (3) Manual process, which can only be done manually at the current tool development status, such as shading calculations.

BIM model information extraction can be automatically exported to different PHPP spreadsheets using the BIM2PHPP toolkit. The toolkit offers an automated process for data extraction and export to “U-values”, “Areas”, “Components”, and “Windows” sheets by using the available BIM model information. Moreover, default values or specific user inputs can be used to fill in the missing information by the tool or by user inputs. On the contrary, all the building components' information and material attributes are manually assigned using the DesignPH plugin as a graphical interface for the PHPP tool. To do so, an energy model must be first created using the Sketchup environment, where the information will finally be assigned to the energy model components. Table 35 highlights the critical differences between DesignPH and BIM2PHPP.

Table 35 Comparison of the main features of the DesignPH and the proposed BIM2PHPP toolkit. Source (Hamed and Wang, 2019)

Comparison area		**DesignPH plugin**	**BIM2PHPP toolkit**
Base software		SketchUp	Autodesk Revit/ Dynamo
Energy model		Requires an energy model and assigning thermal properties, TFA, group areas, window components	Not required/ data extraction from the BIM model
Data availability	Areas	User input	Yes
	Orientation	Yes	Yes
	Elements Thermal properties	User input	Yes/ default values/ user input
	Materials properties	User input	Yes
Data input		Manual input through SketchUp 3D environment. This requires user input or the use of default information in the library	For some missing parameters, user input is required
Shading calculations		Yes	-
In-software analysis		Yes	No, but Results can be read from PHPP
Fully-automated process		Semi-automated process	Manual process

6.5.1 Limitations and future work

This research aimed to enhance sustainable design practices by automating the evaluation process for Passivhaus design. The developed tool demonstrated its capability to significantly reduce time and effort through semi-automated data extraction, mapping, and export from BIM models to PHPP spreadsheets. However, a significant challenge persists in necessary data availability within BIM models. Although the BIM2PHPP tool efficiently extracts and processes the current building information, some data might not be present in the BIM model. As a result, the user needs to define specific missing parameters to enable a fully automated process. The user can either default or manually input these parameters to complete the automation. For future research, fostering multi-disciplinary collaboration could be explored to enhance data exchange and further improve the efficiency of the BIM2PHPP tool.

6.6 Conclusions

In this study, we have introduced an innovative approach based on BIM-VPE (Building Information Modeling - Visual Programming Environment) to address the information exchange challenges between BIM and PHPP (Passivhaus Planning Package) tools. Our proposed approach aims to streamline the design assessment process for Passivhaus by leveraging the BIM authoring tool Autodesk Revit, to automate the transfer of project information into PHPP spreadsheets.

By automating the data exchange, our approach offers several advantages. Firstly, it significantly reduces the manual effort required for data entry, thereby saving time and minimizing errors associated with manual input. This automation allows designers to focus more on the design process itself. In our study, we demonstrated the effectiveness of the BIM2PHPP tool in efficiently retrieving geometric information and material attributes necessary for the Passivhaus design assessment using PHPP.

The author acknowledges that not all required information may always be readily available in a BIM model. To address this issue, we analyzed and addressed these gaps to enable a comprehensive evaluation. The outcome of this analysis led to the development and deployment of a BIM tool within Dynamo for Autodesk Revit, which automatically associates and prepares default or user-defined values for PHPP.

This streamlined process empowers users to explore various design scenarios efficiently and reduces the effort and time required for design validation during the iterative design process. The study presents a novel solution that enhances the integration between BIM and PHPP, facilitating a smoother and more effective design assessment for Passivhaus buildings.

7. Integrated Sustainability Assessment Tool (iSAT)

This chapter provides a detailed description of the integrated sustainability assessment tool (iSAT) development. The purpose of developing the iSAT tool was to facilitate the assessment of green buildings by automating the assessment process of the selected criteria. The design and assessment tools must be integrated with the assessment criteria in one workflow to overcome the identified challenges in the manual assessments. The tool was developed using computer programming and offered the flexibility to expand its functionality and integration with other assessment criteria and building performance simulation tools. The iSAT tool architecture is introduced in the following sections.

7.1 Tool architecture

The iSAT tool consists of core modules. Each module contains functions that can be used for specific purposes, such as data retrieval, building elements' selection and filtering, and conducting performance simulation. The development of the iSAT tool depends on three components: BPS packages, Data processing packages, and assessment criteria packages. **Error! Reference source not found.** below illustrates the tool's architecture by representing the four layers that formulate the

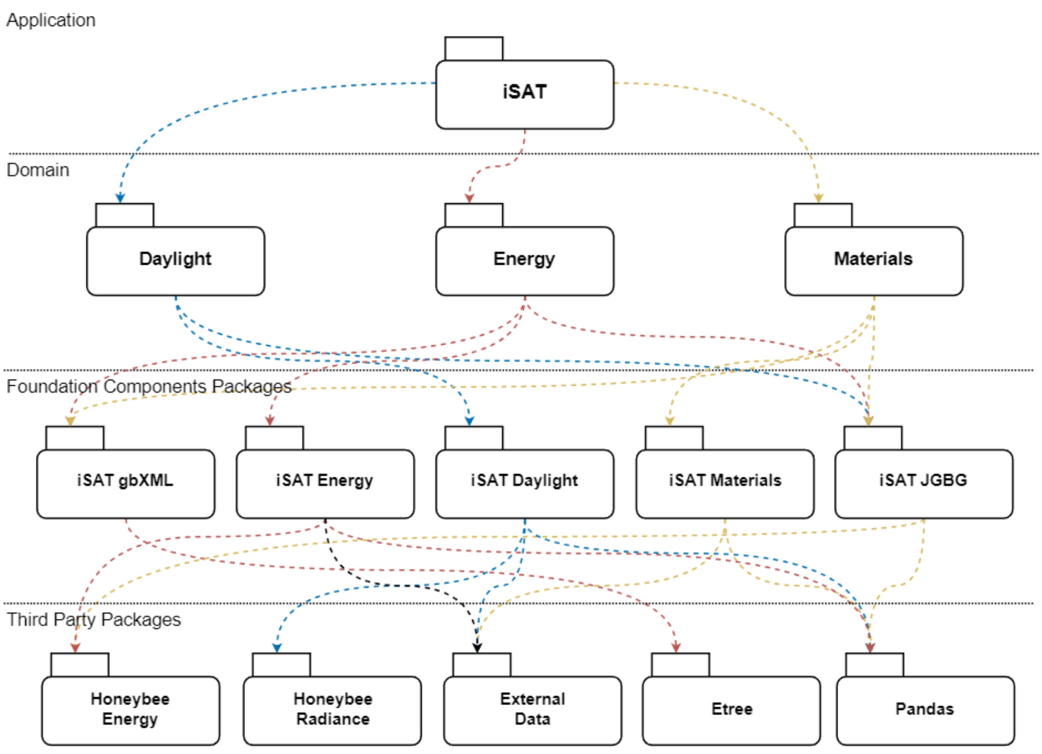


Figure 7-1 Layered package diagram of the iSAT tool

application structure.

The higher layers depend on the ones below with one-to-many functional packages. From the top layer, the iSAT toolkit is represented as an application. The current development of this application can facilitate the assessment of green buildings in different domains, namely, Energy, Daylight, and Materials. Different foundation component packages for each domain were designed and integrated to perform different tasks, such as the iSAT gbXML package, designed to process the gbXML data schema and extract the necessary information for different assessment tasks. Finally, third-party packages, such as Honeybee Radiance and Hoenybee Energy, allowed daylight and energy assessments based on their functionalities and capabilities.

The Data processing package was developed to extract, filter, and process the information from any gbXML file as this application's primary BIM schema input. The BPS packages, such as the Honeybee-Energy and Honeybee-Radiance, were developed by the Ladybug tool developers and are available for public use under the GNU Affero General Public License v3.0 (Ladybug Tools, no date a). These packages, besides others, construct the core of the ladybug tools and are used as plugins in various design programs, such as Grasshopper for Rhino and Pollination tools. The author developed the assessment criteria package iSAT JGBG to automate the assessment of the project information by integrating the packages mentioned above. Other packages, such as Pandas and ETree, are third-party packages used to read, edit, manipulate the input data, and represent the results.

The programming approach allows the tool's architecture to expand flexibility and host other BPS packages. For example, the developers of OpenLCA (GREENDELTA, 2022) provide a Python package that can use the functionalities of the OpenLCA application. Other libraries can also provide capabilities for utilising geographic information systems (GIS), such as Geopy (Adam Tygart *et al.*, 2021) and GeoPandas (Jordahl *et al.*, 2022), which can also facilitate some Site, Materials, and Transportation factors based on the project's location, such as the proximity to amenities, Access to public transit, and Local materials assessment. These packages are not currently integrated into the iSAT toolkit. The assessment criteria packages can also expand into hosting other GBRTs, such as LEED and BREEAM. In this case, a Python package consisting of rules representing the LEED and BREEAM rating systems must be developed to use the functionality of the proposed tool. The assessment criteria packages focus on materials, energy, daylight, site, and water performance evaluation. The gbXML data schema provides essential information about the project geometry, building components, and materials specifications, making it ideal for energy and daylight assessments. However, without other crucial information to conduct performance simulations, such as the zoning schedules, it was essential to compensate for the missing data from external libraries that the tool users could create following a predeveloped schedule template. This also applies to the materials assessment if a specific material's information, such as cost, origin, or conductivity, is unavailable in the gbXML file.

The iSAT tool design was influenced by the GBRTs factors chosen to demonstrate the feasibility of the tool. The chosen factors represented different complexity levels demonstrating direct assessment, such as materials' physical properties; indirect assessment, such as window-to-wall ratio; and complex assessment, which involves external tools to perform further calculations and processes, such as energy simulations. The gbXML schema was considered primarily to afford interoperability between the design and assessment tools, mainly to conduct energy and daylight analysis. Figure 7-2 highlights the main parts of the iSAT toolkit. As the tool aims to facilitate the sustainability assessment of buildings, three central components must be integrated into the proposed workflow to streamline the process.

The first part, the green building rating tools, consists of numerous criteria and requirements that can be described as complex. These criteria have been extracted and translated into computational rules that can be described as machine-readable. In the iSAT case, some of the JGBG have been selected based on their level of complexity and importance (i.e. the criteria weight) to demonstrate the feasibility of the tool development. The second part, the design tool, Autodesk Revit in this workflow is one of the leading BIM authoring tools in the industry. The project model can be prepared using this tool, and its information can be exported using gbXML data schema to facilitate interoperability between the design and assessment tools.

In many cases, the retrieved information is insufficient for a fully automated assessment, as some of the information required may not be available in the BIM model or cannot be transferred using the BIM data schema. Therefore, external data sources must be prepared as a template for the tool to compensate for the missing information. The third part of this tool, the parametric building performance simulation tools (BPS), such as the Ladybug Toolkit, represents the external assessment tools that must be used to complete complex assessment tasks during the design stage. Such tools can facilitate generating different design proposals using their parametric capabilities and aid in reducing the time and effort needed for remodelling and generating design scenarios models for the assessment.

The data exported from these components have been studied and mapped into one workflow that integrates the capabilities of the design and assessment tools with the assessment criteria. This has then facilitated the development of the iSAT toolkit core components. A functional paradigm was adopted for developing the tool due to its benefits of allowing for low maintenance, reproduction of the code, and modularity. It allows others to adopt selected parts of the tool to design customised workflows, which can be tailored to specific criteria in a specific GBRT.

Extending the iSAT toolkit to support other JGBG's criteria and other GBRTs requires a systematic approach and integrating additional data and functionalities. The first step is thoroughly analysing the specific GBRTs and their assessment criteria to understand their unique requirements and assessment methodologies. Based on this analysis, the iSAT toolkit can be expanded to include additional modules and data schemas that accommodate the specific criteria of the selected GBRTs. To support other GBRTs, design teams can identify the additional data and information needed for the assessment process beyond the existing gbXML and IFC files. This may include specific parameters, performance metrics, and data related to the assessment criteria of the chosen GBRTs. By integrating this data into the iSAT toolkit, architects can create a more comprehensive and tailored solution for each rating system.

Moreover, the iSAT toolkit's flexibility allows for the inclusion of new assessment modules that cater to the unique criteria of different GBRTs. Architects can develop customized workflows and simulation processes specific to each rating system, enabling a more accurate and in-depth evaluation of building sustainability. Nevertheless, such integration would require experienced users to develop the procedures needed in the Python environment.

Furthermore, the parametric capabilities of the chosen BPS tools allow for developing countless scenarios assessment. The user can test different design variables, including the window-to-wall ratio, materials and construction sets, schedules, building orientations, and the feasibility of installing shading devices using only a few lines of code. Using parametric capabilities can come in handy when conducting early project assessment, where the design teams test different scenarios or building components, such as insulation properties, and test different building scenarios according to one rating system without manually creating scenarios models. The following sections introduce and describe the main components of the iSAT tool.

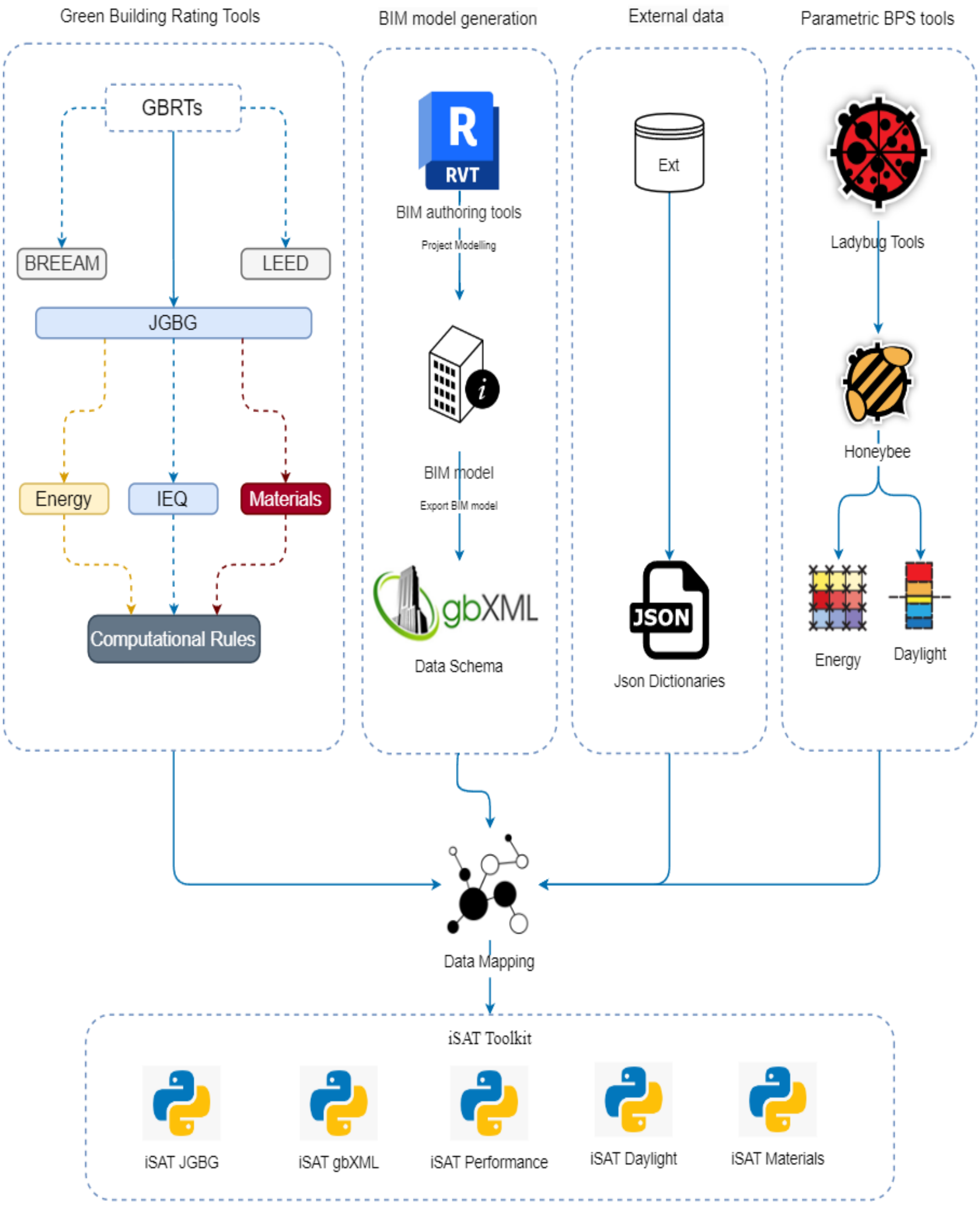


Figure 7-2 iSAT tool components, with examples of the specific tools used in developing the iSAT toolkit.

7.2 iSAT-gbXML

iSAT-gbXML is a Python library developed as part of the iSAT tool to retrieve all the embedded information in a gbXML file. The iSAT-gbXML package allows for data aggregation and processing to perform different assessments that rely on the available data from the exported model. The iSAT-gbXML consists of different functions that can (1) filter a selection of building elements, (2) retrieve the selected elements' information, and (3) perform further analysis, such as calculating the WWR of a building. Figure 7-3 illustrates a sample of the package functionality.

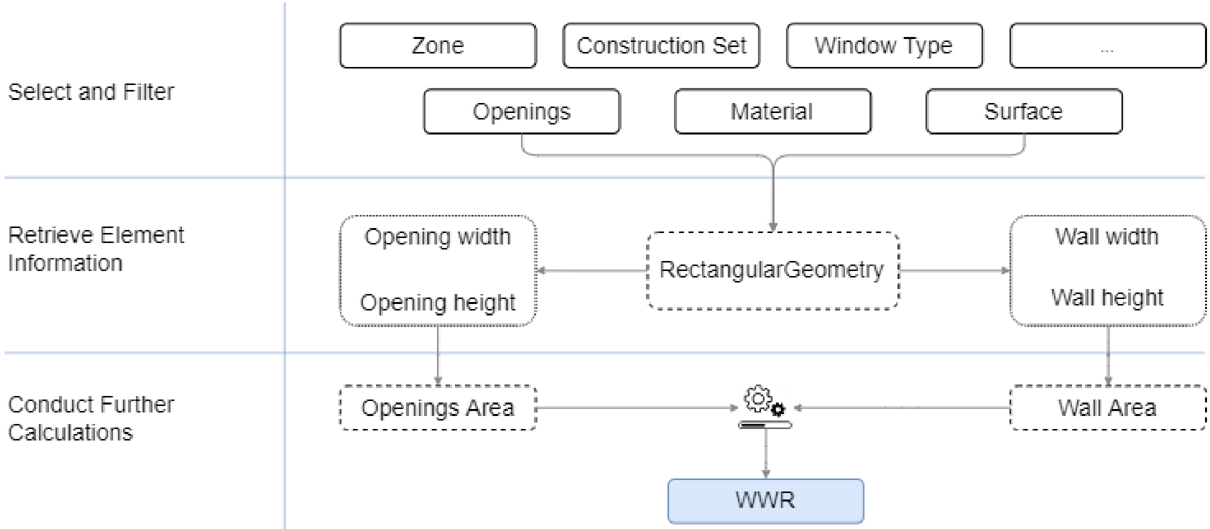


Figure 7-3 A demonstration of the iSAT gbXML package functionality to calculate the window-to-wall ratio.

The gbXML file consists of a set of elements that represent the building textually. Each element (parent element) contains a set of attributes and sub-elements (child elements). An element may consist of one or more elements and the relationship between these elements is defined using the elements' id reference. For instance, in Figure 7-4, the *surface* is the child element of *Campus.* Each *Surface* element contains a *RectangularGeometry* element that describes the surface representation in the space, including the *Azimuth*, *Tilt*, and *Height*. A Surface element may also contain one or more *Opening* elements, which also have a *RectangularGeometry* element to represent the opening geometry in the space.

The *ConstructionIdRef* attribute of a Surface element is the reference used to link the *Construction* element of the specified *Surface* Element. Each *Surface* links to one Construction element that hosts the construction information of a surface, such as the total *U-value*, *Cost*, *Emittance*, and more. Therefore, the iSAT gbXML package was designed according to the relationships between the gbXML

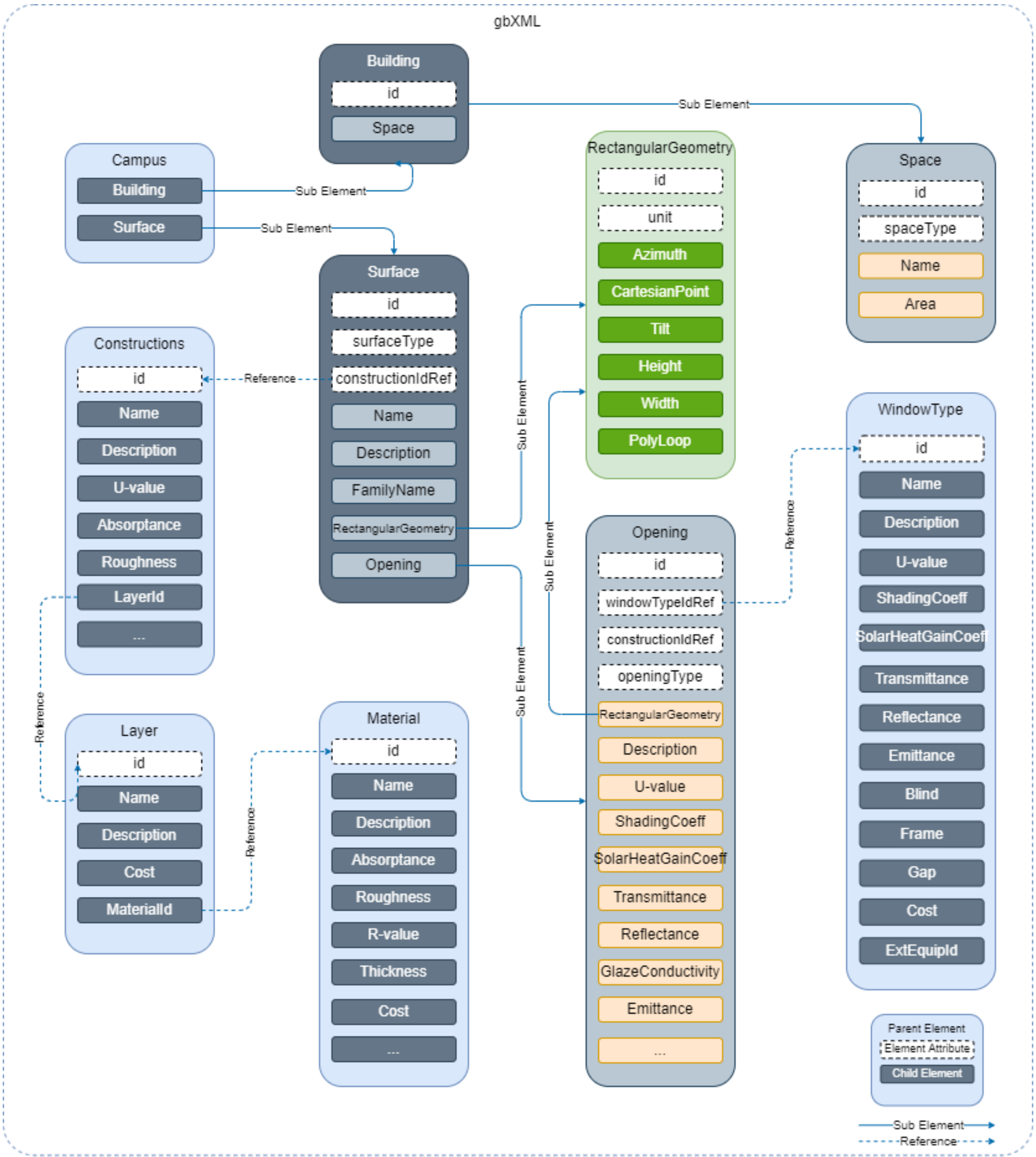


Figure 7-4 The supported gbXML elements in the iSAT gbXML library.

elements to support extracting specific information related to the building geometry, materials, and space attributes. Figure 7-4 above represents the basic architecture of the gbXML structure, the supported gbXML elements and the information that can be retrieved from a gbXML file using the iSAT-gbXML package.

The iSAT-gbXML package can retrieve building information from the gbXML files. These data can be assessed directly or indirectly (semi-complex) depending on the selected GBRT's assessment criteria. For the demonstration, the JGBG's Energy Efficiency criteria consist of requirements that assess the building's performance using information that can be directly retrieved and evaluated from the gbXML model, such as assessing materials properties. Other requirements necessitate developing procedures that process the data needed for further calculations, such as calculating a WWR or total use of materials with recyclable content. Some other criteria are more complex and involve external data and tools, such as daylight assessment using daylight simulation tools and energy performance using energy performance simulation tools. The iSAT-gbXML can facilitate the direct and indirect criteria assessment based on the information available in the used BIM file, and the complex criteria assessment requires integration with other iSAT packages, such as the iSAT-Performance. The following sections demonstrate the usability of the iSAT-gbXML package for retrieving different information to conduct direct and indirect (semi-complex) assessments based on the JGBG requirements.

7.2.1 Use Case One: Retrieve Surfaces Materials

The iSAT-gbXML is a library consisting of different functions that conduct different tasks and retrieve different gbXML elements' information. In the Energy Efficiency category from the JGBG, the second criterion assesses the Roof and Wall building elements and their materials specifications, including the roof type (flat/pitch), wall's finish material roughness, emissivity, solar reflectance coefficient, and absorbance coefficient. See Table 36 for more details.

Table 36 The JGBG's Energy Efficiency 2nd Criterion.

2nd criterion: Roofs and Walls of the building envelope:		
Voluntary Requirements	1st requirement	Flat Roofs and Smooth textures for Walls in Cold zones and un-flat roofs and Rough textures in Hot zones
	2nd requirement	Solar Reflectance Coefficient for Roofs should not be less than 0.7, emissivity 0.75 and absorbance coefficient 0.3 simultaneously.

The gbXML data schema represents all the buildings' envelop elements, such as Walls, roofs, and floors, as Surface elements. Each surface element consists of attributes that describe the surface function, such as "*surfaceType",* which can be assigned to exterior walls as "*ExteriorWall*" and roofs as "*Roof*". The surface element does not contain information about its layers and materials. However, such information can be accessed through other elements linked to the surface using their *"id"* attributes. Therefore, retrieving surface materials must involve different steps, including collecting surfaces and iterating through each surface to link the related construction, layers, and materials elements. Figure 7-5 illustrates the workflow to retrieve the surface materials information.

The algorithm of the *"Get_Surface_Info"* function, for example, consists of multiple steps involved to parse, collect, and filter the information of each element embedded in the gbXML schema related to the specific task required. See Figure 7-6 for further details. In this example, the requirements of the 2nd criterion in the JGBG's EE category represent the directly assessable criteria, as the information required to complete the assessment process can all be found directly in the gbXML file.

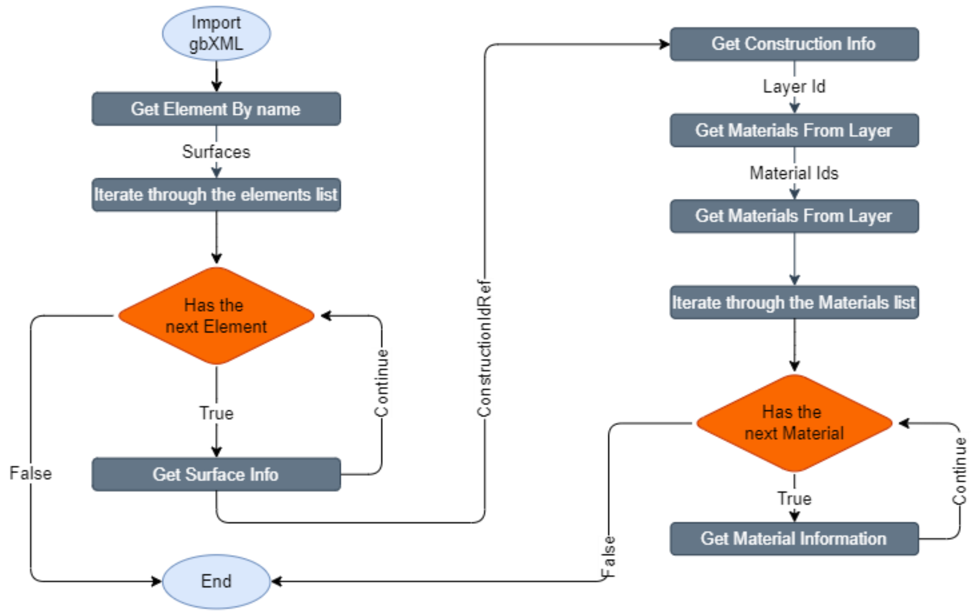


Figure 7-5 iSAT gbXML workflow to retrieve Surface materials information.

```
Define Get_Surface_Information (Surfaces_list):
        for each surface in the Surfaces_list:
                surface_type = surface_attribute [“surfaceType”]
                construction_id_reference = surface_attribute [“constructionIdRed”]
                exposed_to_sun = surface_attribute [“surfaceType”]
                id = surface_attribute [“id”]
                name = get_element_value (“Name”)
                description = get_element_value (“Description”)
                family_name = get_element_value (“FamilyName”)
                adjacent_space_id = get_element_value (“AdjacentSpaceId”)
                for each element in “RectangularGeometry” element:
                        azimuth = get_element_value (“Azimuth”)
                        tilt = get_element_value (“Tilt”)
                        width = get_element_value (“Width”)
                        height = get_element_value (“Height”)
                        area = height * width
        Return information tuple (id, surface type, construction_id_ref, exposed_to_sun, name,
                                  Description, family_name, adjacent_space_id, width, height, area,
                                  azimuth, tilt)
```

Figure 7-6 Pseudocode describes the steps in defining the Get Surface Information function.

7.2.2 Use Case Two: Get the Window-Wall Ratio

Indirectly assessed criteria refer to the criteria that involve conducting further calculations on the available information in a gbXML model to produce the required information to assess the building. These data cannot be found in the gbXML model directly. However, it can be produced by implementing further calculations on the available information in the building model. One example of such criteria is the 5th criterion of the Energy Efficiency category in the JGBG, in which the glass U-value must be selected according to the building's window-to-wall ratio (WWR). See Table 37 for more details.

Table 37 The JGBG's Energy Efficiency 5th Criterion.

		5th criterion: Green Material: B: Local/ Regional Materials
Voluntary Requirements	1st requirement	**If** the window-to-wall ratio **WWR** is **10%-40%,** the **glass U-value** should be **less than 3.30 w/m2.k**
	2nd requirement	**If** the window-to-wall ratio **WWR** is between **40-70%,** the **glass U-value** should be **less than 2.00 w/m2.**k. If the **WWA** ratio is **more than 70%, U-value** should be **less than 1.6 w/m2.k**

The WWR cannot be directly retrieved from the gbXML data schema, as no elements with such information exist. However, the WWR can be calculated by dividing the total area of windows (openings) in a wall by the total area of that wall. The *"RectangularGeometry"* element is a child element of both opening and surface elements, which consists of the information required to calculate the total area of an opening and a wall. Figure 7-7 demonstrates the steps and functions developed in the iSAT-gbXML to calculate the WWR.

Figure 7-8 below demonstrates the *"void_to_solid"* function developed to automate the calculation of the window-to-wall ratio for a building. It can be noted from the pseudocode that this function can be used in different scenarios based on the parameters input, such as calculating the WWR and Skylight Roof Ratio (SRR).

Figure 7-7 iSAT gbXML workflow to retrieve the WWR of a building.

```
Define Void_to_Solid (Surfaces_list, OpeningType):
        Opening_ids_list = []
        total_surfaces_area = 0
        total_openings_area = 0
        For each surface in the Surfaces_list:
                If surface contains Opening:
                        Surface_area = get_surface_information (surface_id, “Area”):
                        Total_surfaces_area = total_surfaces_area + Surface_Area
                For each open in surface:
                        Append open_id to Opening_ids_list
        For each open_id in the Opening_ids_list:
                If the opening_type == OpeningType:
                        Opening_area = get_opening_information (open, “Area”):
                        Total_openings_area = total_openings_area + opening_area
        Ratio = total_openings_area / total_surfaces_area
        Return ratio
```

Figure 7-8 Pseudocode describes the steps in defining the Window Wall Ratio and Skylight Roof Ratio functions.

7.3 iSAT-JGBG

The iSAT-JGBG package is a set of functions representing the assessment criteria in the GBRTs. As highlighted in Chapter 4, the criteria and assessment procedures vary significantly between GBRTs. The iSAT-JGBG package was developed based on the Jordan Green Building Guide as a proof of concept to demonstrate the feasibility of developing an integrated BIM-based sustainability assessment tool. It covers Energy Efficiency, Healthy Indoor Environment, and Materials categories criteria. The criteria selection strategy from these categories was implemented to represent different levels of complexity in retrieving the information or performing the required tasks or processes to conduct the criteria assessment. The GBRTs criteria, as described in section 2.6, can be classified as (1) *unapplicable*, (2) *directly assessable*, (3) *semi-complex*, and (4) *complex* factors based on their readiness for automatic assessment, data availability, and the project phase and required procedure to conduct the assessment, and will be further discussed in the following sections.

Critical factors must be considered when describing the complexity factor of the assessment criteria, such as the data required to be assessed, the processes, and data representation and availability in the BIM model. First, the JGBG criteria were analysed to help understand the required information, assessed elements, and the processes/tools used to map with the available data in the BIM model. The analysed information from the assessment criteria can be classified in Table 38 as follows:

Table 38 GBRTs criteria analysis

GBRTs criteria analysis	Example
Elements involved in the assessment.	Building envelope, building layout, equipment, materials
Parameters involved in the assessment.	U-value, solar reflectance, cost, recycled content
Processes and calculations	Logical operators (Less than, more than)
The use of external tools	Energy simulation, daylight simulation, life cycle assessment tools

Secondly, the required information in the gbXML data schema was analysed to highlight and establish the link between the required information from the GBRT and the BIM model. As discussed in the previous sections, the gbXML data schema consists of information that describes the building information textually. The project information can be found in the schema as elements and attributes. An element consists of child elements and attributes linked through a unique *id* reference number. These gbXML elements were analysed, and the relationships between its elements were linked to retrieve the requested information for each specific assessment. An example of the analysis of the *Surface* element from the gbXML data schema can be highlighted in Table 39 as follows:

Table 39 gbXML schema analysis. The surface element was selected in this example to demonstrate the schema's elements' relationships.

GbXML schema analysis	Example
Element's parent element	*Campus*
Child elements of (Surface)	*Name, Description, FamilyName, Opening, RectangularGeometry*
Attributes of (Surface)	*Id, surfaceType, constructionIdRef*
Attributes enumeration of (surfaceType)	*ExteriorWall, InteriorWall, Roof, SlabOnGrade, ExposedFloor*

7.3.1 Complex Assessment Criteria

Complex assessments often require external tools to assess the building's performance in a particular area. For example, in the Energy Efficiency category, the 10th criterion requires conducting energy performance simulations, the Healthy Indoor Environment's 1st criterion requires conducting indoor air quality simulations, and the 5th criterion requires conducting daylight simulations to assess the glazing factor, the Materials and Resources 5th criterion assesses the use percentage of local materials from the total project materials cost.

In each criterion described above, the assessment requires external tools capable of conducting performance simulations or external calculations, for example, the distance between the project and the source of materials. Such tools have limited integration with GBRTs criteria due to the considerable number of available GBRTs worldwide, each tackling different factors, adopting different assessment methodologies, or requiring meeting different performance benchmarks. Therefore, it became challenging to integrate the GBRTs criteria requirements into one tool capable of assessing the building performance in different aspects based on different GBRTs.

However, as highlighted at the beginning of this chapter, the adopted approach in developing the iSAT toolkit allows the tool to flexibly expand and extend the assessment criteria by developing the desired assessment packages based on the targeted GBRT. This approach allows different design teams to develop customised functions to assess their projects based on different assessment standards and local codes.

In the below example, in Table 27, the energy simulations are required to demonstrate the reduction of the total building energy use compared to the benchmark model as characterised by the national building codes in Jordan. Despite being voluntary, this criterion weighs 12 credits in the JGBG, reflecting its importance corresponding to the local issues regarding building efficiency in Jordan.

Table 40 An example of complex factors in the Energy Efficiency category in the JGBG.

	Requirement	External tools	Assessed factor	Condition
1st	**Conduct computer simulation for energy performance analysis**	Energy performance simulation tools	Energy performance	Proposed design EUI < benchmark model

The assessment methodology of this criterion requires conducting five computer simulations, one for the proposed design and four identical benchmark models characterised by the national building code requirements, with one difference in each model regarding the orientation of the building. The arithmetic mean of the energy simulation results of these benchmark models is then compared against the energy simulation result of the proposed design model to demonstrate the energy savings in the proposed design. Table 41 demonstrates the characteristics of the benchmark and proposed design models.

Table 41 Different characteristics between the benchmark and proposed design models for the energy assessment in JGBG.

Parameters	Proposed Design scenario	Benchmark model scenarios
Weather files	Amman weather file	Amman weather file
Orientation	As designed	North, south, east, west
Window openings	As designed	30% in all elevations
Glass thermal transmittance coefficient	As designed	Energy efficient codes
Shading coefficient	As designed	Energy efficient codes
Schedules	As designed[10]	As designed
Walls, roofs, and floors Thermal transmittance coefficient	As designed	Energy efficient codes
Cold roofs modelling	As designed[11]	Energy efficient codes
Shading devices	As designed	No shading
HVAC systems	As designed	National building codes[12]
Process energy[13]	As designed	As designed

Similar to the energy performance simulations, the daylight assessment described in Table 42 below highlights another example of complex assessment criteria in the JGBG. In this example, the daylighting performance of buildings can be measured in three ways (1) by calculating the glazing

---

[10] Except if there are any necessary differences to simulate innovative energy efficient strategies, such as lighting and natural ventilation control, or reducing water heating loads.
[11] Solar reflectance coefficient can be used.
[12] To compare with the lowest-acceptable efficiency in the national building codes.
[13] Offices equipment, computers, elevators, escalators, cooking equipment, communication rooms, task-lighting, motors, medical equipment. All based on actual/realistic schedules.

factor manually, (2) by conducting on-site measurements using lighting sensors, and (3) by performing computer simulations to predict the illuminance levels based on the JGBG criteria for the assessed space type. Specific tools such as Radiance must be used to perform the daylight assessment.

Table 42 An example of complex factors in the Healthy Indoor Environment category in the JGBG

	Requirement	External tools	Assessed factor	Condition
1st	**Glazing factor >= 2% or achieve a lighting level of more than 270 lux, or Computer Simulation to prove that the lighting level is more than 270 lux.**	Daylight performance simulation tools	illumination level (lux), glazing factor (GF)	illumination level > 270 lux, GF >= 2%

EnergyPlus and Radiance demonstrate an example of the performance simulation tools used for building performance analysis for energy and daylight, respectively. However, the lack of a graphical user interface for EnergyPlus and Radiance makes it challenging to perform energy and daylighting simulations for non-expert users, where the user must manually identify all the building elements, such as the geometry and construction sets.

The recent developments in design and BPS tools have allowed these tools to develop efficient workflows that integrate the design and BPS tools, facilitating the energy simulation process. GbXML is a BIM data schema that facilitates the interoperability of BPS and design tools. Using gbXML allows the design teams to use export analytical models that describe the building geometry, materials, construction sets, equipment, and schedules to the BPS tools, reducing significant time and effort in manual data entry. One of the BPS tools that can integrate with the gbXML data schema is the Ladybug toolkit. Honeybee-Energy and Honeybee-Radiance packages were developed as part of the ladybug toolkit to facilitate the energy and daylighting assessment using Radiance and EnergyPlus.

The ladybug toolkit was chosen as the core library to develop the iSAT-Performance package to facilitate conducting the energy and daylighting performance simulations required in the JGBG rating system. The iSAT toolkit integrates the iSAT-JGBG and iSAT-Performance to tackle complex assessment criteria such as the energy and daylight assessments. The iSAT-Performance is a package developed based on the Ladybug toolkit as one of the parametric BPS tools that allow the integration of BIM models throughout the use of gbXML data schema. The following section describes the development of the iSAT-Performance package to facilitate daylight and energy simulations for BIM models.

7.3.2 Direct Assessment Criteria

The Energy Efficiency 4th criterion, *"Thermal Insulation of Building Envelop",* is one of the criteria that represent the directly assessable criteria in the JGBG. It requires simple data collection and comparison to the identified value in the guide (see Table 43). In this example, no calculations, processes, or external tools are required to assess whether the building envelope meets the criteria or not. The assessment requirements were analysed in this example, and the elements and their parameters were mapped with the gbXML elements, attributes, and targeted parameters.

Table 43 An example of the Directly-assessable criteria from the JGBG

	Requirement	Element	Parameter	gbXML elements	gbXML Attribute	Parameter	Condition
3rd	**U-value** of **Opaque walls** to be **lower than 0.57** w/m2.k	Exterior Wall	U-value	Surface	surfaceType: ExteriorWall	U-value	U-value <= 0.57
4th	**U-value** of **Exposed Roofs** to be **lower than 0.55** w/m2.k	Exposed Roof	U-value	Surface	surfaceType: Roof	U-value	U-value <= 0.5

Based on that, a procedure to collect the information from the gbXML file was produced as part of the iSAT-JGBG package to automate the assessment process. The iSAT-JGBG depends on the iSAT-gbXML package to retrieve the required information from the gbXML models. The pseudocode in Figure 7-9 describes one of the developed iSAT-JGBG functions to assess the U-value of surfaces from the gbXML model.

```
Define assess_U_value (surfaces_list, val_1 =0.4, val_2 = 0.57, val_3 = 0.4, val_4 = 0.5):
        For surface in surfaces_list:
                construction_id = isat.gbxml.get_surface_info ("constructionIdRef")
                u_val = isat.gbxml.get_construction_info (construction_id, "u-value")
                If u-val <= val_1:
                        Score = 2
                        Message = "Surface Passed Voluntary Criteria"
                Else if  u-val < val_4 and u_val >= val_4:
                        Score = 1
                        Message = "Surface Passed Voluntary Criteria"
                Else if u-val < val_2:
                        Score = 0
                        Message = "Surface Passed Mandatory Criteria"
                Else:
                        Score = 0
                        Message = "Surface Failed Mandatory Criteria"
        Return Score, Message
```

Figure 7-9 Pseudocode describing the development of a function to assess the U-value of building components.

7.3.3 Indirect Assessment Criteria

Indirectly assessable criteria are considered semi-complex criteria due to the need to import external data sources or conduct calculations to correspond to the assessment criteria requirements. New information must be generated from the gbXML data for the assessment. As discussed in section 7.2.2, the WWR demonstrates an example of indirect assessment, as the information regarding the project's WWR is unavailable in a gbXML model. First, the criterion requirements were analysed, and the assessed elements and parameters were concluded. Secondly, these elements were mapped with the gbXML data schema elements that represent the design information of the building elements. See Table 44 for more information.

Table 44 Example of indirect assessment criteria from the JGBG

	Criterion	Element	Parameter	GbXML elements	GbXML attributes	Parameter	Condition
1st	**If** the window-to-wall ratio **WWR** is **10%-40%,** the **glass U-value** should be **less than 3.30 w/m2.k**	Exterior Walls, Windows	Walls Area, windows area, Glass U-value	Surface, Opening	surfaceType (ExteriorWall), OpenType (OperableWindow, FixedWindow	WWR U-value	Multi-case scenario
2nd	**If** the window-to-wall ratio **WWR** is **40-70%,** the **glass U-value** should be **less than 2.00 w/m2.k**. If the **WWA** ratio exceeds **70%, U-value** should be **less than 1.6 w/m2.k**	Exterior Walls, Windows	Walls Area, windows area, Glass U-value	Surface, Opening	surfaceType (ExteriorWall)	WWR U-value	
6th	Maximum **skylight area should be less or equal to 5%** of the **roof area**	Skylight, Roof	Roof Area, skylight area	Surface, Opening	surfaceType (Roof), OpenType (FixedSkylight, OperableSkylight)	Skylight-roof-ratio (SSR)	SSR <= 5%

In the above example, different steps are involved in retrieving the required information from the gbXML model, including the collection of the total area of windows, the total area of exterior walls, and the U-value of the glass. After that, the WWR must be calculated, and a multi-scenario assessment is finally conducted to determine the U-value of the glass requirements based on the WWR. These cases in the previous example are described in Figure 7-10, which involve different conditional if statements to assess the targeted building component based on the WWR.

Based on the above analysis, the workflow to complete the assessment of the 5th criterion of the JGBG was concluded. The iSAT-JGBG package depends on the iSAT-gbXML packages, as the functions and methods to collect the project information from the gbXML file are developed in the latter. Figure 7-11 represents the pseudocode that describes the development of a function to assess the u-value of Windows based on the *windowType* property in the gbXML schema. Based on that, a function was developed to assess the 5th criterion's first and second requirements from the EE category. See Figure 7-12 for more details.

```
Case zero:
        If WWR is less than 10%:
                Result = Pass. Criteria inapplicable
Case one:
        If WWR is less than 40% and larger than 10%:
                If U-value_glass is lower than 3.30 w/m2k:
                        Result = Pass
                Else:
                        Result = Fail
Case two:
        If WWR is less than 70% and larger than 40%:
                If U-value_glass is lower than 2.0 w/m2k:
                        Result = Pass
                Else:
                        Result = Fail
Case three:
        If WWR is and larger than 70%:
                If U-value_glass is lower than 1.6 w/m2k:
                        Result = Pass
                Else:
                        Result = Fail
```

Figure 7-10 Breakdown of the multi-scenario requirements of the JGBG's EE 5th criteria: Fenestration in the building envelope.

```
Define assess_window_uval (walls_list, required_uval):
        For each wall in walls_list:
                If wall has openings:
                        For each opening in wall:
                                Win_type_id = isat_gbxml.get_opening_info (window_type_id)
                                Opening_uval = isat_gbxml.get_window_type_info (
                                        win_type_id).U_vale
                                If opening_uval < required_uval:
                                        Result = pass
                                Else:
                                        Result = fail
        Return result
```

Figure 7-11 Pseudocode describing the development of the assess_window_uval function.

```
Define EE_5_M1_M2 (exterior_walls_list):
        WWR = isat_gbxml.window_wall_ratio (exterior_walls_list)
        If WWR < 0.4 and WWR >= 0.1:
                Result = assess_window_uval (exterior_walls_list, required_uval = 3.3)
        Else If WWR < 0.7 and WWR >= 0.4:
                Result = assess_window_uval (exterior_walls_list, required_uval = 2.0)
        Else if WWR >= 0.7:
                Result = assess_window_uval (exterior_walls_list, required_uval = 2.0)
        Else:
                Result = Pass. Criteria inapplicable.
        Return result
```

Figure 7-12 Final function

7.4 iSAT-Performance

As discussed in chapters 2, 4, and 5, the energy performance assessment of buildings is a complex process that requires different information at different stages during the design process. In addition, it requires integrating the design and assessment tools to allow for a flawless information workflow to complete the assessment process. The iSAT-Performance aims to facilitate the assessment of the energy performance of buildings using the gbXML BIM model and Ladybug tools for building performance simulation. The Ladybug toolkit is a comprehensive parametric assessment toolkit that can perform energy and daylight simulations, thermal comfort and shadow analysis, and more. The ladybug toolkit consists of four packages (1) Ladybug, which is used to produce a detailed analysis of the climate data (2) Honeybee, which is used to perform daylighting and energy simulations (3) Butterfly, which is used to perform computational fluid dynamic (CFD) analysis and (4) Dragonfly that allows for creating district-scale models for energy simulations. In this research, the author adopted the ladybug and honeybee packages to facilitate buildings' daylight and energy simulations.

The ladybug toolkit was developed using different validated simulation engines, such as the EnergyPlus simulation engine to perform energy simulations and Radiance to perform daylight simulations. The EnergyPlus and Radiance are considered one of the most reliable simulation engines used in the industry. Furthermore, the ladybug toolkit parametric features allow for exploring different design scenarios, where the analytical models can be generated automatically with minimal effort to assess different design proposals. The ladybug toolkit can read different model inputs, such as the Openstudio (.osm), EnergyPlus (IDF), and gbXML models, in addition to the 3D models generated in different integrated environments, such as Rhino and Grasshopper. These inputs are then translated into the in-house developed data schema "Honeybee Json" (HBJson), which allows using one model to perform different sustainability assessment simulations, such as the energy, thermal comfort, and daylight assessments.

The ladybug toolkit features mentioned above demonstrate an excellent potential to develop a BIM-based tool that supports the design with performance-based assessments. Using the ladybug tools' software development toolkit (SDK), the iSAT toolkit aims to resolve the identified challenges regarding the interoperability between the design and assessment tools to enable an automated assessment workflow.

The methodology adopted to fulfil the 10th criterion of the JGBG's Energy Efficiency requires comparing the performance of the design proposal against four benchmark models, in which the national building codes define their characteristics.

However, with the recent design and assessment tools development, the described workflow can become more integrated and simplified in many aspects. The energy model can be created automatically from the BIM data schema containing the geometry, materials, schedules, and more. Furthermore, the parametric capabilities of the assessment tools, i.e., the ladybug toolkit, allow for different design scenarios to be generated automatically within a predefined procedure without the need to remodel the project for each scenario. Such capabilities can help eliminate the need for generating multiple versions of the performance models, thus reducing the errors in data flow and consistency between the design and performance assessment tools, data leaks, and redundant data processing, and reducing significant time and effort in preparing performance models. Hence, the iSAT-Performance package has been developed utilising the mentioned capabilities for an efficient and automated workflow. Figure 7-13 demonstrates the proposed BIM-based energy assessment workflow.

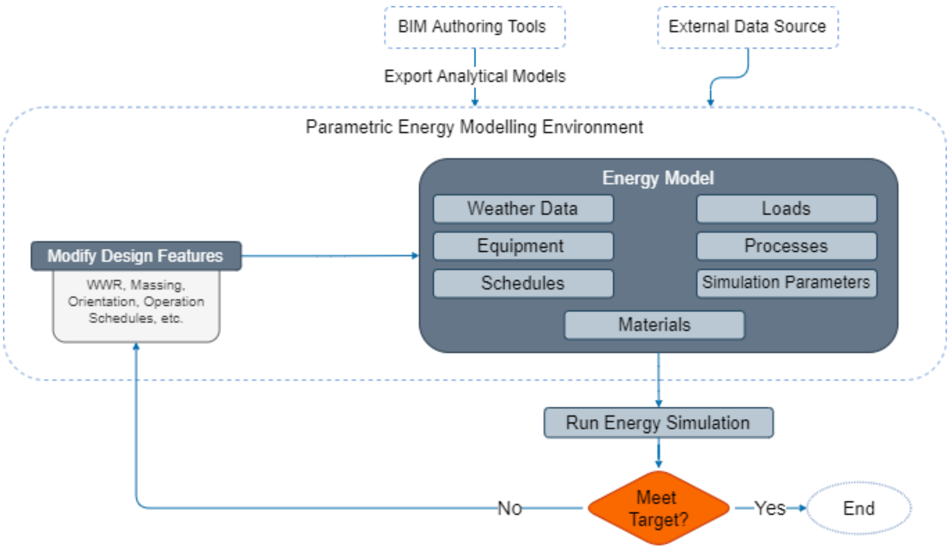


Figure 7-13 Proposed energy assessment workflow

The proposed energy assessment workflow demonstrated in this workflow utilises the gbXML model capabilities in transferring the BIM model information to the parametric energy modelling environment. The parametric capabilities of such environments allow the user to prepare different energy model alternatives with minimal effort using predefined procedures. These models are then assessed to conclude the best alternative based on the design targets.

7.4.1 Use Case: Perform Building Energy Simulations

Different steps are involved in creating a complete energy simulation workflow. This section demonstrates how the proposed iSAT-Performance package can facilitate the energy assessment described earlier in the previous section.

Currently, no tool can export an immaculate gbXML energy analytical model, especially if it is a complex project. Therefore, the iSAT-Performance utilises the features of the ladybug geometry package to read the gbXML model and check for geometry errors. Furthermore, the gbXML web-based viewer Ladybug-Spider can visually inspect the model, check for geometrical errors, such as missing and enclosed zones, and correct wrong surface types.

One of the challenges identified in this workflow is that the honeybee energy package currently does not read the schedules from the gbXML model. This technical limitation caused by the dependency on OpenStudio is identified and is marked as a work in progress by the OpenStudio developers, meaning that it should be resolved in future tool updates. However, the iSAT-Performance package consists of functions that can read external files to assign program types, including the occupancy and activity schedules, the program's people, lighting, electric and gas equipment, infiltration, and ventilation schedules. The external files are simple JSON dictionaries containing the required information to identify a complete program type. The users can create these dictionaries for any program type, allowing for a flexible data integration process.

Following the model inspection, the user can use the iSAT-Performance package to identify the project's program types and spaces, assign the HVAC components for the desired zones, and define the simulation settings and parameters. The tool allows the user to use external JSON dictionaries containing material information. It can be used to formulate different construction sets assigned to the energy model, which can help test different design proposals. Figure 7-14 demonstrates the proposed workflow using the iSAT-Performance package to perform energy performance simulations. In this workflow, the creation of different scenarios can be simplified using the parametric capabilities of the Ladybug toolkit to modify and manipulate the analytical energy model.

The author created a residential building in Autodesk Revit for the demonstration and exported it using gbXML data schema to perform the energy assessment. The quality of the analytical model was checked using the ladybug-spider web application, and the notable errors were resolved. The analytical model was then imported into the iSAT-Performance. Then, the analytical spaces, program types, simulation controls and parameters were assigned to the model. Finally, different scenarios were created to assess the building: (1) the base case (BC) represents the proposed design, (2) the benchmark case (BC1-4), characterised by the requirements specified in Table 41, and (3) a typical scenario based on the commonly used construction characteristics, and (4) an experimental scenario (scenario 6), which evaluates the BC after adding louvres. The generated models are represented in Figure 7-16. See Table 45 for more information regarding the building characteristics. The simulation

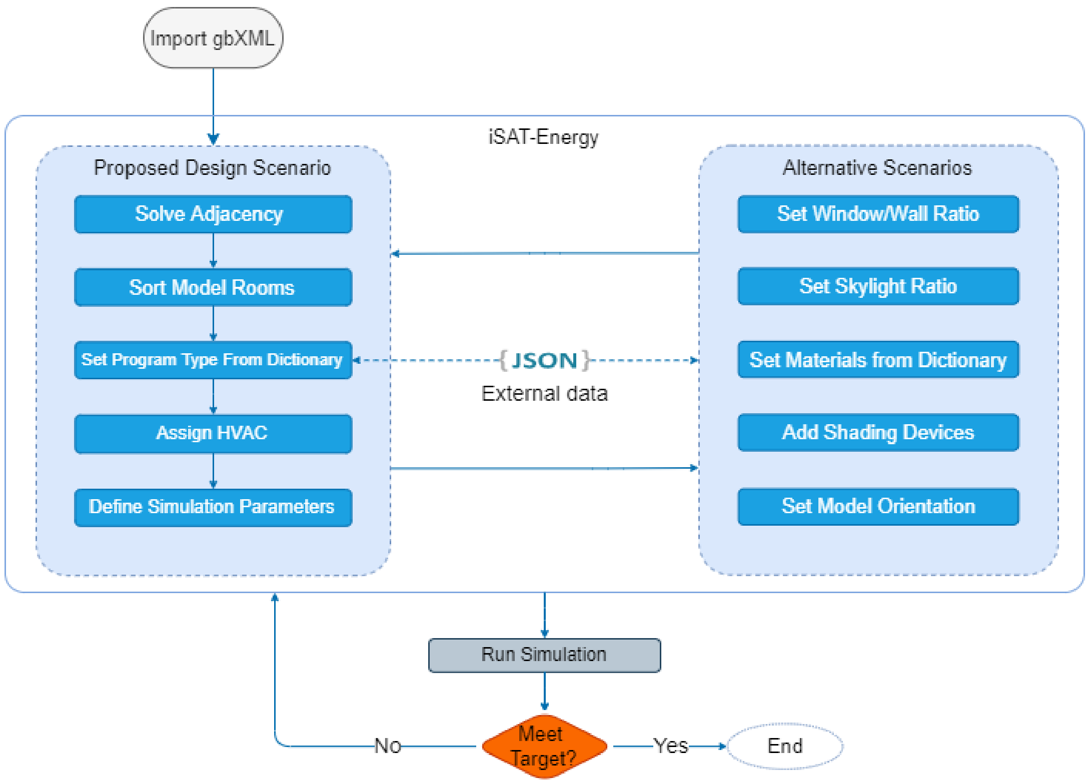


Figure 7-14 Energy Simulations Workflow

results were then compared to measure the actual performance improvement by manipulating the base case scenario and demonstrating each scenario's final energy use. See Figure 7-17 for more information.

The workflow demonstrated above highlights that the iSAT-Performance package could streamline the energy assessment of green buildings based on the 10th criterion of the Energy Efficiency category in the JGBG. Different design proposals and benchmark cases can be generated with minimal effort using the parametric capabilities of the tool. These proposals can be generated by modifying the WWR, adding external shading elements, changing the orientation, building construction sets, and more. The assessed building in this example was used for development and testing purposes. All the mode characteristics were identified and implemented using the existing literature for results validation and calibrations.

```
Analytical_Model = isat_performance,model_from_gbXML (gbXML_file)
Resolve_adjacencies = isat_performance,resolve_adjacency (Analytical_Model)
BC = isat_performance,check_errors (Resolve_adjacencies)

Model_space= isat_performance,sort_model_spaces (BC)
Space_schedule = isat_perfomance.import_space_schedules (Model_space, schedules.json)
Program_type = isat_performance.set_program_type_from_dict (Model_space, space_schedule,)
Program_type_with_ac = isat_performance.is_conditioned (Model_space, Program_type, ac_type)
Sim_control = isat.performance.simulation_control (Model_space)
Sim_parameters = isat.performance.simulation_parameters (sim_control, analysis_period,
                                                         run_period, sizing_parameter)
Typical = isat_performance.set_mateials_from_dict (BC, Typical_Jordanian_materials)
BM = iSAT_performance.set_window_wall_ratio (BC, 30)
BM = isat_performance.set_mateials_from_dict (BM, national_codes_materials)
BM1 = ista_performance.rotate_model (BM, 45)
BM2 = ista_performance.rotate_model (BM, 135)
BM3 = ista_performance.rotate_model (BM, 225)
BM4 = ista_performance.rotate_model (BM, 315)
Scenario_6= isat_performance.add_louvres (BC, distance, depth, vertical)

If run_simulation == True:
        isat_performance.run_simulation (Scenario_6, sim_parameters,)
```

Figure 7-15 Pseudocode describing the workflow to perform energy performance assessment for different design scenarios.

Table 45 Description of the assessed scenarios

Scenario	Exterior Wall (W/m²K)	Roof (W/m²K)	Floor (W/m²K)	Windows (W/m²K)	WWR	Orientation from True North	Total energy use (kWh/m².a)
Typical Jordanian Building[14]	2.4	2.6	2.6	5.8	0.07	0	80
Benchmark scenario 1	0.57	0.55	0.55	3.3	0.3	45	71.2
Benchmark scenario 2						135	71.2
Benchmark scenario 3						225	73.2
Benchmark scenario 4						315	73.5
Benchmark Average						-	72.3
Base Case	0.45	0.18	0.18	2.86	0.07	0	59.1
Base Case with louvres						0	57.7

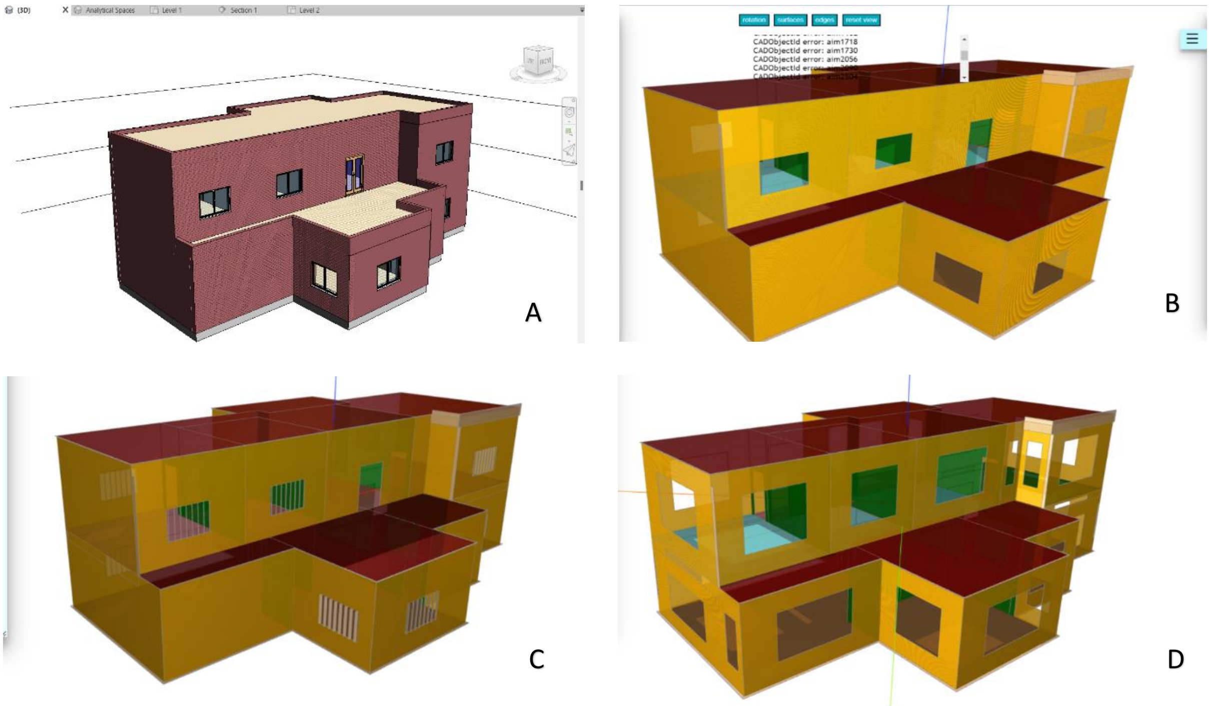


Figure 7-16 3D representation of the Demo case models (A) BIM model in Revit Environment, (B) gbXML model for the Base Case, (C) Base Case with louvres, (D) Benchmark- 1 model

[14] Benchmark scenarios to evaluate the energy performance of buildings in Jordan (Attia and Zawaydeh, 2014; Attia and Al-Khuraissat, 2016; Ali *et al.*, 2020; Abu Qadourah *et al.*, 2022).

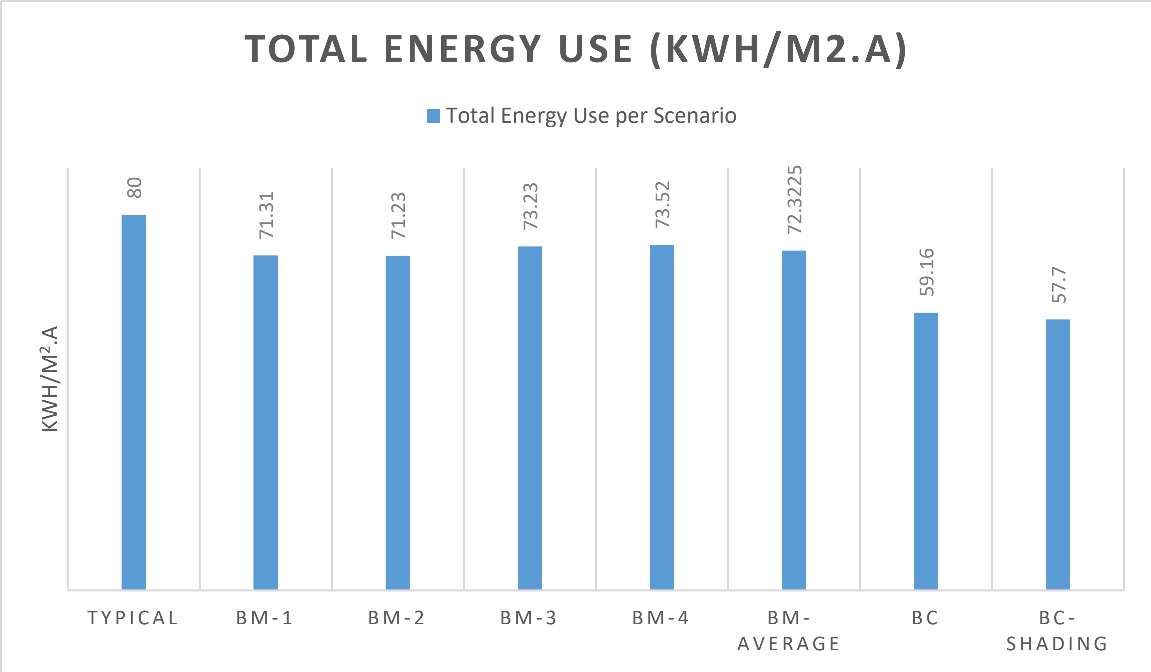


Figure 7-17 Energy performance simulation results

7.5 Tool Usability

The iSAT toolkit can effectively streamline and enhance the sustainability assessment process in green building projects. The first step involves generating BIM models using tools like Revit, where the building design is created in a parametric and data-rich environment. These BIM models serve as the foundation for the sustainability assessment process.

The second step involves using the gbXML models generated from the BIM models as input into the iSAT toolkit. While gbXML provides valuable data for certain assessment aspects, additional information may be required to complete the assessment accurately. To address this, architects can prepare JSON dictionaries containing missing information and complement the gbXML data.

With the gbXML and JSON files combined, the users can utilize the iSAT toolkit to assess the model's sustainability performance. The toolkit's parametric capabilities enable the automated execution of complex tasks, such as energy and daylighting simulations, providing valuable insights into the building's energy efficiency and indoor environment quality based on the JGBG requirements. The iSAT users can leverage this functionality to test different design scenarios, analyzing how various design variables impact sustainability outcomes.

Once the assessment is complete, the users can obtain results highlighting the building's performance based on the selected criteria and rating system. Should they wish to make design modifications or explore alternative approaches, the entire process can be repeated using updated BIM models and data. This iterative approach allows architects and design teams to refine and optimize sustainability performance throughout the building design.

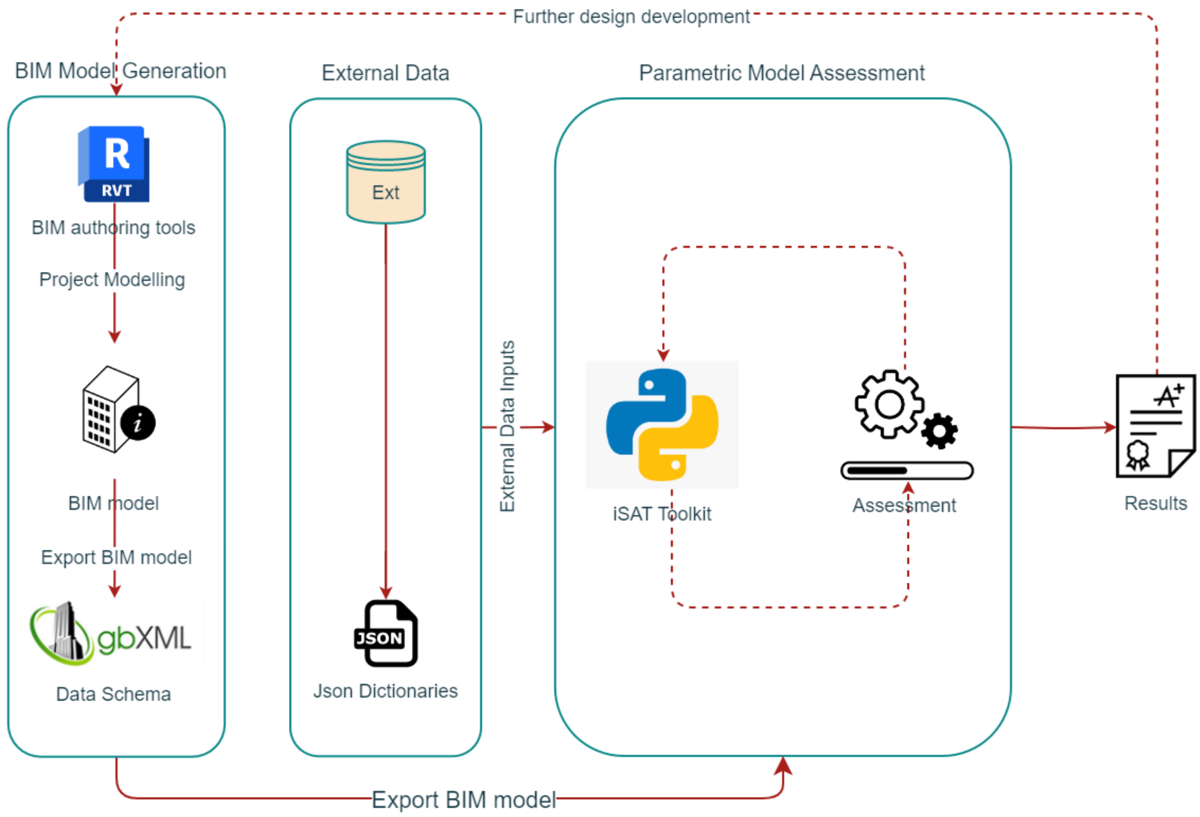


Figure 7-18 The proposed workflow to automate building sustainability assessment using the iSAT toolkit.

7.6 iSAT testing and validation

The iSAT toolkit was tested throughout the design and implementation of its components. Test cases represent extreme scenarios to evaluate the tool's performance, accuracy and reliability. The test cases ranged in size and complexity, from a single Shoebox representing a single zone to complex multi-storey buildings.

Throughout the tool development, technical issues arose for various reasons. These technical issues can be (1) wrong inputs of logical rules in the assessment procedure, (2) lack of information, and (3) inaccurate information retrieval from the targeted elements. Most of the discovered issues were resolved, and the tool was tested to guarantee accurate and reliable performance.

For the demonstration, some errors in this assessment were related to assessing the wrong opening type information. One of the Energy Efficiency criteria requires evaluating the visual transmittance of windows glass. The first step to debugging this issue was 2ensuring all the information was exported correctly from Revit.

A short report was generated representing all the opening types used in this project with their information. It was concluded that the requirements apply only to three of the four opening types found in this project. Secondly, it was discovered that the developed procedure for this assessment was initially developed to retrieve all the openings without specifying the desired opening type. After fixing all the detected bugs found in this procedure, the assessment using the iSAT toolkit was performed again, and the automated assessment could evaluate the building accurately.

7.7 Summary

This chapter has demonstrated the development of the iSAT toolkit, a BIM-based tool designed to automate building sustainability assessment. The iSAT toolkit consists of different components that perform different tasks. The iSAT-gbXML is a package developed to parse, extract, and process the building information required to perform the assessment. The iSAT-JGBG package consists of components used to assess the JGBG criteria as machine-readable rules that can be executed to assess the building components based on the available data in a gbXML model.

The iSAT toolkit currently targets criteria from three categories: Energy, Healthy Indoor Environment, and Materials and Resources, as summarised in Table 46. The energy efficiency category weighs more than 40% of the JGBG criteria, reflecting the tackled criteria's significance in the Jordanian context. As for the natural daylight assessment from the Healthy Indoor Environment category, the adopted workflow facilitates producing the daylight assessment models from the BIM data schema, thus reducing significant efforts and time in assessing the abovementioned requirement. Similarly, the required information to assess the Materials and Resources category criteria can be automated using the BIM data schema and by developing a customised workflow. These criteria were selected as proof of concept on the tool's feasibility in assessing different criteria based on their complexity level and the processes involved in performing a complete automated assessment.

Table 46 The JGBG criteria and credits that can be automated using the iSAT toolkit.

Criteria	Requirements	iSAT-ready assessment	Total available Points	Points achievable using iSAT
		Energy Efficiency		
Building Orientation	2	2	10	10
Roofs and Walls of the building envelop	4	4	4	4
Site Landscaping	1	1	2	2
Thermal Insulation of Building Envelop	19	19	10	10
Fenestration in the Building Envelope	12	12	5	5
Natural Lighting	4	2	10	6
Shading Devices	4	4	5	5
Natural Ventilation	9	5	14	2
Computer Simulation	1	1	12	12
Renewable energy on site	4	4	6	6
		Healthy Indoor Environment		
Natural Daylight	3	1	6	4
		Materials and Resources		
Material Re-use	3	3	6	6

Green Material: A: Recycled Content	2	2	4	4
Green Material: B: Local/ Regional Materials	2	2	4	4
Green Material: C: Rapidly Renewable Materials	1	1	2	2
Green Material: D: Certified Wood	2	2	4	4
Total	73	65	104	86

The potential of using the iSAT toolkit for building sustainability assessment based on the JGBG as a proof of concept can be demonstrated in Figure 7-19. Of the 203 available credit points in the JGBG categories mentioned above, 83 are possibly available for automation using the iSAT toolkit. However, the number of credit points does not reflect the actual number of criteria that can be automated. This can be explained by the number of mandatory criteria in the JGBG that must be met to nominate the building for the certification, while it does not award any credit. For further demonstration, Figure 7-20 presents the percentage of the criteria that can be assessed using the iSAT toolkit in the assessed categories.

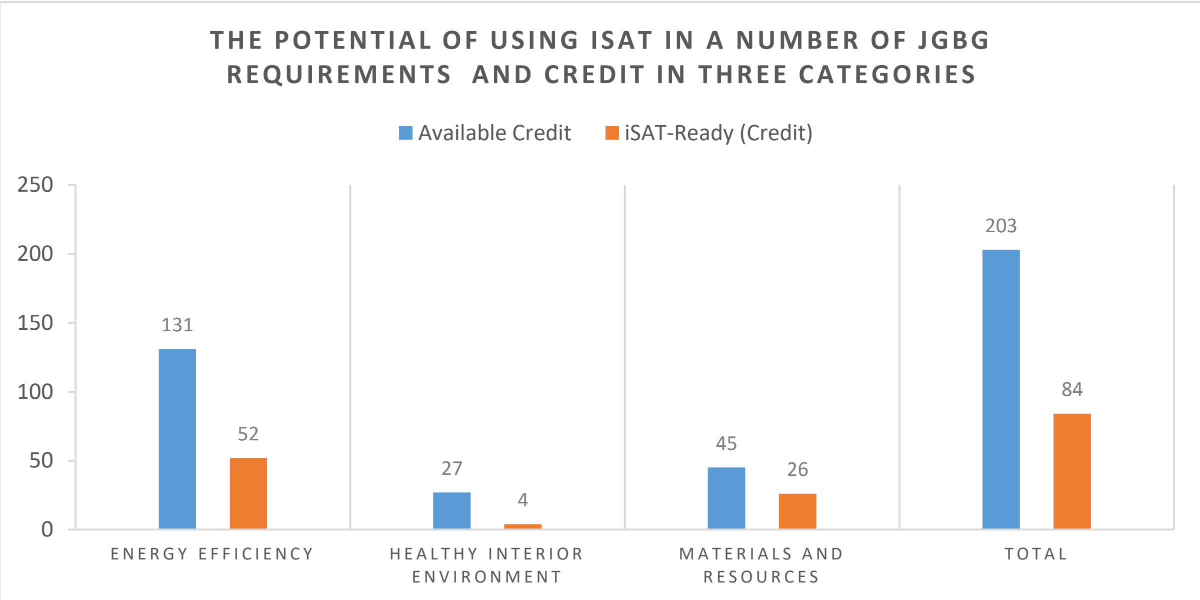


Figure 7-19 The potential of using iSAT in a number of JGBG requirements and credit in three categories

The iSAT-Performance package was built to perform complex assessment processes, such as the daylight and energy performance simulations, using the gbXML file as the data-rich model. The iSAT-Performance is a parametric analysis package built on top of the ladybug toolkit to facilitate the assessment process and allow the design teams to create and evaluate different design proposals with minimal effort. The iSAT toolkit consists of core modules comprising predefined procedures to perform specific tasks, such as data retrieval, building elements' selection and filtering, and conducting performance simulations.

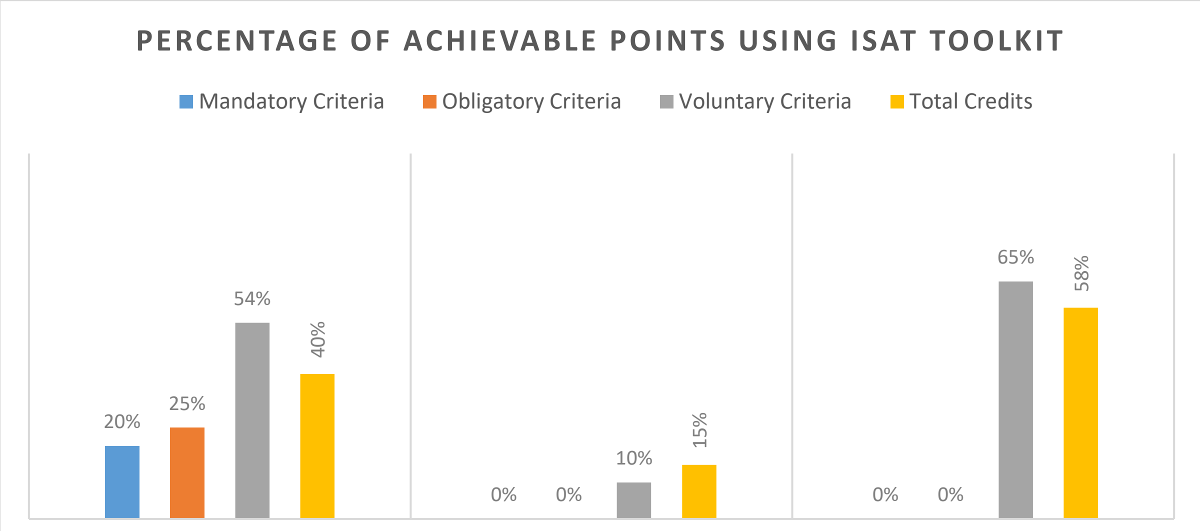


Figure 7-20 Percentage of achievable points using iSAT toolkit.

The implemented approach in the tool development allows for flexibility in expanding the tool functionality, such as hosting different GBRTs and performing different performance assessment tasks by integrating with other packages. Integrating the assessment criteria, BPS, and BIM data processing modules in one toolkit paves the way for introducing and implementing customised solutions that reduce the complexity, cost, and time required for green building assessment. The next chapter demonstrates the use of the tool in real-world case studies that were designed and certified based on the JGBG.

8. Tool validation

This chapter demonstrates using the iSAT toolkit on two case studies designed and certified based on the JGBG. This chapter aims to validate the feasibility of using the iSAT toolkit in assessing green-certified buildings. The tool was validated by comparing the process and results of assessing two case studies manually and using them tool. Two cases studies were used to assess the development of the integrated sustainability assessment toolkit (iSAT). The iSAT was evaluated by comparing the case studies assessment results generated using the iSAT toolkit against the reports provided by the architects of the buildings. The first section of this chapter introduces the selected cases, with a brief description of the related parameters which can be assessed using the proposed tool.

8.1 Introduction

Tool evaluation is vital to learning how much it fits the purpose. It concludes whether or not the tool design contributes to resolving the identified problem (Daud Ahmed and Sundaram, 2011). This chapter used two case studies to assess the development of the integrated sustainability assessment toolkit (iSAT). The iSAT was evaluated by comparing the case studies assessment results generated using the iSAT toolkit against the reports provided by the architects of the buildings. The assessment reports provided by the architects of both cases were generated manually. The main objective of using case studies was to validate the proposed tool's performance in terms of results accuracy and efficiency and to reduce the complexity of conducting complex assessments. This will also allow testing the sufficiency of using gbXML data schema to perform automated sustainability assessments of buildings.

Using the iSAT toolkit to assess JGBG-certified projects demonstrates an improved workflow to assess different aspects of the building. The iSAT contributes to automating the assessment of buildings and facilities conducting complex tasks, allowing for an improved sustainability assessment compared to manually performing the JGBG criteria assessment. This chapter aims to use case studies as a method to test the development of the iSAT toolkit approach. The first case study is a detached single-family residential building. The second is a multi-story office building promoted as a Net-Zero energy office building. Both buildings were used as a proof-of-concept of the tool’s usability in real-world scenarios, designed and constructed based on the JGBG.

Initially, the architectural details for both buildings, including the design drawings, construction details, and others, were available as traditional CAD drawings. Based on this information, the second step in the evaluation process was to remodel both buildings using Autodesk Revit. Revit is a BIM authoring tool that can generate gbXML models, and, according to Matarneh and Hamed (2017), it is the most commonly used BIM authoring tool in Jordan and, therefore, was chosen for this task.

After generating BIM models for both cases, these models are exported from Revit using the gbXML data schema. The gbXML files are used as inputs for the iSAT toolkit to assess their performance based on the available information in each project.

The iSAT toolkit was initially tested and validated throughout the development process using different demo buildings modelled for testing purposes. These models range from a simple shoebox representing one zone to complex models representing multiple levels and zones. The validation process aimed to ensure that the tool performed as expected regarding accuracy and reliability in automating the selected criteria assessment. The validation process results were iteratively assessed by comparing the tested scenarios' characteristics with the output results from the iSAT toolkit. Finally, the iSAT performance was validated based on the available information in the selected case study buildings.

8.2 Case Study One: Nizar Villa

The first building is a private residential villa located in Amman. Nizar Villa is a two-storey building with a total floor area of 400m^2. The construction of this building has achieved 72% of the total available credit and, based on this, awarded Grade B based on the JGBG. This project was provided by Seyam Architects (Seyam Architects, 2022).

The building was designed with the aim of providing a sustainable and comfortable living environment for its occupants. Several strategies were adopted in the development stage of the building, including optimising the orientation, and site vegetation, designing a compact form factor, massing studies, and

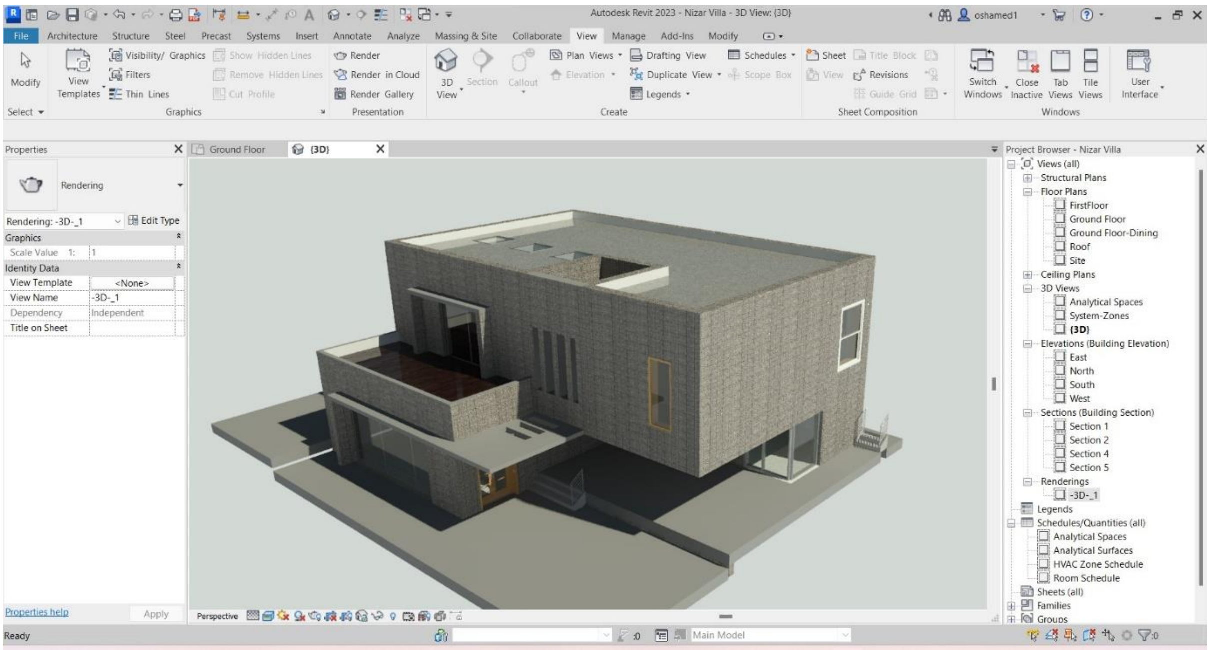


Figure 8-1 Nizar Villa 3D representation. Source (Seyam Architects, 2022).

using shading elements. The design details were provided in AutoCAD format. Therefore, these drawings were used to recreate an identical design using Autodesk Revit as a BIM authoring tool. Figure 8-1 illustrates the villa design provided by the architects (Seyam Architects, 2022), and Figure 8-2 for the created BIM model.

Figure 8-2 3D representation of Nizar Villa in Revit environment

8.2.1 iSAT tool implementation

Based on the data available about the Nizar Villa building, the building has achieved a Grade B rating based on the JGBG. The architect has implemented different strategies to achieve the maximum possible credits in all the JGBG categories. A total credit of 60% was achieved in Green Building Management, 64% in Site Sustainability, 88% in Water Efficiency, 78% in Energy Efficiency, 74% in Healthy Living Environment, and 15% in Materials and Resources.

While the current development of the iSAT toolkit tackles criteria from Energy Efficiency, Healthy Living Environment, and Materials and Resources, the other categories will not be considered for the tool validation. The selected criteria for evaluating the iSAT toolkit demonstrate different levels of complexity, which were discussed earlier in chapters 4 and 7. The assessed criteria in each category and the achieved points are provided in Table 47.

Table 47 The JGBG criteria, with total achieved points in the Nizar Villa project.

Category	Criterion	Number of JGBG's criteria	Achieved criteria	JGBG's Possible points	Achieved points
Energy Efficiency	Building Orientation	2	2	10	10
	Roofs and Walls of the building envelop	4	4	4	4
	Thermal Insulation of Building Envelops	19	19	10	10
	Fenestration in the Building Envelop	12	12	5	5
	Airtightness of Building Envelops	7	7	0	0
	Daylight	4	3	10	7
	Shading Devices	4	4	5	5
	Natural Ventilation	10	6	14	2
	Computer Simulation	1	0	12	0
	Innovative design for energy efficiency	1	1	5	5
Healthy Living Environment	Daytime lighting	3	2	6	4
Materials and Resources	Collecting and Storing Recyclable Materials	2	2	2	2
	Construction waste management	3	2	6	4
	Green Material: B: Local and Regional Materials	2	2	4	4

8.2.1.1 Energy Efficiency Criteria

1) Building Orientation

Building orientation can potentially contribute to reducing buildings' energy use based on the design features and the climate characteristics. According to the architect, the orientation of the Nizar villa was studied based on the recommendations of the JGBG. The proposed building's long axis was oriented North-South. The iSAT toolkit was used to perform an energy performance assessment for the proposed building orientation against the other orientations. Based on the assessment, it was concluded that the proposed orientation had achieved the allocated points for the *Building Orientation* criterion.

2) Roofs and Walls of Building Envelop

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
0	EE_1_V1	Voluntary	True	5	5
1	EE_1_V2	Voluntary	True	5	5

Figure 8-3 Assessment Results for Building Orientation criterion.

The first requirement in this criterion assesses the roof's slope and walls' roughness based on the climate zone where the building is located. The second requirement assesses the solar reflectance coefficient, emissivity, and absorptance of roof elements. The third and fourth requirements assess the use of cold roof techniques if used in the project.

The total score performed manually indicated that the building fulfilled all the requirements in this criterion. However, the automated assessment results using the iSAT toolkit indicated that only the first requirement was fulfilled based on the information extracted from the gbXML model. See Figure 8-4 for the final assessment results for this criterion.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
2	EE_2_V1	Voluntary	True	1	1
3	EE_2_V2	Voluntary	False	1	0
4	EE_2_V3	Voluntary	False	1	0
5	EE_2_V4	Voluntary	False	2	0

Figure 8-4 Final assessment results for Roof and Walls of Building Envelope criterion after debugging the code.

3) Thermal Insulation of Building Envelop

The fourth criterion consists of 19 requirements that assess all the building envelop overall heat transfer coefficient (U-value). It consists of Mandatory and Voluntary requirements. The Mandatory requirements represent the minimum building characteristics accepted in any building and are based on Jordan's national building codes. Complying with these requirements is compulsory and does not reward any credit.

Based on the manual assessment conducted by the design team of the Nizar villa project, the project should pass all the Mandatory and Voluntary requirements. The results of the iSAT assessment show that most criteria were met, except for the second voluntary requirement (see Figure 8-5 below). In this case, the user can export summary reports for the surfaces with their associated information Figure 8-5 highlights the unique exterior surfaces of type *"ExteriorWall".* In this project, the only wall type used for the exterior walls was "*Basic Wall: Exterior -400mm*".

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
6	EE_4_O3	Mandatory	True	0	0
7	EE_4_O4	Mandatory	True	0	0
8	EE_4_O5	Mandatory	True	0	0
9	EE_4_O6	Mandatory	True	0	0
10	EE_4_M7	Mandatory	True	0	0
11	EE_4_V1	Voluntary	True	1	1
12	EE_4_V2	Voluntary	False	2	0
13	EE_4_V3	Voluntary	True	1	1
14	EE_4_V4	Voluntary	True	2	2
15	EE_4_51	Voluntary	True	1	1
16	EE_4_V6	Voluntary	True	2	2
17	EE_4_V7	Voluntary	True	1	1
18	EE_4_V8	Voluntary	True	1	1

Figure 8-6 Final assessment results for Thermal Insulation of Building Envelope criterion for Nizar Villa project.

	Name	Description	U_value	Absorptance	Roughness
0	Basic Wall: Exterior-400mm	None	0.199432	0.7	VerySmooth
5	R-13 wood frame wall	ASHRAE 90.1 compliant R13 sheathing 16 in (400...	0.486858	0.7	None

Figure 8-5 A report highlighting a list of unique exterior walls in Nizar villa, found in the gbXML file.

4) Fenestration of the Building Envelop

The fifth criterion in the JGBG's Energy Efficiency assesses the fenestration characteristics of the building envelope. These characteristics include window-wall and skylight-roof ratio, visual transmittance, solar heat gain coefficient, and glazing heat transfer coefficient (U_g-value). Similar to the requirements of the third criterion, this assessment consists of Mandatory, Obligatory, and Voluntary requirements. A building cannot be nominated for the JGBG's certification without complying with all the Obligatory requirements.

After the assessment was performed using the iSAT toolkit, the automated assessment was able to evaluate the building accurately, matching the results of the manual assessment process. See Figure 8-7.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
19	EE_5_M1	Mandatory	True	0	0
20	EE_5_M2	Mandatory	True	0	0
21	EE_5_M4	Mandatory	True	0	0
22	EE_5_M5	Mandatory	True	0	0
23	EE_5_M6	Mandatory	True	0	0
24	EE_5_M7	Mandatory	True	0	0
25	EE_5_M8	Mandatory	True	0	0
26	EE_5_O1	Obligatory	True	1	1
27	EE_5_V1	Voluntary	True	2	2
28	EE_5_V2	Voluntary	True	1	1
29	EE_5_V3	Voluntary	True	1	1

Figure 8-7 Final assessment results for Fenestration of the Building Envelope criterion for Nizar Villa project.

5) Airtightness of the Building Envelop

This criterion consists of mandatory requirements that assess the overall building envelop airtightness. The requirements of this criterion evaluate the joints between the architectural elements, such as windows and doors, and building fixtures, such as service ducts. These requirements are evaluated by submitting supporting documents such as architectural details and design drawings. These details cannot be retrieved from a gbXML model and, as a result, cannot be automatically assessed using the iSAT toolkit.

It is beneficial for the design teams to keep track of all the criteria met while designing their projects. Therefore, the tool provided a method requiring user interaction to perform similar tasks that require providing supplementary documents. In this case, the user could interact with the iSAT toolkit by corresponding to the requirements by inputting Boolean values (True, False) to keep track of the assessment procedure. Figure 8-8 below demonstrates a sample of the code to complete the assessment based on the user inputs. Based on this, the assessment can be completed as presented in Figure 8-9.

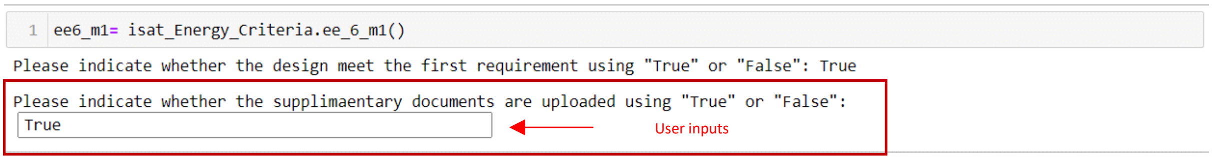


Figure 8-8 User interaction required to be completed by the user

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
30	EE_6_M1	Mandatory	True	0	0
31	EE_6_M2	Mandatory	True	0	0
32	EE_6_M3	Mandatory	True	0	0
33	EE_6_M4	Mandatory	True	0	0
34	EE_6_M5	Mandatory	True	0	0
35	EE_6_M6	Mandatory	True	0	0
36	EE_6_M7	Mandatory	True	0	0

Figure 8-9 Assessment results for Airtightness of the Building Envelope criterion for Nizar Villa project.

6) Daylight

The daylight Criterion consists of voluntary requirements evaluating design features to achieve optimal daylight quality. The assessment of this criterion demonstrates an example of the complex assessment processes. It requires complex calculations using the available model geometry information to conduct the assessment.

The architects of Nizar Villa have worked on optimising the daylight potential by implementing different strategies, such as designing windows with a height of 2.25 meters above the finish floor level and allowing for the most occupied spaces to be naturally lit from two sides. The manual assessment indicates that three out of four requirements, with a total of 7 points, were met, compared to two requirements with 6 points achieved using the iSAT. The iSAT could not assess the third and fourth requirements because of the lack of information representing the surrounding buildings' geometry required to perform further calculations and use smart control devices in the building, respectively.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
37	EE_7_V1	Voluntary	True	5	5
38	EE_7_V2	Voluntary	True	1	1
39	EE_7_V3	Voluntary	False	1	0
40	EE_7_V4	Voluntary	False	3	0

Figure 8-10 Assessment results for Daylight criterion for Nizar Villa project.

7) Shading devices

This criterion consists of three mandatory requirements for the installed shading devices specifications and one voluntary requirement that can be met by installing the proper shading system on windows based on their orientation.

The Nizar villa project does not have shading devices installed in any orientation. However, it utilises deep and narrow openings that benefit from the walls around the openings as shading elements and, therefore, was rewarded with voluntary credits.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
41	EE_8_M1	Mandatory	True	0	0
42	EE_8_M2	Mandatory	True	0	0
43	EE_8_M3	Mandatory	True	0	0
44	EE_8_V1	Voluntary	True	5	5

Figure 8-11 Assessment results for Shading Devices criterion for Nizar Villa project

8) Natural Ventilation

The natural ventilation criterion consists of mandatory and voluntary requirements that assess optimising natural ventilation strategies to reduce buildings' cooling and heating loads.

Similar to the airtightness of the building envelope criterion, the assessment can be completed by providing supplementary documents demonstrating the design compliance with the requirements. Again, such information cannot be produced based on the gbXML as these due to the schema's limitations, and therefore, the iSAT toolkit can only perform the assessment through user inputs in a questionnaire.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
45	EE_9_M1	Mandatory	True	0	0
46	EE_9_M2	Mandatory	True	0	0
47	EE_9_M3	Mandatory	True	0	0
48	EE_9_V1	Voluntary	True	1	1
49	EE_9_V2	Voluntary	True	1	1
50	EE_9_V3	Voluntary	False	1	0
51	EE_9_V4	Voluntary	False	1	0
52	EE_9_V5	Voluntary	False	5	0
53	EE_9_V6	Voluntary	False	5	0

Figure 8-12 Assessment results for Natural Ventilation criterion for Nizar Villa project

9) Computer Simulation for Energy Performance

Computer Simulation for Energy Performance is a voluntary criterion in the JGBG. It is required to perform building energy simulations for the proposed design to demonstrate energy savings compared to the benchmark models.

Twelve credits can be rewarded by complying with this criterion. However, conducting energy simulations requires significant time and effort due to the processes required to prepare the design and benchmark analytical models.

The Nizar Villa project was designed to achieve the energy efficiency targets by implementing different strategies demonstrated in the compact form factor, high-performance glazing and building envelope, and utilising the passive design features to reduce the cooling and heating loads. Nevertheless, due to the assessment's complexity, the proposed design did not meet this criterion.

One of the essential features of the iSAT toolkit is the ability to automate performing complex assessments, including energy performance simulations. The iSAT toolkit was used to perform the energy simulations of the building. With the absence of field measurements and actual data regarding the energy use for the Nizar villa building, the simulation results were validated using the existing literature for similar building types, as described in Table 48.

Table 48 Energy performance simulation results for residential buildings in Amman.

Author	**Exterior Wall (W/m^2K)**	**Roof (W/m^2K)**	**Floor (W/m^2K)**	**Windows (W/m^2K)**	**Total energy use ($kWh/m^2.a$)**
(Attia and Al-Khuraissat, 2016)	0.49	0.79	1.47	5.70	85
(Attia and Zawaydeh, 2014)	2.0	1.0	1	5.8	45
(Ali *et al.*, 2020)	2.38	2.37	2.37	5.8	51.2
(Abu Qadourah *et al.*, 2022)	2.47	0.84	1.85	5.92	85

Figure 8-13 below highlights the overall energy savings for the proposed design by comparing the assessment results for the benchmark and proposed design models. Based on the simulations performed for Nizar villa, it was concluded that 30% of the total energy consumption could be achieved compared to the average benchmark model's performance. A breakdown of the energy use for the proposed design was produced using the iSAT toolkit, demonstrated in Figure 8-14.

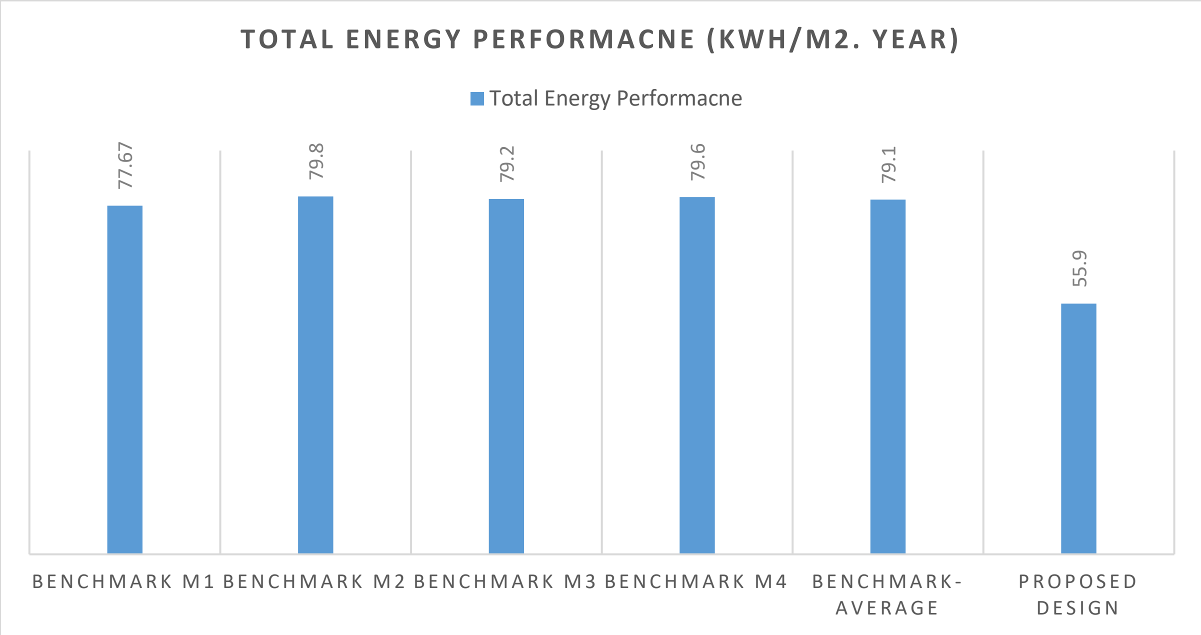


Figure 8-13 Energy performance assessment for the Nizar Villa project.

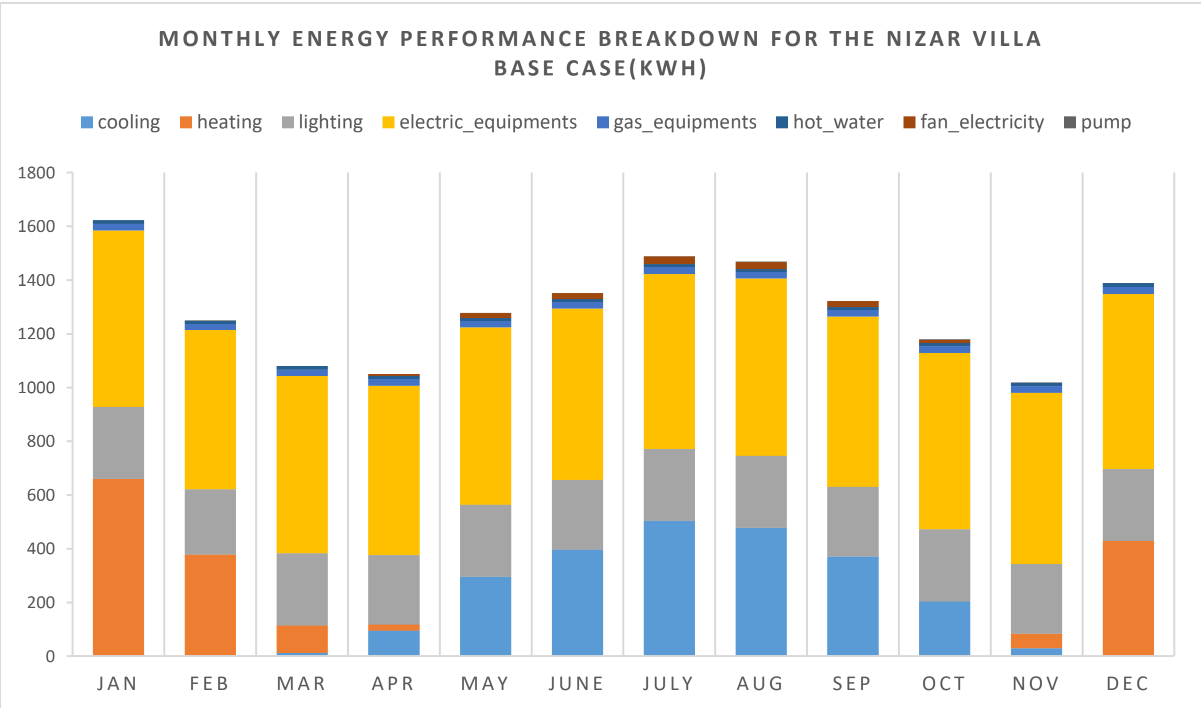


Figure 8-14 Energy performance breakdown for the Nizar villa Base Case.

8.2.1.2 Healthy Indoor Environment Criteria

The JGBG's Healthy Indoor Environment category consists of criteria that assess the indoor thermal comfort, lighting and daylighting, indoor air quality, and acoustic performance of buildings. The current implementation can only assess the Daytime lighting criterion from this category. Other criteria that depend on building performance simulations will be implemented into future tool updates, such as indoor air quality assessment.

1) Daytime lighting

According to the JGBG, daylight quality can be assessed using different methods, such as field measurements after the project's construction or during the design development using performance simulation tools. This criterion is also cross-referenced in the 7th criterion in the JGBG's Energy Efficiency category.

The Nizar villa project has fulfilled this criterion by conducting field measurements to measure the daylight levels in different zones. Like energy performance simulations, daylight simulations can be automated using the iSAT toolkit. Different results can be generated using iSAT, such as the Point in time view, daylight factor, and annual daylight. Figure 8-16 and Figure 8-15 demonstrate rendered images for one of the Nizar Villa spaces, and Figure 8-17 illustrates the Useful Daylight Illuminance (UDI) heatmap for the same space produced using the iSAT toolkit.

Based on the UDI heatmap presented below, it can be concluded that the examined space has successfully achieved the minimum requirements to meet the first voluntary requirement.

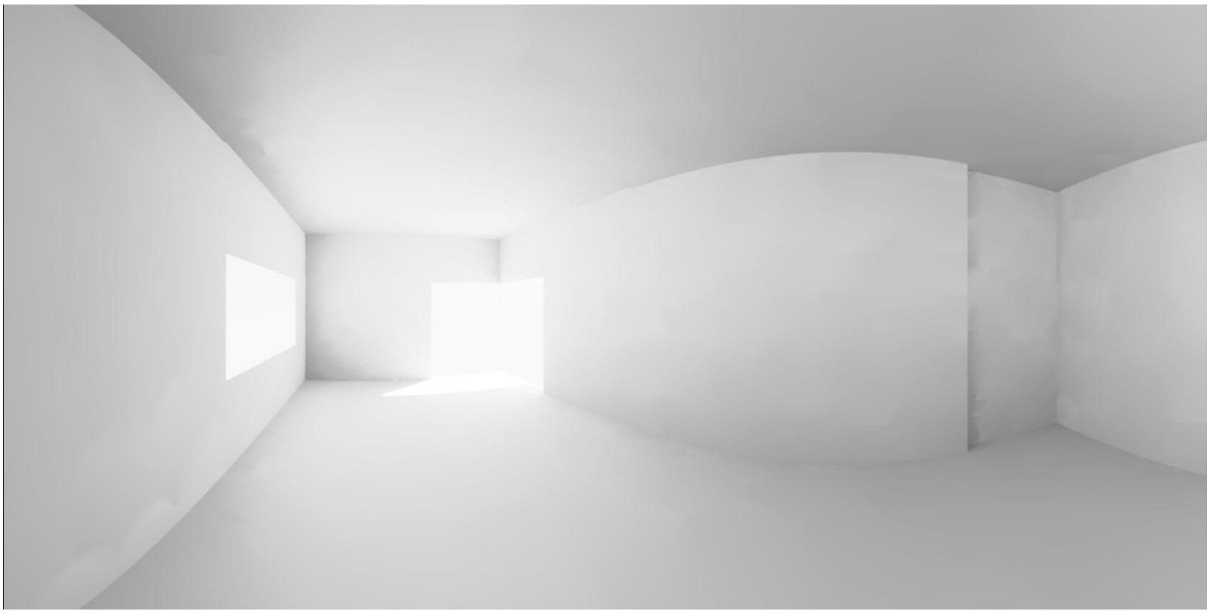


Figure 8-16 Point-In-Time-View produced using the iSAT toolkit for the Kitchen zone.

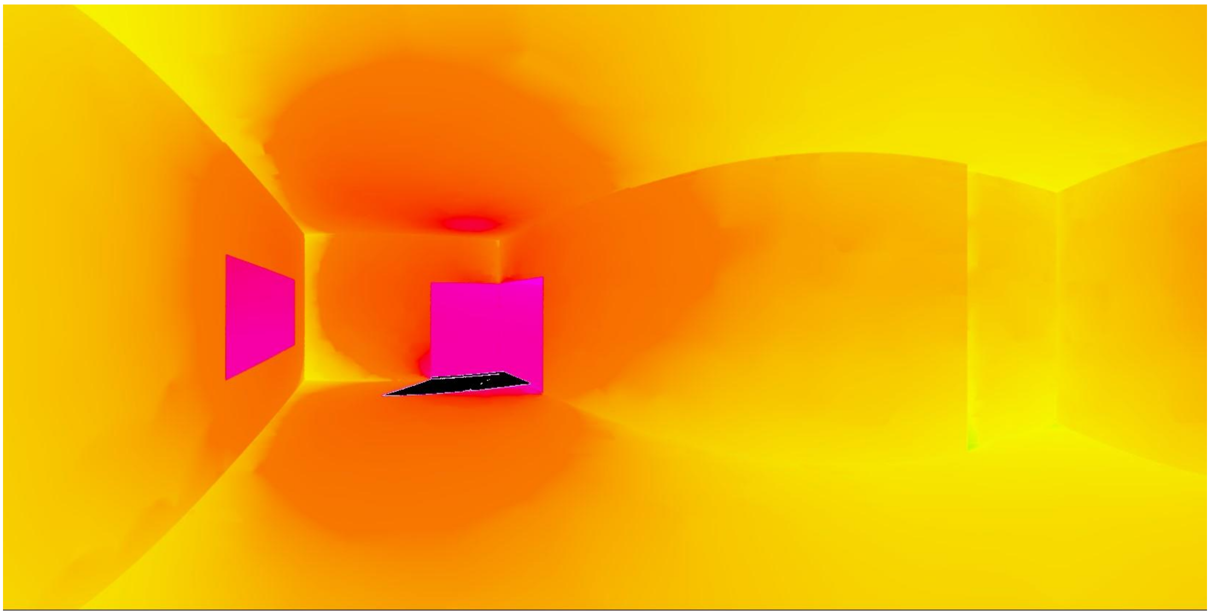


Figure 8-15 Point-In-Time-View (false color) image produced using the iSAT toolkit for the Kitchen zone.

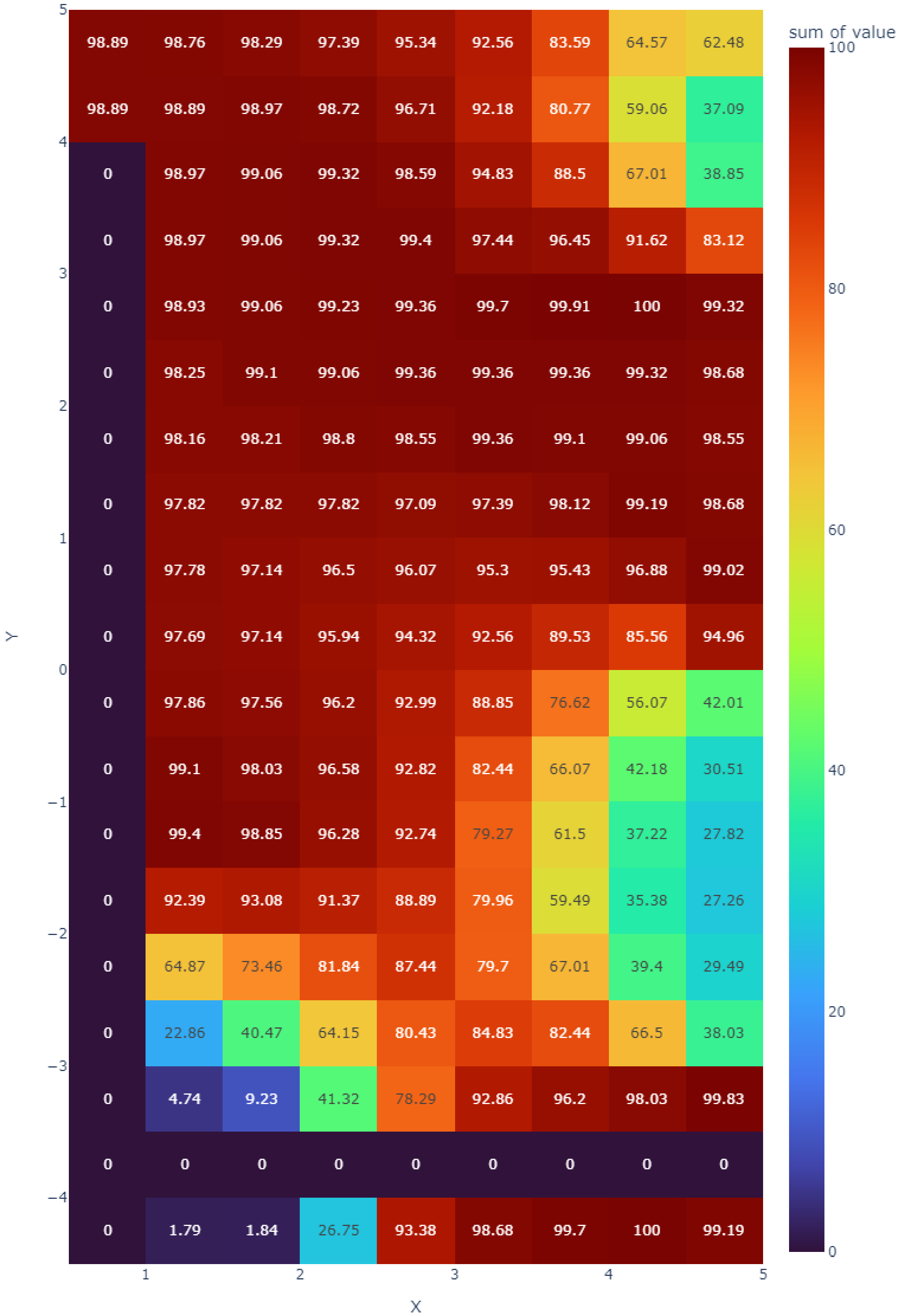


Figure 8-17 Heatmap representing the Useful Daylight Illuminance (UDI) for the for the Kitchen zone using the iSAT toolkit.

8.2.1.3 Materials and Resources

Materials and Resources consist of different criteria to assess the use of materials in different aspects, aiming to reduce the demand for virgin materials and encourage the use of renewable, recyclable, and local materials. It also consists of criteria to assess issues related to occupants' health, such as using low-emittance materials.

The gbXML schema consists of a *Material* element that embeds most of the required information to conduct the assessment of the JGBG's Materials and Resources criteria. However, the material information exported models from the BIM authoring tool does not consist of the required information. Therefore, automating the criteria assessment became challenging. This issue has been resolved by providing a supplementary data dictionary generated with the required materials information and using the iSAT toolkit, and the information was mapped with the gbXML data.

After implementing the iSAT to assess the material's performance, it was noted that the results did not match the ones provided by the architect. The mismatch between the results occurred because of the inaccurate surfaces and furniture in the gbXML file. gbXML models can be successfully integrated into energy and daylight assessments because of the excellent geometry representation within the space boundary conditions. External surfaces outside the boundary condition are not always represented accurately, and the furniture elements cannot be represented in the schema.

For an accurate materials assessment, the quantities of these materials must be accurately represented, and the necessary information must be present. Based on this, it was concluded that Materials and Resources calculations could not be implemented in the iSAT within the limited data representation in the existing gbXML models.

8.3 Case Study Two: National Energy Research Centre

The National Energy Research Centre (NERC) is a six-storey office building designed by Dabbas architectural office (Dabbas Architectural Office, no date). It comprises several office spaces, laboratories, workstations, and others, with a total floor area of 2940 m^2. The NERC was designed to become a Net Zero Energy building by implementing passive and active design techniques to reduce its heating and cooling loads and provide a healthy living environment for its occupants. The NERC project was awarded Grade A for office buildings based on the JGBG's assessment results.

Figure 8-19 3D representation of the NERC office building. Source (Dabbas Architectural Office, no date).

Figure 8-18 3D representation of the NERC office building in the BIM modelling environment.

8.3.1 iSAT tool implementation

Similar to the Nizar villa project, the selected assessment criteria are limited to Energy Efficiency, Healthy Indoor Environment, and Materials and Resources. However, the difference between both buildings lies in the slight variations between the office and residential building types requirements. The NERC represent a complex project due to its built area, complex geometry, and space types and use patterns.

Table 49 NERC achieved criteria

Category	Criterion	Number of criteria	Achieved criteria	Possible points	Achieved points
Energy Efficiency	Building Orientation	2	2	10	10
	Roofs and Walls of the building envelop	4	4	4	4
	Site landscaping	1	1	2	2
	Thermal Insulation of Building Envelops	19	19	10	10
	Fenestration in the Building Envelop	12	12	5	5
	Airtightness of Building Envelops	7	7	0	0
	Daylight	4	3	10	7
	Shading Devices	4	4	5	5
	Natural Ventilation	10	6	14	2
	Computer Simulation	1	0	12	0
	Renewable Energy	4	4	8	8
	Innovative design for energy efficiency	1	1	5	5
Healthy Living Environment	Daytime lighting	3	2	6	4

8.3.1.1 Energy Efficiency Criteria

1) Building Orientation

Building orientation can potentially contribute to reducing buildings' energy use based on the design features and the climate characteristics. According to the architect, the orientation of the NERC building was studied based on the recommendations of the JGBG. The proposed building's long axis was oriented North-South.

The iSAT toolkit assessment highlights significant energy savings for the proposed orientation compared to the other benchmark scenarios. Thus, the NERC was awarded 10 points for this criterion, matching the manual assessment results. See Figure 8-20.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
0	EE_1_V1	Voluntary	True	5	5
1	EE_1_V2	Voluntary	True	5	5

Figure 8-20 NERC assessment results for Building Orientation criteria.

2) Roofs and Walls of Building Envelop

The total score performed manually indicated that the building had fulfilled all the requirements in this criterion. However, the automated assessment results using the iSAT toolkit indicated that only the first requirement was met for the NERC project. The results presented in Figure 8-21 are similar to the first case study due to the lack of information representation in the gbXML file.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
2	EE_2_V1	Voluntary	True	1	1
3	EE_2_V2	Voluntary	False	1	0
4	EE_2_V3	Voluntary	False	1	0
5	EE_2_V4	Voluntary	False	2	0

Figure 8-21 NERC assessment results for Roofs and Walls of the Building Envelope criterion

3) Site Landscaping

The site landscaping criterion consists of one voluntary requirement that assesses using the proper vegetation specifications to provide shading for the building to reduce its heating and cooling demand. It is considered only for buildings with green and open spaces.

The NERC has fulfilled the requirement through the manual assessment. However, the iSAT toolkit could not accurately assess this criterion because of the lack of information in the gbXML model, even though the schema consists of elements that define the vegetation elements in the project. See Figure 8-22 below for more information.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
6	EE_3_V1	Voluntary	False	2	0

Figure 8-22 NERC assessment results for Site Landscaping criterion

4) Thermal Insulation of Building Envelop

Based on the manual assessment, the NERC project has passed all the mandatory and most voluntary requirements, as demonstrated in Figure 8-23. Again, the results of this assessment match the assessment performed manually.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
7	EE_4_O3	Mandatory	True	0	0
8	EE_4_O4	Mandatory	True	0	0
9	EE_4_O5	Mandatory	True	0	0
10	EE_4_O6	Mandatory	True	0	0
11	EE_4_M7	Mandatory	True	0	0
12	EE_4_V1	Voluntary	True	1	1
13	EE_4_V2	Voluntary	False	2	0
14	EE_4_V3	Voluntary	True	1	1
15	EE_4_V4	Voluntary	True	2	2
16	EE_4_51	Voluntary	True	1	1
17	EE_4_V6	Voluntary	True	2	2
18	EE_4_V7	Voluntary	True	1	1
19	EE_4_V8	Voluntary	True	1	1

Figure 8-23 NERC assessment results for Thermal Insulation of the Building Envelope criterion

5) Fenestration of the Building Envelope

The NERC southern and northern elevations in the NERC consist of a sizeable window-wall ratio (WWR) to allow maximum daylight and natural ventilation. The openings of the building have been assessed using the iSAT toolkit, and the results presented in Figure 8-24 match the manual assessment results for this criterion.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
20	EE_5_M1	Mandatory	True	0	0
21	EE_5_M2	Mandatory	True	0	0
22	EE_5_M4	Mandatory	True	0	0
23	EE_5_M5	Mandatory	True	0	0
24	EE_5_M6	Mandatory	True	0	0
25	EE_5_M7	Mandatory	True	0	0
26	EE_5_M8	Mandatory	True	0	0
27	EE_5_O1	Obligatory	True	1	1
28	EE_5_V1	Voluntary	True	2	2
29	EE_5_V2	Voluntary	True	1	1
30	EE_5_V3	Voluntary	True	1	1

Figure 8-24 NERC assessment results for the Fenestration of the Building Envelope criterion

6) Airtightness of the Building Envelop

Similar to the Nizar villa project, this criterion was assessed using a simplified questionnaire to allow tracking of the project information throughout the assessment process. Hence, all the mandatory requirements were passed, and the results are presented in Figure 8-25.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
30	EE_6_M1	Mandatory	True	0	0
31	EE_6_M2	Mandatory	True	0	0
32	EE_6_M3	Mandatory	True	0	0
33	EE_6_M4	Mandatory	True	0	0
34	EE_6_M5	Mandatory	True	0	0
35	EE_6_M6	Mandatory	True	0	0
36	EE_6_M7	Mandatory	True	0	0

Figure 8-25 NERC assessment results for the Airtightness of the Building Envelope criterion

7) Daylight

The NERC design features more than 80% of the occupied spaces to be naturally lit. It was achieved by maximising the openings in the northern and southern elevations and using proper shading elements that reduce glare. The criterion is cross-referenced in the 5th criterion in the Healthy Indoor Environment category, and a sample from the simulation results will be presented later in the next section. However, only the second voluntary requirement was met using the iSAT toolkit (see Figure 8-26). Most spaces are not lit from two sides, and the third requirement applies only to residential buildings, while the fourth requirement assesses information unavailable in the gbXML model.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
38	EE_7_V1	Voluntary	False	5	0
39	EE_7_V2	Voluntary	True	1	1
40	EE_7_V4	Voluntary	False	3	0

Figure 8-26 NERC assessment results for the Daylight criterion

8) Shading devices

As described earlier, the NERC project design has used proper shading elements for the northern and southern elevations. However, the shading elements were not presented in the gbXML model; therefore, the automated assessment using iSAT failed to evaluate the requirements of this criterion. Figure 8-27 presents the assessment results using the iSAT toolkit.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
41	EE_8_M1	Mandatory	False	0	0
42	EE_8_M2	Mandatory	False	0	0
43	EE_8_M3	Mandatory	False	0	0
44	EE_8_V1	Voluntary	False	5	0

Figure 8-27 NERC assessment results for the Shading Devices criterion

9) Natural Ventilation

Similar to the airtightness of the building envelope criterion, part of the assessment can be completed by providing supplementary documents demonstrating the design compliance with the requirements through a simple questionnaire to the user. However, for the remaining requirements, although the design features allow for natural ventilation through different strategies, such as the use of Atrium space, the iSAT toolkit was unable to detect the atrium space despite being exported to the gbXML model. The manual assessment awarded the project six out of 14 points, while zero credit was achieved using the iSAT toolkit. See Figure 8-28 below.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
45	EE_9_M1	Mandatory	True	0	0
46	EE_9_M2	Mandatory	True	0	0
47	EE_9_M3	Mandatory	False	0	0
48	EE_9_V1	Voluntary	False	1	0
49	EE_9_V2	Voluntary	False	1	0
50	EE_9_V3	Voluntary	False	1	0
51	EE_9_V4	Voluntary	False	1	0
52	EE_9_V5	Voluntary	False	5	0
53	EE_9_V6	Voluntary	False	5	0

Figure 8-28 NERC assessment results for the Natural Ventilation criterion

10) Computer Simulation for Energy Performance and Renewable Energy

Up to 20 points can be achieved by performing energy simulations (12 credits) and installing renewable energy that produces 2.5% (2 credits) and up to 10% or more (8 credits) of the total building energy use.

The NERC was initially designed to reach a Net Zero energy performance by implementing passive and active techniques, such as reducing the heating and cooling loads through natural ventilation and daylighting, installing shading elements, and using energy-efficient systems. After reducing the overall energy demand, renewable energy systems were installed to cover a large portion of the energy use.

The design teams of the NERC project did not perform the energy performance simulations to assess the building's energy use. The simulation results demonstrate that the NERC proposed design could potentially reduce around 13% of total energy use compared to the Benchmark models, and therefore, ten credits were achieved using the iSAT toolkit. Figure 8-30 presents the energy performance simulation results, and Figure 8-29 presents a breakdown of the total energy use for the base case for the NERC project.

Furthermore, using the iSAT toolkit, it was estimated that the total energy produced by the photovoltaic (PV) panels covers up to 32% of the total energy use, assuming that 50% of the roof area was used for the PV panels, with 15% panel efficiency. Figure 8-31 presents the total score achieved using the iSAT toolkit for the Renewable energy criterion.

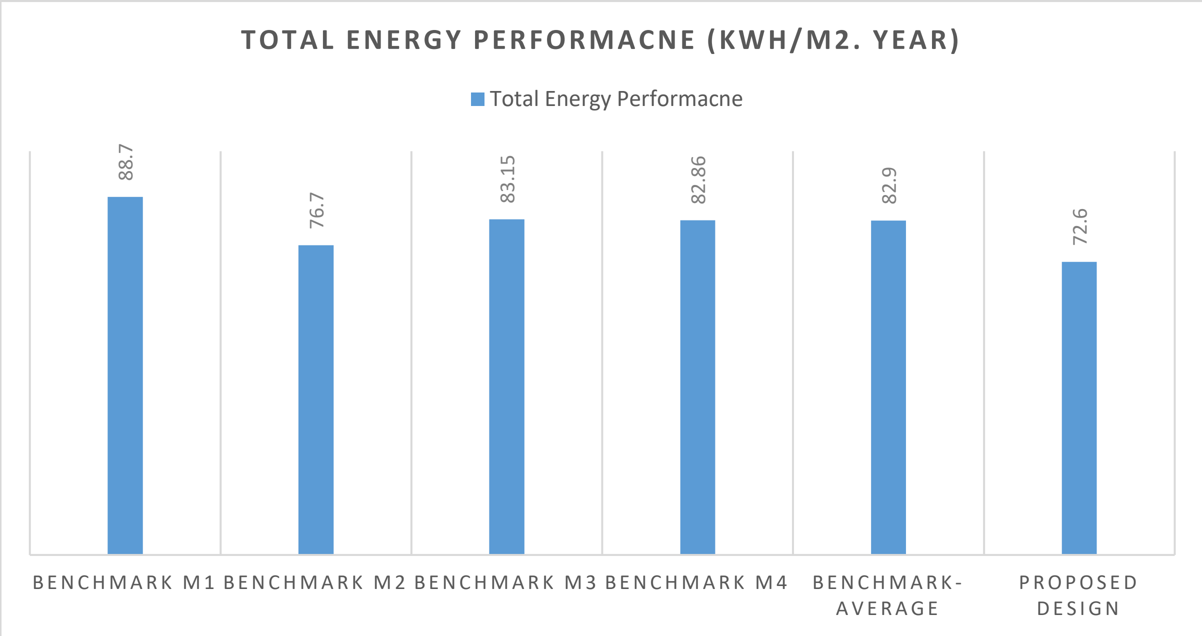


Figure 8-30 Energy performance assessment for the NERC project.

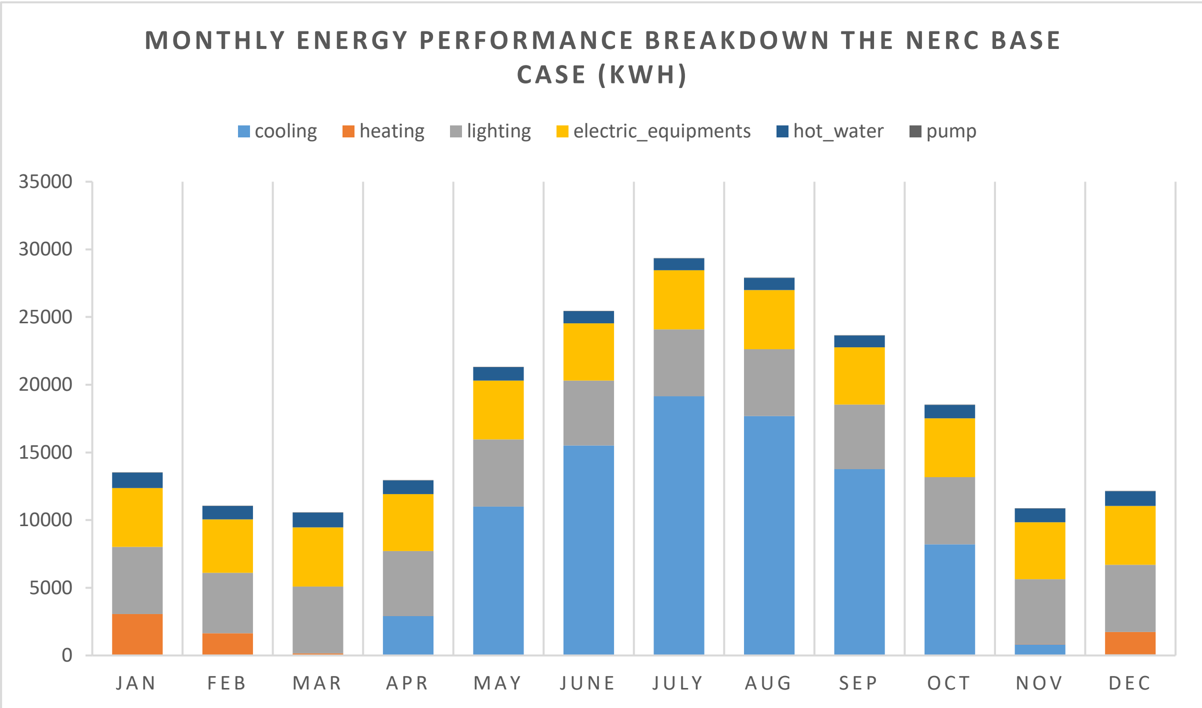


Figure 8-29 Energy performance breakdown for the NERC Base Case.

	Criteria	RequirementType	isCriteriaMet	PossibleScore	AchievedScore
54	EE_27_V1	Voluntary	True	2	2
55	EE_27_V2	Voluntary	True	4	4
56	EE_27_V3	Voluntary	True	6	6
57	EE_27_V4	Voluntary	True	8	8

Figure 8-31 NERC assessment results for the Renewable Energy criterion

8.3.1.2 Healthy Indoor Environment Criteria

The JGBG's Healthy Indoor Environment category consists of criteria that assess the indoor thermal comfort, lighting and daylighting, indoor air quality, and acoustic performance of buildings. The current implementation can only assess the Daytime lighting criterion from this category. Other criteria that depend on building performance simulations will be implemented into future tool updates, such as indoor air quality assessment.

1) Daytime lighting

The design teams did not assess the NERC daylight performance. However, using the iSAT toolkit, the assessment was performed automatically, and this section presents part of the simulation results.

The JGBG criteria require meeting a minimum threshold of 270 lux in office buildings for 50% or more of the occupied spaces in the offices and commercial buildings. This section presents the results of the first floor's Lobby space inside the NERC building.

Figure 8-33 and Figure 8-32 demonstrate rendered and false colour images for the assessed space, respectively. Figure 8-34 illustrates the UDI heatmap for the same space produced using the iSAT toolkit. Based on the UDI heatmap presented below, it can be concluded that the examined space has successfully achieved the minimum requirements to meet the first voluntary requirement.

Figure 8-33 Point-In-Time View produced using the iSAT toolkit for the First Floor Lobby space in the NERC building.

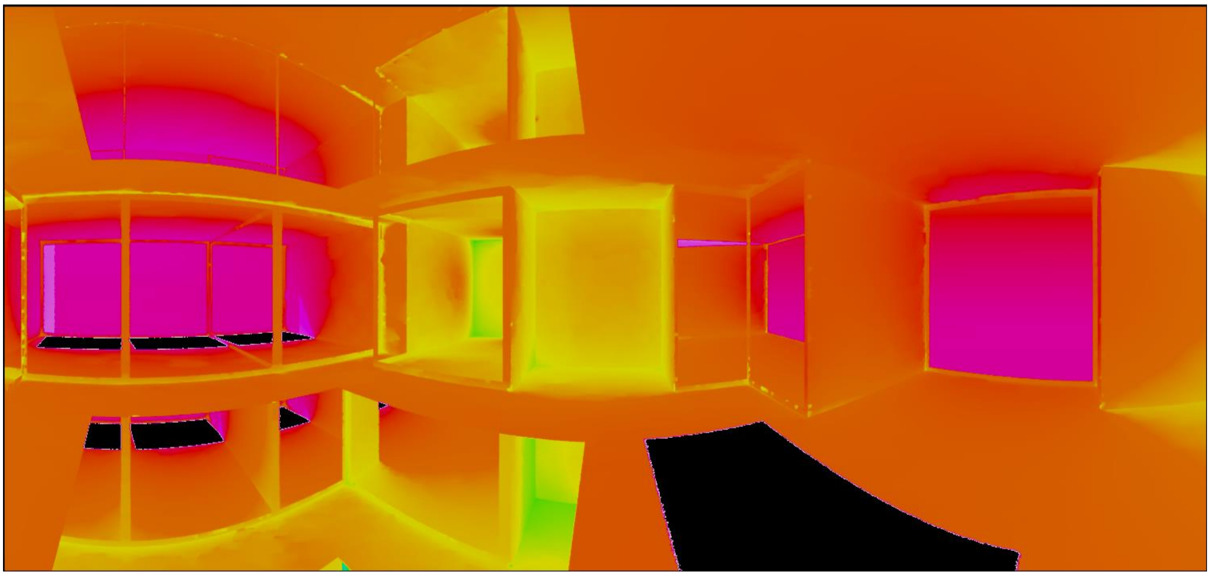


Figure 8-32 Point-In-Time View (false color) produced using the iSAT toolkit for the First Floor Lobby space in the NERC building.

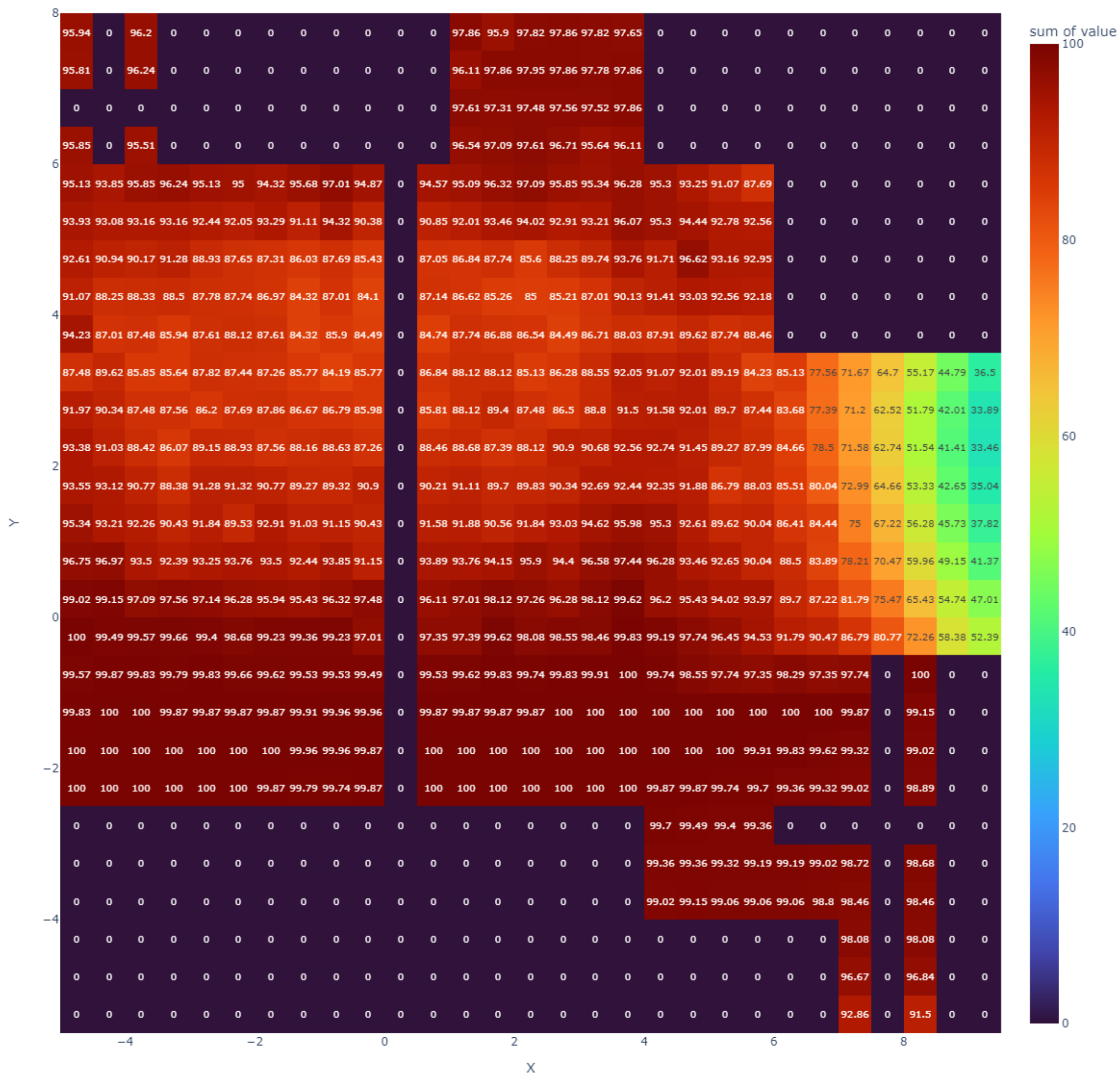


Figure 8-34 Heatmap representing the Useful Daylight Illuminance (UDI) for the for the First Floor Lobby area using the iSAT toolkit.

8.4 Results and Discussion

The information presented earlier highlighted that using the iSAT toolkit allows multiple criteria to be assessed automatically. The presented results highlighted that, in most cases, the automated assessment results matched the ones performed manually. However, because of the limitations of the gbXML data schema, assessing some requirements was not possible. The main reasons for this limitation can be demonstrated as (1) the lack of data presentation in the gbXML model despite being available from the BIM authoring tool in the case of site vegetation and materials' physical properties, (2) the complexity of extracting the relevant information in the case of detecting the atrium space for natural ventilation, and (3) the inaccurate data representation, in the case of materials quantification.

Nevertheless, within the assessment of the Nizar villa project, the iSAT could assess 54/65 requirements, with a total of 54/57 credits. See Figure 8-36 and Figure 8-35 for more information.

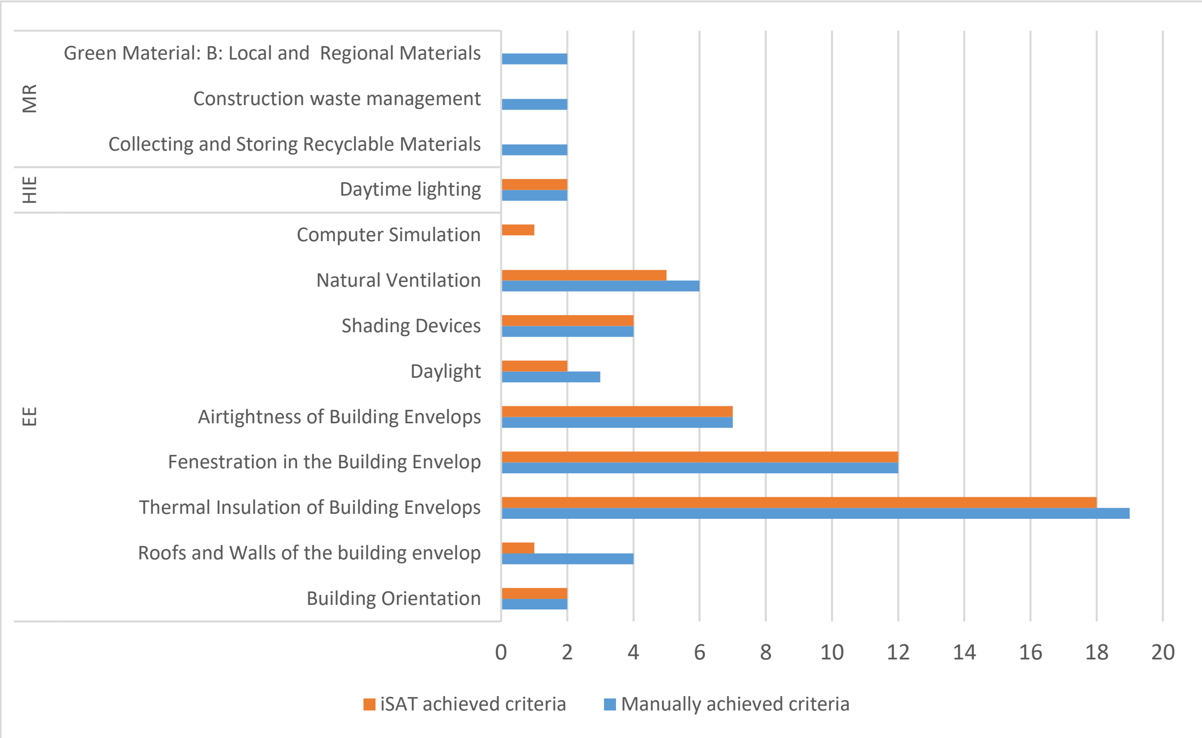


Figure 8-36 Comparison of the total achieved requirments in Nizar Villa project using the iSAT and manual assessment.

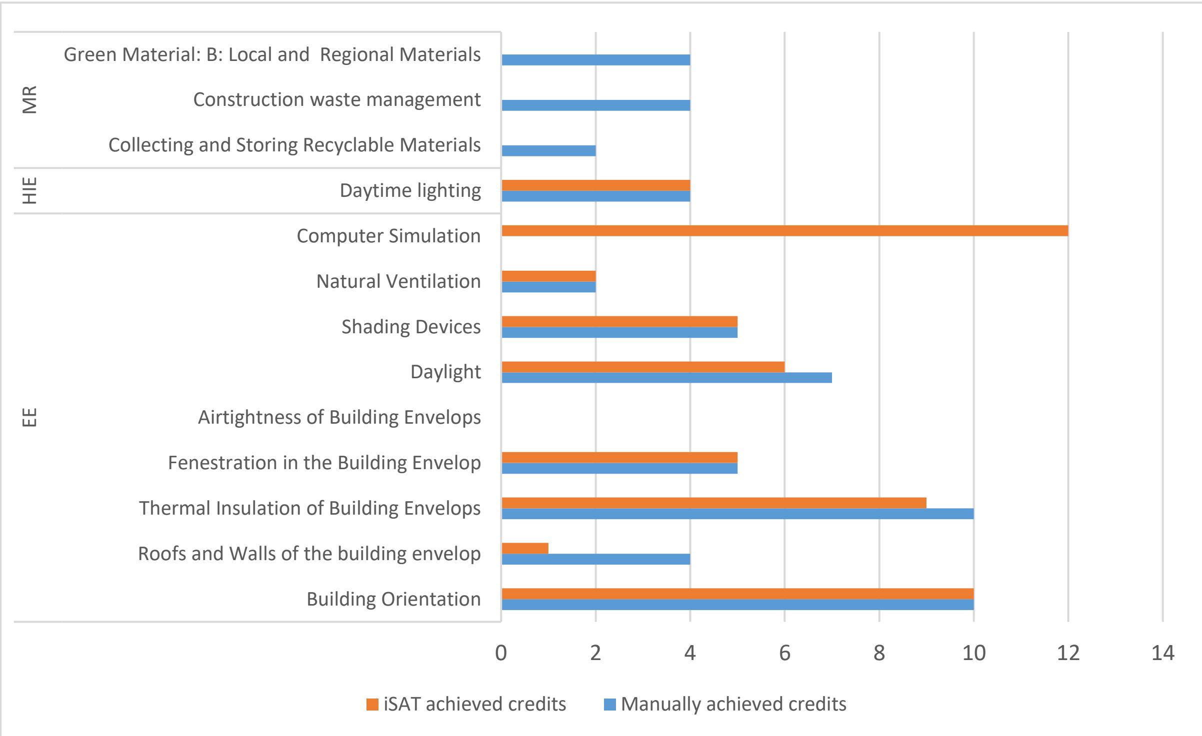


Figure 8-35 Comparison of the total achieved credits in Nizar Villa project using the iSAT and manual assessment.

As for the NERC building, 53 requirements were successfully assessed using the iSAT tool, with a total of 50 credits, compared to 63 requirements and 58 credits achieved manually.

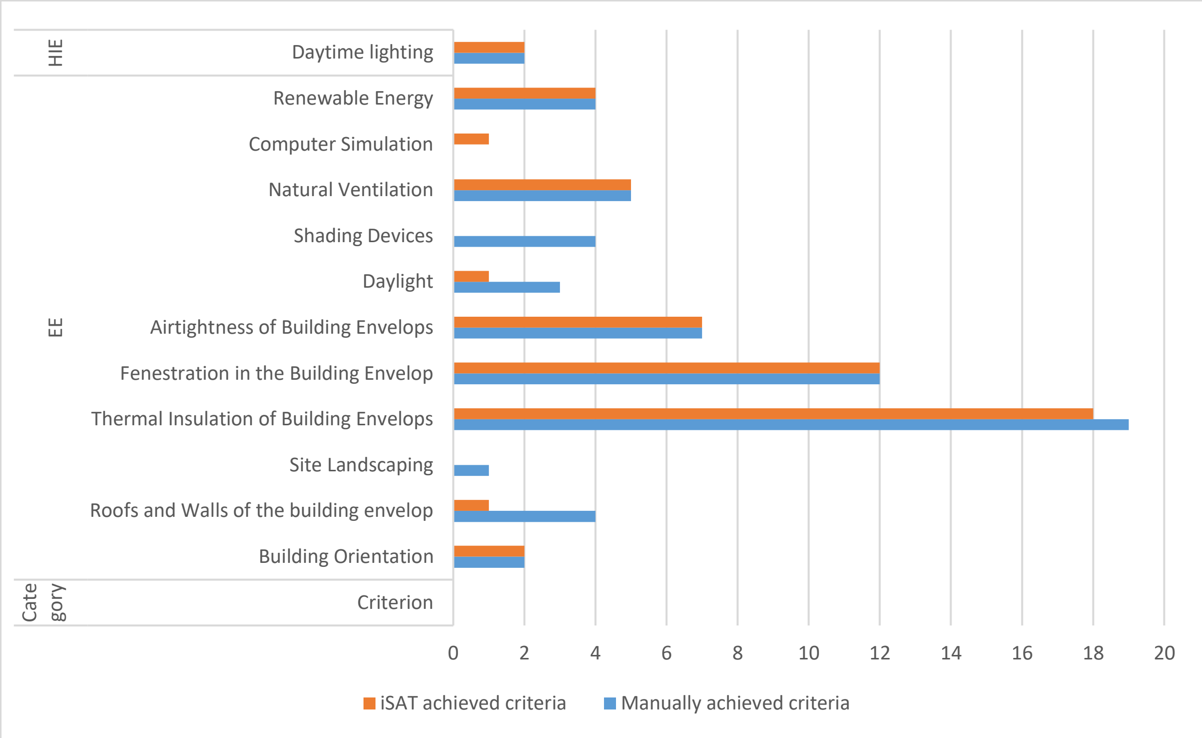


Figure 8-38 Comparison of the total achieved requirments in the NERC project using the iSAT and manual assessment.

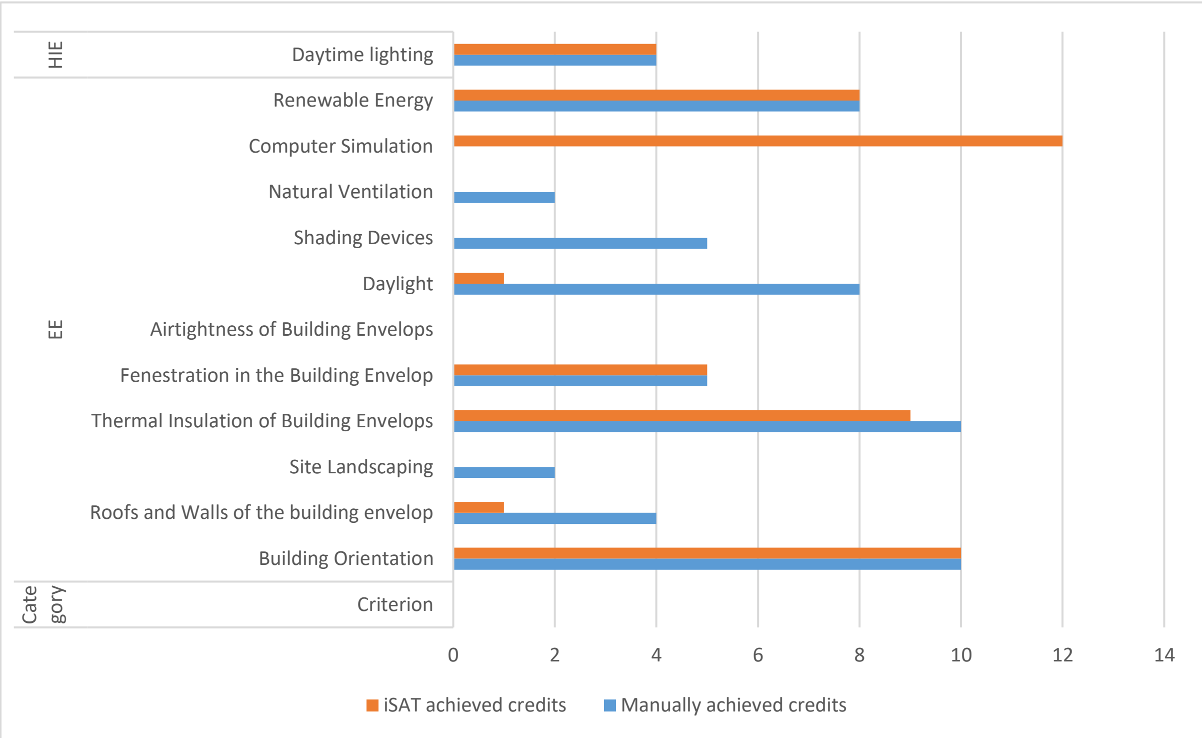


Figure 8-37 Comparison of the total achieved credits in the NERC project using the iSAT and manual assessment.

The JGBG assessment criteria consist of numerous factors, some of which require integrating different design and assessment tools. As discussed earlier, manually assessing such criteria could lead to errors caused by generating multiple design and assessment models, which could lead to multiple data entries, data leaks, redundant data processing, errors in data consistency and flow between the design and performance models, and would require significant time and effort to prepare.

On the other hand, The iSAT tool demonstrates significant advantages over the manual assessment process in supporting the JGBG criteria assessment. By automating and streamlining complex tasks, such as energy performance and daylighting simulations, the iSAT tool enables quick checks for project compliance with assessment criteria. It seamlessly integrates design and assessment models into a single workflow, allowing design teams and project stakeholders to achieve more points than manual assessments. Many green building projects face challenges in performing complex tasks due to time constraints and resource limitations when targeting the JGBG criteria. With iSAT's support, projects have the potential to earn more points based on the JGBG’s criteria, enhancing their overall sustainability performance. The iSAT tool's automation and efficiency empower designers to make informed decisions and implement sustainable design strategies effectively, making significant strides towards environmentally conscious and energy-efficient design practices.

The accuracy of the tool results is highly reliable on the input models and the information embedded in them. While implementing BIM authoring tools can help reduce redundant tasks, allow for tool integration, and produce data-rich models, the design teams must be aware of the capabilities and limitations of the adopted workflows to transfer data between tools. Within this research’s technical capabilities and timeframe, the current implementation of the iSAT is only through programming. The iSAT toolkit lacks a graphical user interface (GUI), which might limit the tool's usability for non-experienced users.

The iSAT toolkit adopted the gbXML data schema to automate performance assessment tasks that require integration with BPS tools. The tool validation results confirm that, in many cases, the iSAT performed the assessment accurately and that the tool excelled in facilitating the performing of complex assessments that were not conducted through the manual assessment.

Developing a comprehensive assessment tool requires further integration with data sources that are comprehensive in describing all building elements, including geometry, furniture, materials, site, and more. Such information is comprehensively described in the IFC data schema, demonstrating a potential source of information that can fill this gap.

The iSAT toolkit offers a flexible and customizable approach that allows for the integration of additional criteria and rating systems. The core modules of the iSAT toolkit, including iSAT-gbXML and iSAT-JGBG, can be expanded and adapted to accommodate the requirements of different rating systems and assessment criteria. However, although the iSAT toolkit's flexibility and modular design make it well-suited to support other criteria and rating systems beyond the JGBG, it requires experienced users with programming capabilities to expand the iSAT toolkit functionality.

9. Discussions and Conclusions

This chapter highlights the importance of this research and its contributions to the field. It begins by recapping the research problem and how the study has addressed the existing knowledge gap. The research aims, and specific research questions are outlined, setting the foundation for the subsequent discussions. The focus then shifts to the key findings derived from the research on BIM-based sustainability assessment and the development of the Integrated Sustainability Assessment Tool (iSAT). The primary objective of this study was to explore the potential of BIM technology in automating and streamlining green building assessments while integrating assessment criteria with assessment tools for improved accuracy and efficiency. The iSAT toolkit was proposed to overcome the challenges in green building assessment, leveraging BIM capabilities. By developing the iSAT toolkit, this research aimed to bridge the gap in knowledge by automating complex tasks required by selected criteria from the Jordan Green Building Guide (JGBG) as one of the Green Building Rating Tools (GBRTs), offering a seamless and efficient approach to sustainability assessment in green building projects. This chapter presents the key findings, highlights this research's novelty, and illustrates its potential future impact and the challenges that may lie ahead. Through integrating BIM technology and innovative tools like iSAT, this research contributes valuable insights and practical implications for advancing sustainability assessment practices and promoting more sustainable and environmentally friendly building design practices.

9.1 Discussion

In the last decades, various GBRTs have been developed worldwide to address and cut the significant impact of the construction sector on the built and natural environment. Most of these GBRTs share common categories in these rating systems. Generally, these categories indicate that almost all GBRTs consider indoor environment quality, ecological loadings, and resource use (Cole, 2005).

The assessment of green buildings is a critical aspect of sustainable construction and design practices as it evaluates the overall performance efficiency of buildings throughout their lifecycle. In this regard, integrating building performance assessment tools with BIM technology and BIM data schema has emerged as a promising approach to achieve more accurate and comprehensive green building assessments. However, this integration faces certain challenges that need to be addressed.

The assessment criteria in many green building rating tools (GBRTs) require the utilization of different building performance simulation (BPS) tools to evaluate the performance of buildings. Currently, the assessment workflow encounters several challenges (Motawa and Carter, 2013). Gervásio *et al.* (2014); Santos *et al.* (2014); and Ferrero *et al.* (2015) reported that there is a lack of necessary information in the early design stages, making it difficult to conduct comprehensive assessments. Secondly, the design stages often undergo rapid changes, leading to increased time consumption for remodelling, assessing different design proposals, and completing repetitive tasks. This obstructs the efficient evaluation of building performance. Furthermore, conducting assessments based on assumptions or defaulted values rather than actual data leads to performance gaps and inaccuracies.

The integration between GBRTs and BPS tools is limited due to various factors. The complexity and variety of GBRTs requirements challenge integrating them into a single assessment workflow. The capabilities and complexity of simulation programs also contribute to the limitations, as different design and assessment tools may have varying functionalities and compatibility issues. Interoperability between the design and assessment tools further hampers the seamless exchange of information and data integration. Different GBRTs use different assessment methodologies to assess similar criteria, such as energy and material performance. Furthermore, GBRTs often serve as evaluative rather than guiding tools, making it challenging to achieve design optimization that balances multiple targets such as energy efficiency, daylighting, thermal comfort, and other GBRT requirements.

Such challenges highlight the importance of addressing the integration and compatibility issues between the design, GBRTs and BPS tools. The recent development of BIM technology has allowed efficient design workflows that produce intelligent, data-rich models with parametric capabilities to integrate with BPS tools using BIM data schemas, such as gbXML and IFC. However, this integration requires the development of adequate data management procedures to allow for effective and automated integration between the assessment tools with the digital information models to facilitate the sustainability assessment.

Based on this, this research aims to explore the potential of BIM technology in automating green building assessments and integrating assessment criteria and tools for more efficient and comprehensive evaluations. To achieve this research aim, we investigated the capabilities of BIM technology to streamline the sustainability assessment process and enable seamless integration between various assessment criteria and tools.

The research aimed to develop a BIM-based approach for automating building sustainability assessment, addressing the challenges of integrating assessment criteria and tools. The research questions were formulated to comprehensively explore BIM technology's potential, information requirements, and integration with GBRTs and BPS tools.

This thesis adopted an exploratory mixed-methods approach, utilizing qualitative document analysis and quantitative data collection. A comprehensive literature review examined the current state-of-the-art in BIM technology, GBRTs, and BPS tools to identify potential solutions and challenges. The Integrated Sustainability Assessment Tool (iSAT) was developed as the core outcome of the research. It comprises several components, including iSAT-gbXML and iSAT-JGBG, designed to parse, process, and execute machine-readable rules for assessing Jordan Green Building Guide (JGBG) criteria based on gbXML data.

The potential users of the iSAT toolkit encompass a wide range of stakeholders in the green building industry. Green building consultants and sustainability experts can utilize iSAT to automate and streamline the assessment process, significantly reducing manual efforts and enhancing the accuracy of sustainability evaluations. Architects and designers can benefit from the tool's parametric capabilities, enabling them to explore different design scenarios and evaluate different design variables for optimal sustainability performance. Furthermore, projects could achieve more criteria credit than the manual assessment by using the iSAT tool, as it allows for performing complex tasks, such as the energy and daylight performance assessment. The flexibility of iSAT allows for widespread adoption and customization to facilitate the assessment of different GBRTs and regional green building requirements, making it a valuable asset for the green building community.

Tool validation was a crucial step in developing and implementing the iSAT toolkit. It involved systematically assessing and verifying the tool's performance, accuracy, and reliability to ensure it functions as intended and meets its primary objectives. Throughout the development of the iSAT toolkit, the tool's performance was tested using different demo buildings that represent extreme scenarios to test and debug any error that it counters. Finally, the tool's performance of the iSAT was validated using two real-world case studies that achieved the JGBG's certificate. Throughout the implementation, the tool demonstrated significant advantages over the manual assessment process in supporting the JGBG assessment, allowing for quick checks for the project compliance with the assessment criteria, and facilitating complex assessments, such as performing energy and daylighting simulations by automatically integrating the design and assessment models in one workflow.

However, the accuracy of the tool results is highly reliable on the input models and the information embedded in them. While implementing BIM authoring tools can help reduce redundant tasks, allow for tool integration, and produce data-rich models, the design teams must be aware of the capabilities and limitations of the adopted workflows to transfer data between tools.

The key findings of this research directly address four research questions, providing valuable insights into the feasibility and challenges of utilizing BIM technology in green building assessment:

- *To what extent can BIM technology facilitate green building assessment?*

In addressing the first research question, this study sought to assess the feasibility of utilizing BIM technology to automate the sustainability assessment process in green building projects. The comprehensive literature review highlighted the increasing adoption of BIM in the construction industry and its potential for enhancing sustainability practices. The findings indicated that BIM's parametric capabilities and data-rich models offer a suitable foundation for automating the assessment process. Additionally, integrating BIM with specific BPS tools, such as Dynamo for Revit and Grasshopper for Rhino, demonstrated the ability to streamline tasks and customize workflows through visual programming environments. However, some limitations, such as limited interoperability with other performance simulation engines, were identified, which required further investigation.

The research findings demonstrate that BIM technology offers technical superiority over traditional CAD tools. The parametric capabilities and data-rich models of BIM significantly reduce the time and effort required to remodel design and assessment models, minimizing the risk of data inconsistency and loss of information. Integrating BIM technology with BPS tools allows for more efficient workflows and enhances collaboration among design and assessment teams.

- What information is required to conduct the assessment of green buildings?

The second research question aimed to identify the information required for the sustainability assessment process and explore possibilities for improving integration between Green Building Rating Tools (GBRTs) and Building Performance Simulation (BPS) tools. Analysis of selected GBRTs (BREEAM, JGBG, LEED, GSAS, and PEARL) and their assessment criteria revealed the complexity of the evaluation process, posing challenges in data collection and interpretation. Additionally, the limited integration between BPS and GBRTs tools hindered seamless information exchange. To address these issues, potential solutions were explored, including developing data management procedures and utilising open data schemas like gbXML and IFC to enhance interoperability between tools.

Overall, the study identifies the limited integration between GBRTs and BPS tools as a significant challenge in green building assessment. The complexity and diverse criteria of GBRTs and the complex nature of BPS tools make seamless interoperability between them difficult. The research highlights the need for adequate data management procedures that allow for flowless data tranafer between design and assessment tools to enable effective and automated integration between assessment tools and digital information models. Exploring potential solutions, such as open data schemas, further emphasizes the importance of addressing these challenges to enhance the sustainability assessment process.

- How can BIM tools integrate GBRTs with BPS tools to facilitate green building design assessment?

With the third research question, the study focused on understanding the effective integration of BIM tools in the sustainability assessment process. Various BIM-based approaches adopting the concept of GreenBIM were examined, such as Visual Programming Environments (VPE) and developing BIM-based plugins, utilising BIM technology's capabilities to generate data-rich models and facilitate collaborative design workflows. The research revealed challenges and opportunities associated with integrating BIM tools into the assessment process, emphasizing the significance of adopting open data schemas to enable effective information exchange and generate parametric performance simulation models.

The findings highlighted that the integration between GBRTs and BPS tools is currently limited due to the various challenges. GBRTs' numerous criteria, diverse assessment methodologies, and the nature and complexity of BPS tools present significant barriers to seamless integration. Addressing these issues becomes crucial for achieving a streamlined and automated assessment process that fully harnesses the potential of BIM technology.

- Can BIM data schemas carry sufficient building information required for performance evaluation tools?

The fourth research question addressed the sufficiency of BIM data schemas in conducting sustainability assessments and explored ways to achieve data interoperability between different tools. The study found that while gbXML and IFC data schemas offered the potential for specific domains of sustainability assessment, using one schema solely could limit the scope of the evaluation. As a result, the developed integrated sustainability assessment tool (iSAT) employed gbXML to represent energy and daylight models, aiming to cover some of the complex green building assessment criteria. While these data schemas enable the transfer of specific data relevant to particular domains of green building assessment, such as Energy, and Materials, limitations exist in carrying out all the necessary project information required for comprehensive evaluations. Improving the quality of BIM models and modelled information is essential to overcome these limitations and achieve more accurate and reliable automated assessments. Therefore, the research identifies open data schemas, such as gbXML and IFC, as potential solutions for partial information exchange between design and assessment tools.

The development of the iSAT toolkit demonstrated that implementing sustainability assessments in green building projects is feasible and achievable through integrating BIM technology with assessment criteria and tools. The iSAT toolkit was designed to streamline the assessment process and enhance the accuracy of sustainability evaluations. By leveraging BIM technology's parametric capabilities and data-rich models, the iSAT toolkit effectively reduced the time and effort required for modelling and analysis, minimizing the risk of data inconsistency and loss of information.

A functional paradigm was adopted in developing the iSAT toolkit offering several benefits, including low maintenance, code reproducibility, and modularity. This approach allowed for greater flexibility and enabled others to adopt specific parts of the tool to design customized workflows tailored to specific criteria in a particular GBRT. Moreover, the parametric capabilities of the selected BPS tools allow the user to assess countless design scenarios by testing different design variables. This empowers users to explore various design options and evaluate their impact on sustainability criteria, enhancing the assessment process's accuracy and comprehensiveness.

The iSAT toolkit demonstrated a workflow that addresses the limited integration between Green Building Rating Tools (GBRTs) and Building Performance Simulation (BPS) tools, a significant challenge in green building assessment. It provided a seamless and efficient approach to integrate selected criteria from the Jordan Green Building Guide (JGBG) as one of the GBRTs with BPS tools, allowing for a more comprehensive assessment of green building performance.

Additionally, the iSAT toolkit demonstrated the potential of open data schemas, such as gbXML and IFC, partially exchanging information between design and assessment tools. Using the gbXML data schemas, the iSAT toolkit facilitated the integration of energy and daylight models, materials, and other relevant criteria, contributing to a more holistic evaluation of green building sustainability.

However, it is essential to acknowledge that despite the success of the iSAT toolkit in semi-automating the assessment process, achieving full automation still faces technical challenges related to data interoperability between different tools. Improving the quality of BIM models and modelled information remains crucial to overcoming limitations in carrying out all the necessary project information required for comprehensive sustainability evaluations.

The feasibility of using various GBRT and BIM for semi-automated evaluation has been illustrated in current research (Wu and Issa, 2012; Jalaei and Jrade, 2015; Ryu and Park, 2016; Sanhudo and Martins, 2018). Visual Programming Environments (VPE), such as Dynamo for Revit and Grasshopper for Rhino, help design teams use a node-based environment with a user-friendly graphical user interface to customise functions for task automation. As part of this study, Hamed and Wang (2019) tested this approach and developed a pilot study to automate energy model generation and data extraction between Revit and the Passive House Planning Package (PHPP), which was discussed further in Chapter 6. Reinhardt and Matthews (2017) have also developed a VPE plugin to automate local code-compliance checking through BIM environments. Typically, VPE-based approaches depend on the native BIM model as the data and processing source and lack interoperability capabilities with other deisng and performance simulation engines. In the contrary, the adopted appproach in developing the iSAT toolkit offers interoperability capabilities as it does not rely on specific design tool, and could work with any tool that can produce gbXML data scema.

The literature review concluded that using an Application Programming Interface (API) to develop BIM plugins was noted as the most adopted approach. Autodesk Revit's API is a powerful tool often used to develop new workflows and extend application functionalities by collecting, extracting, processing and exporting model information between Revit and other tools. Jalaei, Jalaei and Mohammadi (2020) have developed a Revit plugin that integrates the native BIM model with machine learning to automate LEED sustainability assessment. Han *et al.* (2017) have also developed a Revit plugin to automate LEED's Sustainable Site assessment. Despite the various benefits of such an approach, one of the shortcomings of following this approach is the dependency on proprietary software. If a plugin was developed for Revit, it could only work with Revit. This limitation draws a setback to adopting this approach for automating the sustainability assessment.

Therefore, this study has investigated the feasibility of integrating BIM data exchange schemas, such as IFC and gbXML, to export and augment the necessary information for sustainability assessment to different simulation tools, such as openstudio, Ecotect and IES-VE. Hence, the iSAT investigated the feasibility of using gbXML and IFC data schema.

Most BIM authoring tools can produce data exchange files that support open data schemas. Data exchange methods extract the BIM model information for various applications. For example, Ilhan and Yaman (2016) have developed an IFC-based approach to automate BREEAM's Materials assessment, and Biswas and Krishnamurti (2012) developed an IFC-based approach to automate LEED's Sustainable Site assessment. Azhar *et al.* (2011) have developed a gbXML-based approach to automate LEED's Water efficiency, Indoor Environment Quality, and Energy and Atmosphere assessment. Alwan, Greenwood and Gledson (2015) developed a gbXML-based approach to rapidly assess LEED's Indoor Environment Quality and Energy and Atmosphere criteria. Jalaei, Jalaei and Mohammadi (2020) have developed an integrated solution that utilises gbXML to represent the project's energy, daylight, and indoor environment quality models IFC for materials and other criteria, attempting to cover most of the LEED criteria.

As highlighted earlier, both gbXML and IFC data schemas can support certain domains of the project, and therefore, using one of these schemas solely can only facilitate limited sustainability assessment targets. This issue has been highlighted and discussed in Chapter 8: tool validation, as it was concluded that the gbXML schema could not produce sufficient information that allows, for example, to conduct the building material quantification and other criteria by using the tool. Hence, other data schemas, such as the IFC, must be integrated into the iSAT toolkit for a comprehensive building assessment.

The programming approach adopted in developing the iSAT toolkit allows the tool's architecture to expand flexibility and host other BPS packages. For example, the developers of OpenLCA (GREENDELTA, 2022) provide a Python package that can use the functionalities of the OpenLCA application. Other libraries can also provide capabilities for utilising geographic information systems (GIS), such as Geopy (Adam Tygart *et al.*, 2021) and GeoPandas (Jordahl *et al.*, 2022), which can also facilitate some Site, Materials, and Transportation factors based on the project's location, such as the proximity to amenities, Access to public transit, and Local materials assessment. These packages are not currently integrated into the iSAT toolkit. The highlighted issues above formulate vital future research opportunities to help address the research gap.

Overall, the development and implementation of the iSAT toolkit demonstrated the potential of BIM technology in automating and enhancing the sustainability assessment process for green building projects. By addressing key challenges and integrating assessment criteria with assessment tools, the iSAT toolkit represents a significant advancement in green building assessment, contributing to more efficient and accurate sustainability evaluations. Further research and development efforts in this area will be essential to fully harness the capabilities of BIM technology and advance sustainable building design practices.

9.2 Summary

This section summarises the main highlights in each of the eight chapters that structure this thesis, presents conclusions, and proposes future work. Whereas Chapter 1 highlights the research gap and the main steps required to answer the research questions.

Chapter 2 has provided an overview of the sustainability assessment of buildings. Here, we differentiated between green building rating tools (GBRTs) and building performance simulation (BPS) programs. The assessment criteria in GBRTs require using different BPS tools to assess the performance of buildings. This chapter has identified critical challenges in performing building performance simulations during the design stage of green projects. These challenges can be summarised as follows: (1) lack of necessary information in the early design stages; (2) rapid changes throughout the design stages, which consumes more time in remodelling and performing repetitive tasks and simulations; (3) conducting the evaluation based on assumptions or defaulted values, which leads to performance gaps.

In addition, this chapter has highlighted the challenges that lead to the limited integration between GBRTs and BPS tools, such as (1) complexity and variety of sustainability requirements, (2) simulation programs' capabilities and their complexity, (3) interoperability between tools, and (4) the challenge of design optimisation to balance the energy, daylight, thermal comfort, and other GBRT targets at once.

Chapter 3 discussed the research methodological framework conducted to investigate BIM capabilities in facilitating green building assessment.

In chapter 4, five GBRTs were selected and analysed to inform how these tools vary significantly in their structure and tackle sustainability factors. The analysis has introduced a generic structure that hosts GBRTs, highlighting all the measured factors among all the analysed tools. The factors of GBRTs were analysed and re-categorised based on a generic mapping considering the assessed factor instead of the criterion. The analysis helped better understand how each GBRT tackles particular criteria and what factors are assessed. Furthermore, the analysis of these rating systems concluded that the requirements of GBRTs can be categorized into four categories based on their complexity level and assessment process.

Chapter 5 has introduced the concept of integrating Building Information Modelling (BIM) and GBRTs, defined as Green BIM, and has explored the potential of using BIM as a design tool to resolve several issues in traditional design workflows. This chapter discussed the interoperability issue in depth, highlighting the development of open data schemas, such as the Industrial Foundation Classes (IFC) and Green Building Extensible Markup Language (gbXML). The potential of using these data schema was reviewed. Based on the research aim, integrating gbXML with BPS tools is more feasible than the IFC schema due to its complexity and the limited support from BPS tools compared to the gbXML.

Chapter 6 presented a pilot study investigating a potential workflow to automate the sustainability assessment. In this regard, Dynamo, a visual programming environment, was used to extract the model information from the BIM modelling environment into the Passive House Planning Package (PHPP), an Excel spreadsheet used to evaluate the performance of Passivhaus buildings.

Chapter 7 demonstrated the development of the integrated sustainability assessment toolkit (iSAT). The iSAT toolkit was developed to facilitate the sustainability assessment of buildings by automating complex tasks required by GBRTs. It consists of different core components (1) the iSAT-gbXML, a package developed to parse, process, and extract the information from gbXML models, (2) the iSAT-JGBG, which consists of the assessment criteria developed based on the JGBG requirements, and (3) the iSAT-Performance, which is a parametric performance assessment tool, capable of performing parametric performance assessments for daylight and energy simulations. Through different use cases, this chapter has also demonstrated how the iSAT toolkit can facilitate the assessment of green buildings using the developed packages. These cases were used to represent different complexity levels in sustainability assessment.

Chapter 8 aimed to use case studies to validate the iSAT toolkit performance. The first case study is a detached single-family residential building. The second is a multi-story office building promoted as a Net-Zero energy office building. Both buildings were used as a proof-of-concept of the tool's usability in real-world scenarios, designed and constructed based on the JGBG. The automated assessment results were compared with the manual assessment results performed by the architects. The validation results concluded that complex processes could be automatically performed using the iSAT toolkit, reducing the significant time and effort required by the manual assessment processes.

9.3 Research Contribution

The iSAT toolkit showcased in this research significantly contributes to the field of green building assessment using BIM technology. Its key features include:

- Automation of Sustainability Assessment: The iSAT toolkit demonstrates the feasibility of automating building sustainability assessments, streamlining workflows, and reducing manual efforts. It addresses the limitations of manual assessment processes and enhances assessment accuracy.
- Integration with GBRTs and BPS Tools: By integrating GBRTs and BPS tools based on the BIM environment, the iSAT toolkit enables seamless information exchange and collaboration among design and assessment teams, enhancing efficiency and accuracy.
- Flexible and Customizable Approach: The iSAT toolkit's core modules offer predefined procedures for data retrieval, building element selection, and performance simulations. Its flexible design allows further expansion and integration with different GBRTs and performance assessment packages.
- Comprehensive Assessment Coverage: The toolkit covers Energy Efficiency, Healthy Indoor Environment, and Materials and Resources criteria. It includes automated natural daylight assessment and parametric analysis for evaluating various design proposals.
- Contextual Relevance: The iSAT toolkit caters to the specific needs of the Jordanian context by focusing on criteria relevant to the Jordan Green Building Guide. It addresses the country's sustainability goals and requirements.

Overall, the research contributes insights into the capabilities and challenges of BIM-based workflows and technologies in green building assessment. The iSAT toolkit represents a potential contribution to automating sustainability assessments, making them more efficient, accurate, and customizable. This study provides a comprehensive understanding of BIM technology's potential in facilitating green building assessment by linking the research findings with the formulated research questions. Integrating BIM technology through developing a BIM-based assessment toolkit offers numerous advantages in semi-automating the assessment process. However, technical issues and data interoperability limitations between the assessment criteria, design, and assessment tools remain significant barriers to achieving fully automated and comprehensive green building assessments. Addressing these challenges will be crucial for maximizing the potential of BIM technology and advancing sustainable building design practices. Further research and development efforts in this area are necessary to harness the full benefits of BIM technology in green building assessment.

9.4 Limitations of the study

This research has been limited by the emergence of the covid-19 pandemic as it was impossible to conduct further analysis, site surveys, and consult potential tool users (green building consultants) and local architects.

Currently, there are several green building rating tools with hundreds of requirements. Although many of these requirements are shared among GBRTs, the requirements in each rating system have slight variations from other systems, and differences in the assessment methodology adopted can be found, which limits any tool functionality for a comprehensive assessment of different GBRTs

The gbXML data schema could automate building performance simulation tasks related to daylight and energy. However, it has failed to automate processes requiring further project information not supported by the schema. This highlights that such tools' performance depends on the quality and comprehensiveness of data inputs to perform a fully automated assessment.

The iSAT toolkit validation requires further data collection and analysis using case studies and collaboration with green building experts, where their feedback as the end users could allow for further improvements.

Finally, due to the technical challenges, the current tool implementation does not have a graphical user interface (GUI). This can limit the potential tool users. Therefore, a simple GUI must be developed.

9.5 Future work

Further research can be conducted to automate further the sustainability assessment of a building, which can be demonstrated as follows:

- Develop a graphical user interface for the iSAT toolkit for better usability.
- Integrate the IFC data schema with the iSAT toolkit. This involves conducting data analysis and mapping for the schema and green building rating tools to help identify the required information for assessment and their availability in the data schema and conclude how the IFC schema could improve the iSAT implementation.
- Integrate additional assessment tools and criteria. The current implementation of the iSAT covers specific assessment requirements from the JGBG. These requirements must cover most of the JGBG and other green building rating tools for better functionality.
- Data collection for the iSAT validation for more case studies. This involves working with the occupants of the targeted buildings to provide necessary data related to the occupancy patterns, loads, and actual energy consumption, to validate the energy performance assessment using the iSAT accurately.
- Implement action research methods to help with further validation of the tool's performance.

10. References

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11. Appendix A: JGBG Criteria

11.1 Energy Efficiency

criterion			Single Residential		Multiple residential		Office/ Commercial		Educational	
			with AC	Without AC	with AC	Without AC	with AC	Without AC	with AC	Without AC
1st criterion: Building Orientation										
Mandatory Requirements	-		-	-	-	-	-	-	-	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Orienting main elevation/used zone to the South for Cold zones, and North for Hot zones	5	5	5	5	5	5	5	5
	2nd requirement	Elongation of the Long axis to East-West	5	5	5	5	5	5	5	5
2nd criterion: Roofs and Walls of the building envelope:										
Mandatory Requirements	-		-	-	-	-	-	-	-	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	flat roof and Smooth textures for Walls in Cold zones, and un-flat roofs and Rough textures in Hot zones	1	1	1	1	1	1	1	1
	2nd requirement	Solar Reflectance Coefficient for Roofs not less than 0.7, emissivity 0.75 and absorbance coefficient 0.3 at the same time.	1	1	1	1	1	1	1	1
	3rd requirement	Cold roof for (80) per cent of the area	1	1	1	1	1	1	1	1
	4th requirement	Cold roof for (100) per cent of the area	2	2	2	2	2	2	2	2
3rd criterion: Site Landscaping										
Mandatory Requirements	-		-	-	-	-	-	-	-	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Proper heights and orientation of trees on site	2	2	2	2	2	2	2	2
4th criterion: Thermal Insulation of Building Envelope										
Mandatory Requirements	1st requirement	Adherence to the thermal insulation code	0	0	0	0	0	0	0	0
	2nd requirement	Right place of insulation based on climate zone	0	0	0	0	0	0	0	0
	3rd requirement	U-value of Opaque walls- 0.57 w/m2.k	0	0	0	0	0	0	0	0
	4th requirement	U-value of Exposed Roofs- 0.55 w/m2.k	0	0	0	0	0	0	0	0
	5th requirement	U-value of Exposed Floors- 0.80 w/m2.k	0	0	0	0	0	0	0	0
	6th requirement	U-value of Separating walls- 2.00 w/m2.k	0	0	0	0	0	0	0	0
	7th requirement	U-value of Separating roof, floor- 1.20 w/m2.k	0	0	0	0	0	0	0	0
	8th requirement	Total U-value of walls- 1.60 w/m2.k	0	0	0	0	0	0	0	0
	9th requirement	Total U-value of Exposed roof, floor <1.60 w/m2.k	0	0	0	0	0	0	0	0
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	U-value of Opaque walls- 0.50-0.40 w/m2.k	1	1	1	1	1	1	1	1

	2nd requirement	U-value of Opaque walls less than 0.40 w/m2.k	2	2	2	2	2	2	2	2
	3rd requirement	U-value of Exposed roofs- 0.50-0.40 w/m2.k	1	1	1	1	1	1	1	1
	4th requirement	U-value of Exposed roofs less than 0.40 w/m2.k	2	2	2	2	2	2	2	2
	5th requirement	U-value of exposed floors- 0.75-0.55 w/m2.k	1	1	1	1	1	1	1	1
	6th requirement	U-value of exposed floors less than 0.55 w/m2.k	2	2	2	2	2	2	2	2
	7th requirement	U-value of separating walls- less than 1.80 w/m2.k	1	1	1	1	1	1	1	1
	8th requirement	U-value of separating floor, roof <1.00 w/m2.k	1	1	1	1	1	1	1	1
	9th requirement	Total U-value of walls- less than 1.45 w/m2.k	1	1	1	1	1	1	1	1
	10th requirement	Total U-value of Exposed roof, floor<1.00 w/m2.k	1	1	1	1	1	1	1	1
5th criterion: Fenestration in the Building Envelope										
Mandatory Requirements	1st requirement	if window -to-wall ration WWA is 10%-40%, glass U-value should be less than 3.30 w/m2.k	0	0	0	0	0	0	0	0
	2nd requirement	if the window-to-wall ratio WWA is between 40-70%, the glass U-value should be less than 2.00 w/m2.k. if the WWA ratio is more than 70%, U-value should be less than	0	0	0	0	0	0	0	0
	3rd requirement	comply with the minimum U-value of opaque walls despite the choice of window types and areas.	0	0	0	0	0	0	0	0
	4th requirement	The solar Heat Gain Coefficient for all windows should be less than 0.25	0	0	0	0	0	0	0	0
	5th requirement	Solar Heat Gain Coefficient for skylights <2% area, < 0.40. Skylights (2.1-5%), < 0.25	0	0	0	0	0	0	0	0
	6th requirement	maximum skylight area should be less or equal to 5% of the roof area	0	0	0	0	0	0	0	0
	7th requirement	Visual transmittance of Glass in windows should be more than 0.45	0	0	0	0	0	0	0	0
	8th requirement	In residential buildings, Window-to-Wall Ratio WWA shall not be less than (10 %) for service spaces, and (15 %) for living spaces	0	0	-	-	-	-	-	-
Obligatory Requirements	1st requirement	Glass shading coefficient should not exceed 0.35 in all windows in all elevations	1	1	1	1	1	1	1	1
	1st requirement	if window -to-wall ration WWA is 10%-40%, glass U-value should be less than 3.00 w/m2.k	2	2	2	2	2	2	2	2
	2nd requirement	Glass shading coefficient should not exceed 0.30 in all windows in all elevations	1	1	1	1	1	1	1	1
	3rd requirement	Solar Heat Gain Coefficient should not exceed 0.2 in all skylights	1	1	1	1	1	1	1	1
		6th criterion: Airtightness of Building Envelope								
Mandatory Requirements	1st requirement	3 L/s/m2 air leakage in revolving doors, 2 L/s/m2 air leakage in other doors and opening	0	0	0	0	0	0	0	0
	2nd requirement	Sealing of Thermal Insulation to cover all joint points during construction to ensure a thermal-bridge-free construction.	0	0	0	0	0	0	0	0
	3rd requirement	Sealing of joints in architectural openings such as windows and doors to avoid water and air leaks.	0	0	0	0	0	0	0	0
	4th requirement	Sealing of conjunction and connection points such as walls, foundations, roofs and floors to avoid water and air leaks.	0	0	0	0	0	0	0	0
	5th requirement	Sealing of all fixture connections, such as service ducts and other holes, to avoid water and air leaks.	0	0	0	0	0	0	0	0
	6th requirement	Sealing of Shutter boxes to avoid water and air leaks.	0	0	0	0	0	0	0	0
	7th requirement	Testing of doors and windows air leakage by Blower Door Test	0	0	0	0	0	0	0	0

Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	-		-	-	-	-	-	-	-	-
		7th criterion: Daylight								
Mandatory Requirements	-		-	-	-	-	-	-	-	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Design at least 50% of the area to be naturally lit. windows must be designed on two sides in each used zone.	5	5	5	5	5	5	5	5
	2nd requirement	Raise the level of windows heights to the maximum height possible from the level of the tiles.	1	1	1	1	1	1	1	1
	3rd requirement	for residential buildings, the angle between the highest point in the window and any surrounding obstacle should not exceed 70 degrees	1	1	-	-	-	-	-	-
	4th requirement	Smart daylight control systems	3	3	3	3	3	3	3	3
		8th criterion: Shading Devices								
Mandatory Requirements	1st requirement	Small space between the shading device and the facade	0	0	0	0	0	0	0	0
	2nd requirement	Shading devices from light weight materials	0	0	0	0	0	0	0	0
	3rd requirement	Shading coefficient <0.2 for shading devices	0	0	0	0	0	0	0	0
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Proper use of shading devices for orientations	5	5	5	5	5	5	5	5
		9th criterion: Natural Ventilation								
Mandatory Requirements	1st requirement	Avoid rain leakage inside ventilation openings	0	0	0	0	0	0	0	0
	2nd requirement	Relative humidity between 40-70% indoors	0	0	0	0	0	0	0	0
	3rd requirement	Ventilation openings near shaded areas	0	0	0	0	0	0	0	0
	4th requirement	Ventilation openings away from polluted air								
Obligatory Requirements			-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Use of Mashrabeyya, Colestra brick, …etc.	1	1	1	1	1	1	1	1
	2nd requirement	Use of night ventilation strategy	1	1	1	1	1	1	1	1
	3rd requirement	Use of Air Shaft for Ventilation purposes	1	1	1	1	1	1	1	1
	4th requirement	Use of Chimney for ventilation purposes	1	1	1	1	1	1	1	1
	5th requirement	Use of Air Catcher for ventilation	5	5	5	5	5	5	5	5
	6th requirement	Use of Atrium in cold areas, and Courtyard in hot areas	5	5	5	5	5	5	5	5
		10th criterion: Computer Simulation								
Mandatory Requirements	-		-	-	-	-	-	-	-	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	computer simulation for energy performance analysis	12	12	12	12	12	12	12	12
		11th criterion: Mechanical Ventilation								
Mandatory Requirements	1st requirement	Control system for Mechanical ventilation	0	-	0	-	0	-	0	-
	2nd requirement	Automatic Controls and separate electrical circuits for mechanical ventilation equipment	0	-	0	-	0	-	0	-

	3rd requirement	Throttling for air intakes and out	0	-	0	-	0	-	0	-
	4th requirement	Mechanical ventilation for indoor garages	-	-	0	0	0	0	0	0
	5th requirement	Vent. Fans of kitchens and bathrooms	0	0	-	-	-	-	-	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Speed verified motors	1	0	1	0	1	0	1	0
	2nd requirement	CO sensors and monitoring in indoor garages	1	1	1	1	1	1	1	1
		12th criterion: HVAC system equipment								
Mandatory Requirements	1st requirement	All equipment accredited, energy efficient	0	-	0	-	0	-	0	-
	2nd requirement	All equipment certification, energy efficient	0	-	0	-	0	-	0	-
	3rd requirement	All equipment- Jordanian codes requirement	0	-	0	-	0	-	0	-
	4th requirement	All electrical applications- Jordanian codes compliance	0	-	0	-	0	-	0	-
	5th requirement	Energy Label on equipment	0	-	0	-	0	-	0	-
	6th requirement	Minimum energy efficiency requirements	0	-	0	-	0	-	0	-
Obligatory Requirements	1st requirement	Equipment motors at least two speeds or equipped with multi-speed controllers	1	-	1	-	1	-	1	-
Voluntary Requirements	1st requirement	Better than minimum energy efficiency- 5%	1	-	1	-	1	-	1	-
	2nd requirement	Better than minimum energy efficiency- 10%	2	-	2	-	2	-	2	-
		13th criterion: Air Conditioning Systems								
Mandatory Requirements	1st requirement	Capacity variation >5 loads	0	-	0	-	0	-	0	-
	2nd requirement	Control device for each system, thermostat	0	-	0	-	0	-	0	-
	3rd requirement	Water temperature control, separate devices for each zone	0	-	0	-	0	-	0	-
	4th requirement	Thermal pumps with secondary electric heaters	0	-	0	-	0	-	0	-
	5th requirement	No Air heating for humidity control- energy loss	0	-	0	-	0	-	0	-
Obligatory Requirements	1st requirement	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	-	-	-	-	-	-	-	-	-
		14th criterion: Control system for HVAC								
	1st requirement	Timers- control system of all systems	0	-	0	-	0	-	0	-
	2nd requirement	Thermostat- thermal control for all systems	0	-	0	-	0	-	0	-
	3rd requirement	Thermal control- Dead band-3 Cº	0	-	0	-	0	-	0	-
	4th requirement	Thermostat- no interfering between heating and cooling	0	-	0	-	0	-	0	-
Obligatory Requirements	1st requirement	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Smart automatic control systems	2	-	2	-	2	-	2	-
15th criterion: Thermal Insulation of HVAC system										
Mandatory Requirements	1st requirement	Insulation, R=0.7 c.m2/w, heating >60 Cº	0	-	0	-	0	-	0	-
	2nd requirement	Insulation, R=0.35 c.m2/w, heating 40-60 Cº	0	-	0	-	0	-	0	-

	3rd requirement	Insulation, R=0.35 c.m2/w, cooling <15 Cº	0	-	0	-	0	-	0	-
	4th requirement	Proper covering of insulation, waterproofing	0	-	0	-	0	-	0	-
	5th requirement	Proper duct insulation	0	-	0	-	0	-	0	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Insulation, R>1.0 c.m2/w, heating >60 Cº	1	-	1	-	1	-	1	-
	2nd requirement	Insulation, R>0.70 c.m2/w, heating 40-60 Cº	1	-	1	-	1	-	1	-
	3rd requirement	Insulation, R>0.70 c.m2/w, cooling <15 Cº	1	-	1	-	1	-	1	-
	4th requirement		2	-	2	-	2	-	2	-
16th criterion: HVAC balance										
Mandatory Requirements	1st requirement	Balance of systems according to Jordanian Code requirements	0	-	0	-	0	-	0	-
	2nd requirement	Proper adjustment of fan speed for motors more than 0.75 kW power-	0	-	0	-	0	-	0	-
	3rd requirement	Diffusers balancing- according to design plans	0	-	0	-	0	-	0	-
	4th requirement	Balance of water-using systems- decrease throttling or other means.	0	-	0	-	0	-	0	-
	5th requirement	For motors with more than 7.5 kW power- the balance of pump speed	0	-	0	-	0	-	0	-
Obligatory Requirements	1st requirement	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	-	-	-	-	-	-	-	-	-
17th criterion: Thermal Condensers										
Mandatory Requirements	1st requirement	Cooled condensers- proper installation	-	-	0	-	0	-	0	-
	2nd requirement	High standard- treated water for condensers	-	-	0	-	0	-	0	-
	3rd requirement	When using thermal condensers- cooling should be from the central unit or split AC units, or heat pump	-	-	0	-	0	-	0	-
	4th requirement	When using thermal condensers- heating should be from the central unit or split AC units or underfloor heating from the boiler	-	-	0	-	0	-	0	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	-		-	-	-	-	-	-	-	-
18th criterion: Economisers										
Mandatory Requirements	1st requirement	All cooling systems that work on fans and have a design capacity of more than 1200 L/s and mechanical cooling capacity of more than 22 kW should have an air or water economizer	0	-	0	-	0	-	0	-
	2nd requirement	Air economizers should be able to adjust dampers and provide 100% of the air intake through an automatic control system	0	-	0	-	0	-	0	-
	3rd requirement	Water economizers should be able to provide 100% of cooling loads through an automatic control system	0	-	0	-	0	-	0	-
	4th requirement	Economizers should be able to provide partial additional thermal loads with no increase in energy consumption	0	-	0	-	0	-	0	-
	5th requirement	-	0	-	0	-	0	-	0	-

	6th requirement	-	-	-	-	-	-	-	-	-
	7th requirement	-	-	-	-	-	-	-	-	-
	8th requirement	-	0	-	0	-	0	-	0	-
Obligatory Requirements	-	-	-	-	-	-	-	-	-	-
Voluntary Requirements	-	-	-	-	-	-	-	-	-	-
19th criterion: Heat Recovery Systems										
Mandatory Requirements	1st requirement	-	-	-	0	-	0	-	0	-
	2nd requirement	The heat recovery system should be able to provide the building with 60% of the maximum load	-	-	0	-	0	-	0	-
	3rd requirement	-	-	-	0	-	0	-	0	-
	4th requirement	Heat recovery efficiency- more than 50%	-	-	0	-	0	-	0	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	The use of heat recovery systems in all AC systems	1	-	1	-	1	-	1	-
	2nd requirement	Heat recovery efficiency- more than 75%	1	-	1	-	1	-	1	-
20th criterion: Water Heating										
Mandatory Requirements	1st requirement	The use of one renewable energy source in water heating	0	0	0	0	0	0	0	0
	2nd requirement	Water heating systems with a capacity of more than 300L or power of more than 15 kW should be isolated and separated	0	0	0	0	-	-	-	-
	3rd requirement	calculate design loads for hot water so the maximum hot water temperature degree does not exceed 50 Celsius if water is heated by fossil fuel or electricity.	0	0	0	0	0	0	0	0
	4th requirement	Thermal insulation of Pipes and tanks	0	0	0	0	0	0	0	0
	5th requirement	Minimum efficiency requirements for water heating equipment	0	0	0	0	0	0	0	0
	6st requirement	Proper thermal control system utilization	0	0	0	0	0	0	0	0
	7th requirement	systems that use pumps for water cycling to keep the stored water temperature, pumps should have controllers that ensure it stops within 5 minutes.	0	0	0	0	0	0	0	0
	8th requirement	For heated swimming pools, they should be covered with the proper material	0	0	0	0	0	0	0	0
Obligatory Requirements	1st requirement	Include anti- deposition pole for all water heater systems	1	1	1	1	1	1	1	1
Voluntary Requirements	1st requirement	-	1	1	1	1	1	1	1	1
	2nd requirement	Thermal insulation of tanks- 7cm	1	1	1	1	1	1	1	1
	3rd requirement	provide water heating system with heat conservers systems at consumption points	1	1	1	1	1	1	1	1
	4th requirement	Heat recovery for pools	1	1	1	1	1	1	1	1
	5th requirement	Solar system for heating of swimming pools	1	1	1	1	1	1	1	1
21st criterion: Lighting Control System										

Mandatory Requirements	1st requirement	Automatic controls for indoor lighting	0	0	0	0	0	0	0	0
	2nd requirement	Occupancy sensors for offices	-	-	0	0	-	-	-	-
	3rd requirement	Control systems are divided based on zones	0	0	0	0	0	0	0	0
	4th requirement	-	-	-	0	0	0	0	0	0
	5th requirement	Provide task lighting- control systems	0	0	0	0	0	0	0	0
	6th requirement	-	0	0	0	0	0	0	0	0
	7th requirement	-	0	0	0	0	0	0	0	0
Obligatory Requirements	-	-	-	-	-	-	-	-	-	-
	1st requirement	Provide light intensity sensors for day-lighted areas of more than 25 m2 area	2	2	2	2	2	2	2	2

Voluntary Requirements	2nd requirement	Provide motion sensors for corridors and entrances	1	1	1	1	1	1	1	1
	3rd requirement	Provide occupancy sensors for classrooms, meetings and conference rooms	-	-	1	1	1	1	1	1
	4th requirement	Smart Key- for hotels and motels	-	-	2	2	-	-	-	-
	22nd criterion: External Lighting									
Mandatory Requirements	1st requirement	Photocell with timer for external lighting	-	-	-	-	0	0	0	0
	2nd requirement	Separate control system for external lighting of facades	0	0	0	0	0	0	0	0
	3rd requirement	Billboard lighting- separate control system	-	-	-	-	0	0	-	-
	4th requirement	60 lumen/w for light bulbs of external plazas	0	0	0	0	0	0	0	0
	5th requirement	-	0	0	0	0	0	0	0	0
Obligatory Requirements	1st requirement	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Entrances and corridors leading to external areas- motion sensors	1	1	1	1	1	1	1	1
	2nd requirement	80 lumen/w light bulbs for external lighting	1	1	1	1	1	1	1	1
	3rd requirement	penlight the minimum area with the minimum time, provide lighting for the occupied spaces in terms of security requirements	1	1	1	1	1	1	1	1
	4th requirement	using motion sensors for safety and security reasons.								
	5th requirement	Renewable energy sources for external lighting	3	3	3	3	3	3	3	3
	23rd criterion: Lighting Power									
Mandatory Requirements	1st requirement	Energy Efficient Building code requirements	0	0	0	0	0	0	0	0
Obligatory Requirements	-	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	coordinate ceiling lighting with furniture planning to cover corridors and servicing zones with light from the same lighting units distributed in the working places.	-	-	-	-	1	1	1	1
	2nd requirement	Proper Daylight design- to be introduced into corridors and large halls	1	1	1	1	1	1	1	1

	3rd requirement	Light indoor colours	1	1	1	1	1	1	1	1
	4th requirement	Low partitions- open plan offices	-	-	-	-	1	1	-	-
	5th requirement	Task lighting	1	1	1	1	1	1	-	-
	6th requirement	Technological solutions for introducing natural light into deep areas- fibber optics	2	2	2	2	2	2	2	2
	24th criterion: Lighting Efficiency									
Mandatory Requirements	1st requirement	Light condensers- power factor more than 0.92 in magnetic ballasts	0	0	0	0	0	0	0	0
Obligatory Requirements	-	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	High-efficiency light bulbs	1	1	1	1	1	1	1	1
	2nd requirement	Light fixtures with a high utilization factor	1	1	1	1	1	1	1	1
	3rd requirement	Use of T5 florescent lamps instead of T8	2	2	2	2	2	2	2	2
	4th requirement	Electronic ballasts instead of magnetic ballasts	2	2	2	2	2	2	2	2
	5th requirement	install electric converters for the low-voltage lighting bulbs	1	1	1	1	1	1	1	1
	25th criterion: Electric Motors Efficiency									
Mandatory Requirements	1st requirement	-	-	-	0	0	0	0	0	0
	2nd requirement	-	-	-	0	0	0	0	0	0
	3rd requirement	Power factor efficiency- labelled on motors	-	-	0	0	0	0	0	0
	4th requirement	Testing certifications	-	-	0	0	0	0	0	0
Obligatory Requirements	-	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	High-efficiency motors	1	1	1	1	1	1	1	1
	2nd requirement	Earthing of motors- separately	1	1	1	1	1	1	1	1
	26th criterion: Electric power Correction Factor									
Mandatory Requirements	1st requirement	power factor more than 0.92 for loads that equal or higher than 100 KFA	0	0	0	0	0	0	0	0

Obligatory Requirements	-	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	power factor more than 0.95 for ALL loads	2	2	2	2	2	2	2	2
	27th criterion: Renewable Energy on site									
Mandatory Requirements	1st requirement	-	-	-	-	-	-	-	-	-
Obligatory Requirements	-	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Renewable energy- 2.5% of total electric use	2	2	2	2	2	2	2	2
	2nd requirement	Renewable energy- 5% of total electric use	4	4	4	4	4	4	4	4
	3rd requirement	Renewable energy- 7.5% of total electric use	6	6	6	6	6	6	6	6
	4th requirement	Renewable energy- 10% of total electric use	8	8	8	8	8	8	8	8
	28th criterion: Elevators, escalators and conveyor belts systems									
Mandatory Requirements	1st requirement	-	-	-	-	-	0	0	0	0
Obligatory Requirements	1st requirement	Elevators- fan off after 5 minutes of non-use	-	-	1	1	1	1	1	1
	2nd requirement	Elevators- Lights off after 5 minutes of non-use	-	-	1	1	1	1	1	1
	3rd requirement	Escalators and conveyor belts- slow speed after 3 minutes of non-use	-	-	1	1	1	1	1	1
	4th requirement	Escalators and conveyor belts- stops after 15 minutes of non-use	-	-	1	1	1	1	1	1
Voluntary Requirements	1st requirement	Non-hydraulic Elevators- proper control systems equipped with a Synchronous motor with a Permanent Magnet in elevator design should not be equipped with Drive System with Gearless Type Motor	-	-	1	1	1	1	1	1
	2nd requirement		-	-	1	1	1	1	1	1
	3rd requirement		-	-	1	1	1	1	1	1
	4th requirement	elevators should be equipped with Elevator Traffic Control System	-	-	1	1	1	1	1	1
	5th requirement	Lightweight materials for elevators	-	-	1	1	1	1	1	1
	29th criterion: Innovative design for energy efficiency									
Mandatory Requirements	-	-	-	-	-	-	-	-	-	-

Obligatory Requirements	-	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	the project should achieve a positive environmental effect on energy efficiency through new-creative methods	5	5	5	5	5	5	5	5
	total points		72	61	84	71	89	76	85	72
	extra points		54	52	44	44	39	39	41	41
	Points below are to be added only if they contain the following:									
	Projects with gardens or green areas		2	2	2	2	2	2	2	2
	Swimming Pools		2	2	2	2	2	2	2	2
	Elevators		-	-	7	7	7	7	7	7
	Escalators		-	-	2	2	2	2	2	2

*	If achieved, the point will be calculated without considering the previous requirement points.
**	Points will be added to the possible points' final sum only if courts or landscape areas are found within the project.
***	Not required, but if achieved, extra point(s) will be added
	Points will be added to the total points only for buildings that contain swimming pools

11.2 Healthy Indoor Environment

criterion			Single Residential		Multiple residential		Office/ Commercial		Educational	
			with AC	Without AC	with AC	Without AC	with AC	Without AC	with AC	Without AC
	1st criterion: Minimum internal air quality									
Mandatory Requirements	1st requirement	To achieve the minimum requirements for proper ventilation by referring to the relevant codes	0	0	0	0	0	0	0	0
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Computer simulation of indoor air quality	1	1	1	1	1	1	1	1
	2nd criterion: Environmental control of tobacco smoke									
Mandatory Requirements	1st requirement	Prevent smoking or allocate a smoking area	-	-	0	0	0	0	0	0
	2nd requirement	Provide guidance information on the smoking strategy	-	-	0	0	0	0	0	0
Obligatory Requirements	-	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Control of smoke transmission in residential units	1	1	-	-	-	-	-	-
	3rd criterion: Extra Ventilation									
Mandatory Requirements	-	-	-	-	-	-	-	-	-	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Increase the amount of ventilation by 30 %	4	4	4	4	4	4	4	4
	4th criterion: Control of pollutants and their sources									
Mandatory Requirements	-	-	-	-	-	-	-	-	-	-
Obligatory Requirements	-	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Special system for the constantly used entrance floors	2	2	2	2	2	2	2	2
	2nd requirement	Isolate the attached rooms and separate their ventilation systems, such as photocopying, printing, washing and other rooms	-	-	-	-	1	1	1	1
	3rd requirement	Provide an appropriate filtering medium (MERV-	1	1	1	1	1	1	1	1
	5th criterion: Daytime lighting									
Mandatory Requirements	1st requirement	5th criterion- Energy Efficiency	0	0	0	0	0	0	0	0
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	glazing factor => 2% , or achieve lighting level	4	4	4	4	4	4	4	4
	2nd requirement	Use intelligent automatic controls	2	2	2	2	2	2	2	2
	6th criterion: Artificial lighting									
Mandatory Requirements	-	-	-	-	-	-	-	-	-	-
Obligatory Requirements	1st requirement	Provide a separate control system for zones	-	-	1	1	1	1	1	1
Voluntary Requirements	1st requirement	Provide a separate control system for the area of	-	-	-	-	1	1	-	-

	7th criterion: Thermal Comfort									
Mandatory Requirements	-		-	-	-	-	-	-	-	-
Obligatory Requirements	1st requirement	achieve thermal comfort	2	-	2	-	2	-	2	-
Voluntary Requirements	-		-	-	-	-	-	-	-	-
	8th criterion: Thermal Comfort Control									
Mandatory Requirements	-	-	-	-	-	-	-	-	-	-
Obligatory Requirements	-	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	In naturally ventilated places, windows shall be	2	2	2	2	2	2	2	2
	9th criterion: Optimized audio performance									
Mandatory Requirements	-	-	-	-	-	-	-	-	-	-
Obligatory Requirements	-	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Conduct sound tests before occupancy	3	3	3	3	3	3	3	3
	10h criterion: Innovative design for Interior Environment									
Mandatory Requirements	-	-	-	-	-	-	-	-	-	-
Obligatory Requirements	-	-	-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	the project should achieve a high interior healthy	5	5	5	5	5	5	5	5
	total points		15	12	22	19	24	21	22	19
	extra points		12	12	5	5	5	5	6	6

11.3 Materials and Resources

	4th criterion: Material Reuse									
Mandatory Requirements	-		-	-	-	-	-	-	-	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Use of stored or refurbished/recycled materials that cost at least 5% of	2	2	2	2	2	2	2	2
	2nd requirement	Use of stored or refurbished/recycled materials that cost at least 10%	4	4	4	4	4	4	4	4
	3rd requirement	Use of stored or refurbished/recycled materials that cost at least 15%	6	6	6	6	6	6	6	6
	5th criterion: Green Material: A: Recycled Content									
Mandatory Requirements	-		-	-	-	-	-	-	-	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Materials mixed with recycled content; 10% of the cost	2	2	2	2	2	2	2	2
	2nd requirement	Materials mixed with recycled content; 20% of the cost	4	4	4	4	4	4	4	4
	5th criterion: Green Material: B: Local/ Regional Materials									
Mandatory Requirements	-		-	-	-	-	-	-	-	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	the use of Building materials that are extracted, collected treated or	2	2	2	2	2	2	2	2
	2nd requirement	the use of Building materials that are extracted, collected treated or	4	4	4	4	4	4	4	4
	5th criterion: Green Material: C: Rapidly Renewable Materials									
Mandatory Requirements			-	-	-	-	-	-	-	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Rapidly Renewable Materials 2% of the total cost	2	2	2	2	2	2	2	2
	5th criterion: Green Material: D: Certified Wood									
Mandatory Requirements	-		-	-	-	-	-	-	-	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	use of 40% certified wood	2	2	2	2	2	2	2	2
	2nd requirement	use of 70% certified wood	4	4	4	4	4	4	4	4
	5th criterion: Green Material: E: low-emittance building materials									
Mandatory Requirements	1st requirement		-	-	-	-	-	-	-	-
Obligatory Requirements	-		-	-	-	-	-	-	-	-
Voluntary Requirements	1st requirement	Use of low-emission sealing and adhesives materials	2	2	2	2	2	2	2	2
	2nd requirement	Use low-emission paints and dyes	2	2	2	2	2	2	2	2
	3rd requirement	Use of low-emission compound carpets	2	2	2	2	2	2	2	2
	4th requirement	use of low-emission composite wood	2	2	2	2	2	2	2	2
	6th criterion: Innovative design for Materials and Recourses									
Mandatory Requirements	-	-	-	-	-	-	-	-	-	-
Obligatory Requirements	-	-	-	-	-	-	-	-	-	-

Voluntary Requirements	1st requirement	reduce materials consumption in the project through new-creative	5	5	5	5	5	5	5	5
	total points		35	35	36	36	36	36	36	36
	total points for rehabilitated buildings		39	39	40	40	40	40	40	40
	extra points		6	6	5	5	5	5	5	5

11.4 Hierarchy of JGBG categories

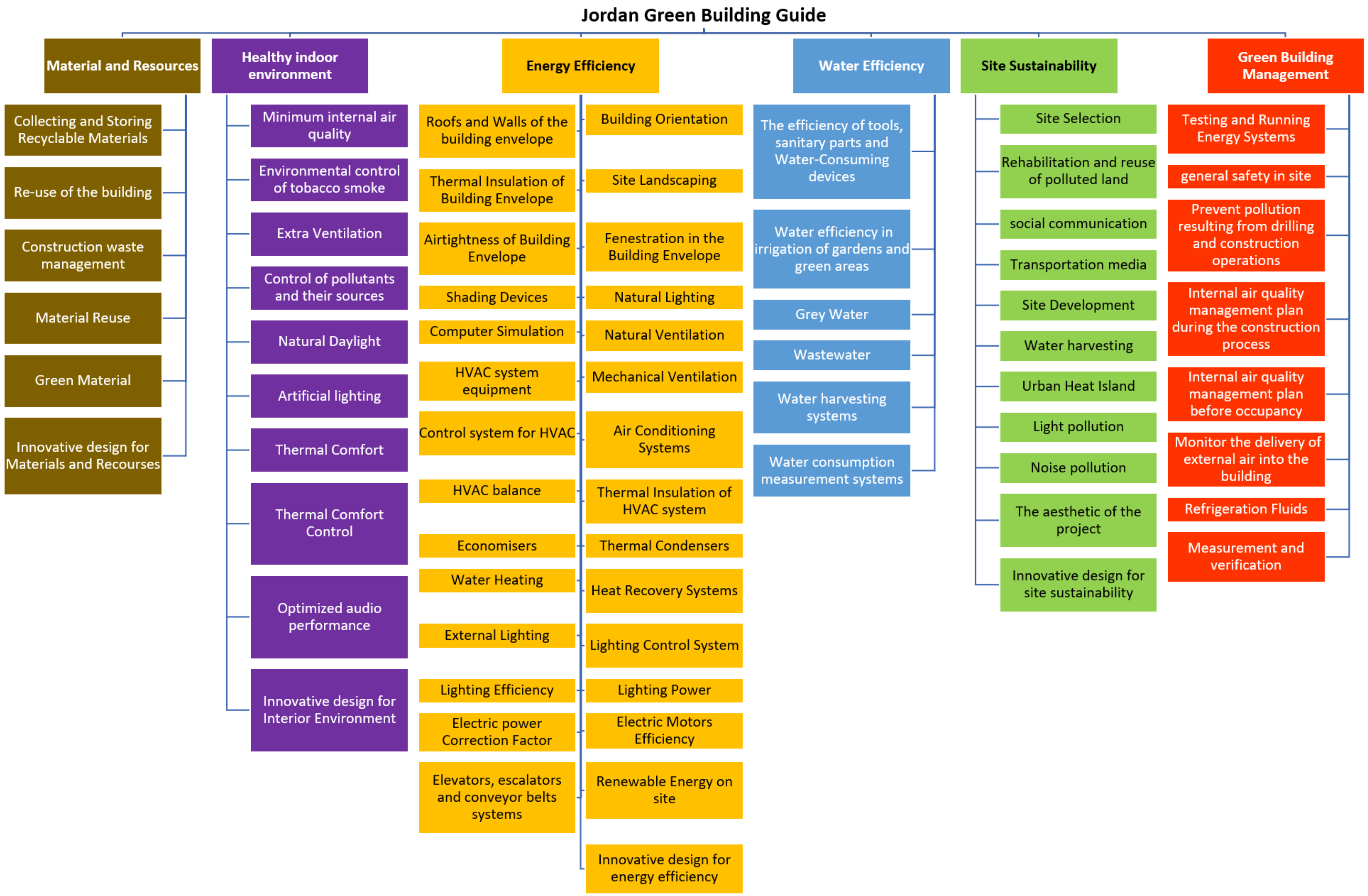

Figure 11-1 Hierarchy of JGBG.

12. Appendix B: Remapped Green Building Rating Tools

Figure 12-1 PEARL rating system

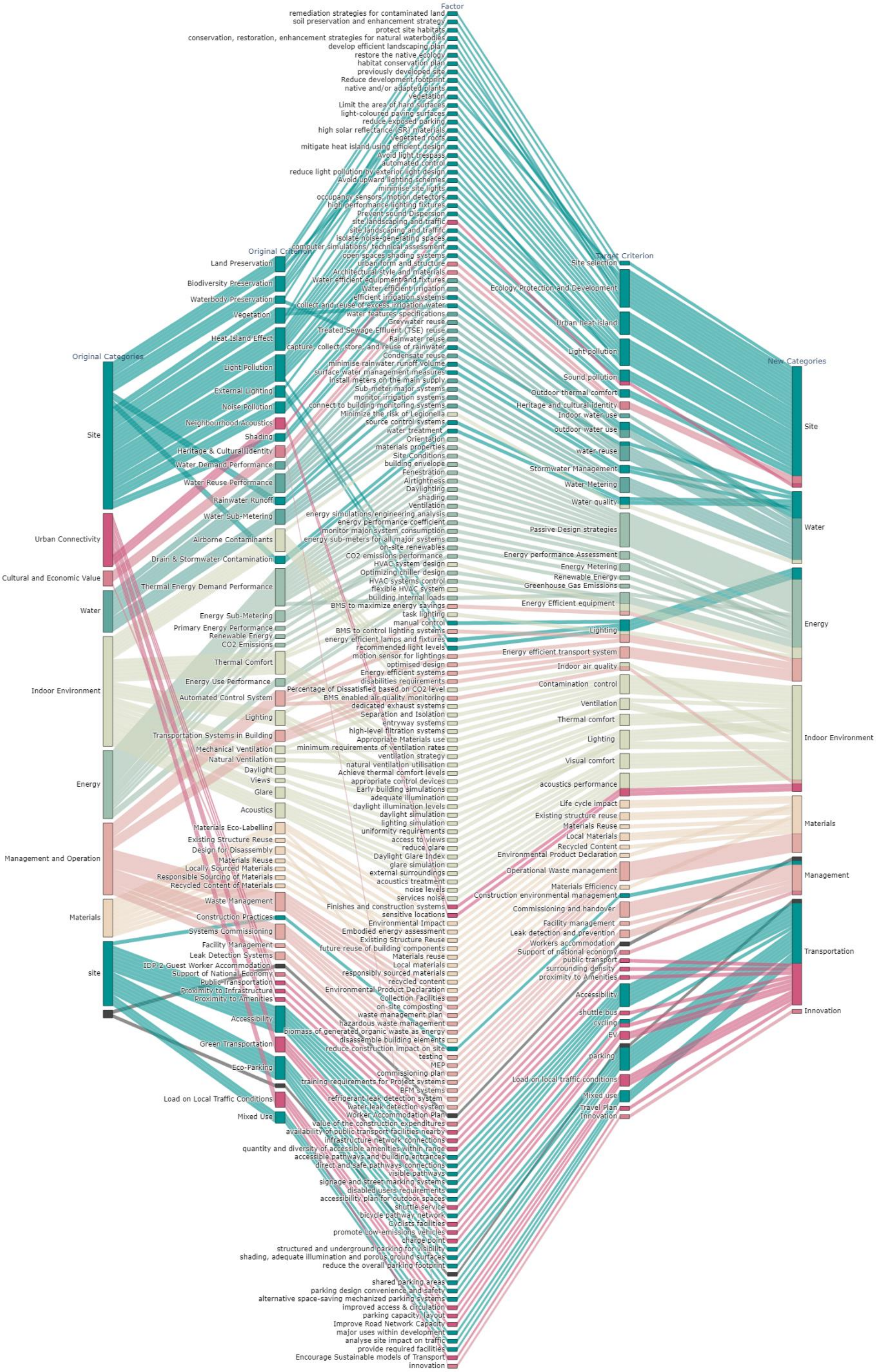

Figure 12-2 GSAS rating system

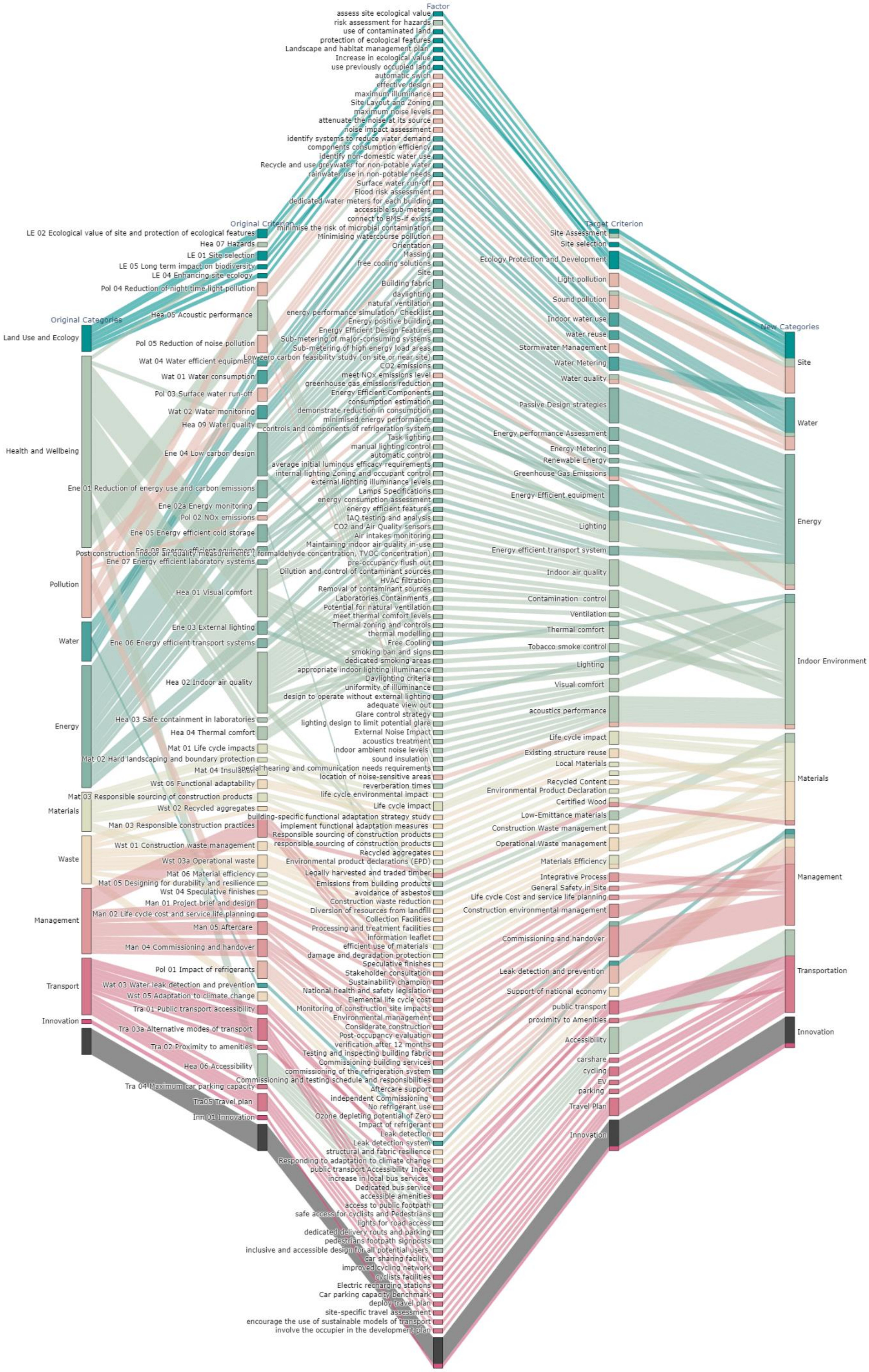

Figure 12-3 BREEAM rating system

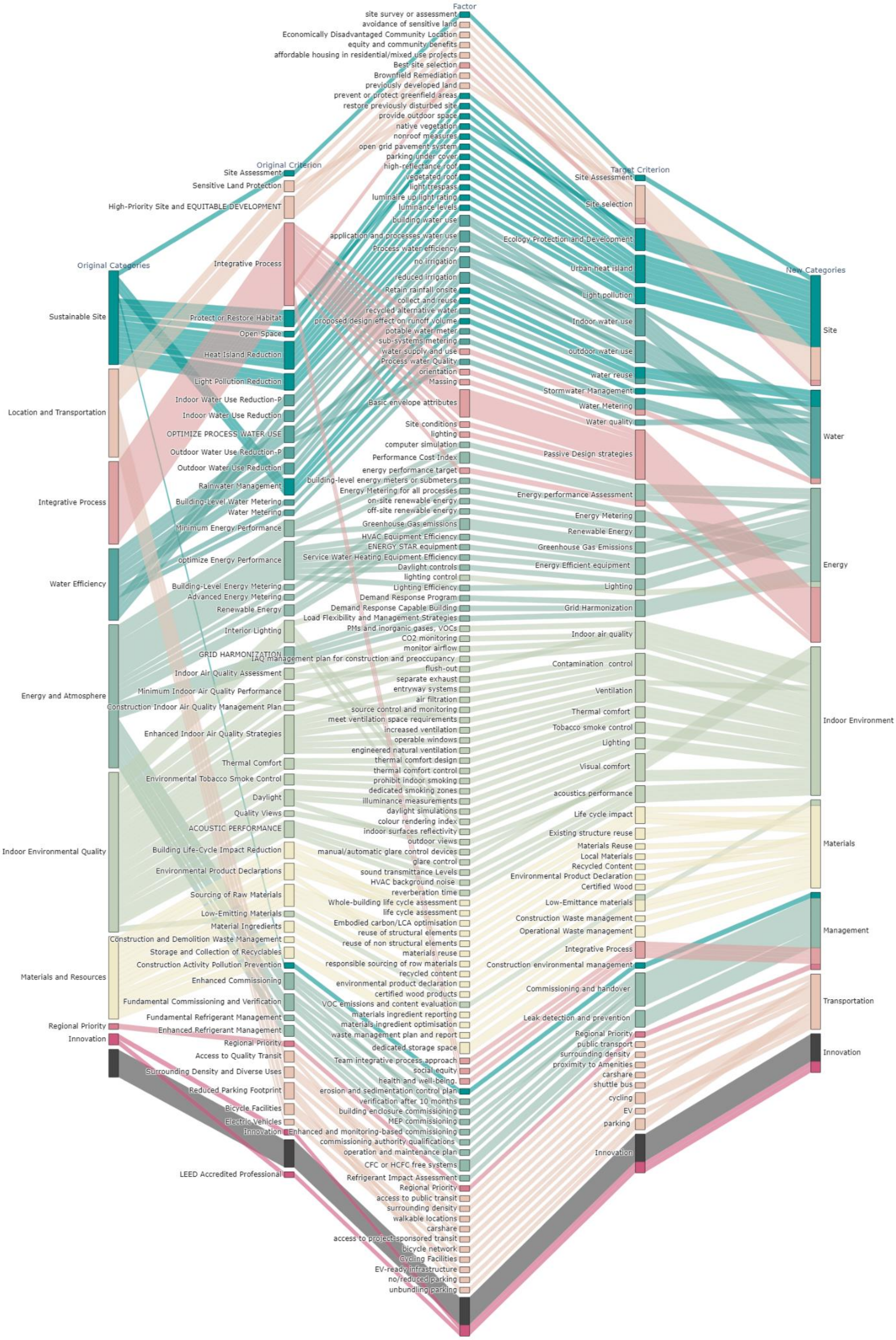

Figure 12-4 LEED rating system

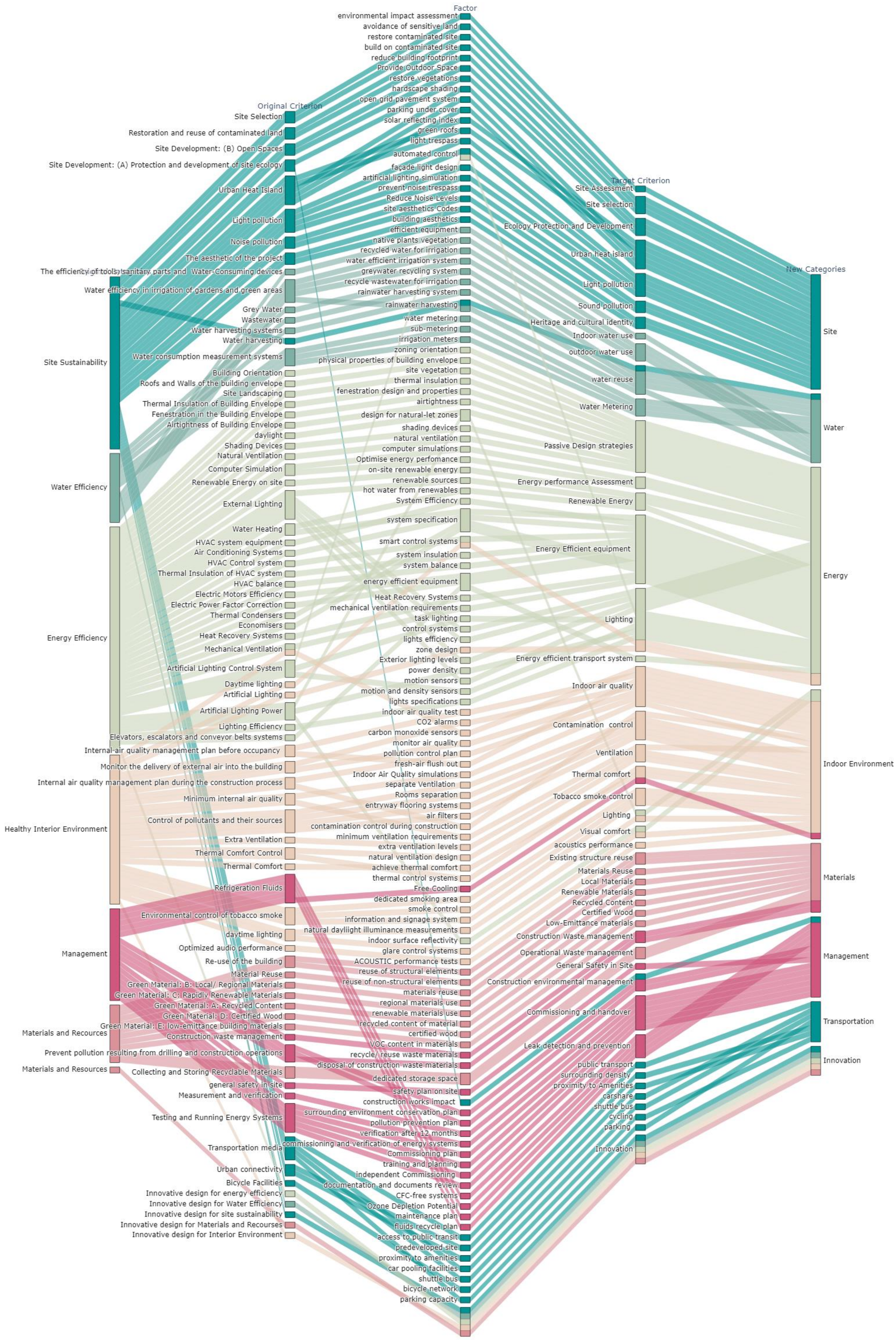

Figure 12-5 JGBG Remapping

13. Appendix C: Analysis of the required project information for Jordan's Green Building Guide (JGBG)

gbXML Element	gbXML Schema Elements	gbXML export from Autodesk Revit	JGBG
Campus	id	Id	
	designHeatWeathIdRef		
	designCoolWeathIdRef		
	ifcGUID		
	Name		
	Descreption		
	Location	Location	Location
	Building	Building	
	Surface	Surface	
	YearModeled		
	DaylightSaving		
	Life		
	AltEnergySource		
	ShellGeometry		
	Vegetation		Vegetation
	Transportation		
	MeterId		
	ExtEquipId		
	Lighting		
	LightControlId		
			Orientation
			Elongation
Building	id	Id	
	buildingType	buildingType	Building Type
	ifcGUID		
	Name		
	Description		
	StreetAddress		
	Area	Area	
	Space	Space	
	AverageNumberOfFloors		
	InfiltrationFlow	InfiltrationFlow	Blower Door Test
	ShellGeometry		
	SpaceBoundary		
	Lighting		
	IntEquipId		
	MeterId		
	PeakDomesticHotWaterFlow		
	BuildingStory	BuildingStory	
	id		
	spaceType (Stairway,ActiveStorage,DiningArea, Lobby, Restrooms, etc.)		Space Type
	zoneIdRef		
	sheduleIdRef		
	lightShefIdRef		
	equipmentSheduleIdRef		
	peopleSheduleIdRef		
	conditionType		
	buildingStoreyIdRef		
	ifcGUID		

	Name		
	Description		
	Lighting		
	LightingControl		
	InfiltrationControl		
	InfiltrationFlow		
	PeopleNumber		
	PeopleHeatGain		
	LightPowerPerArea		
	EquipPowerPerArea		
	AirChangesPerHour		
	Area		
	Temperature		
	Volume		
	PlannerGeometry		
	ShellGeometry		
	AirLoopId		
	HydronicLoopId		
	MeterId		
	IntEquipId		
	AirLoopEquipmentId		
	HydronicLoopEquipmentId		
Material Element	id	Id	
	DOELibIdRef		
	Name	Name	
	Descreption		
	Absorptance		Absorptance Coefficient
	Roughness		Roughness
	Albedo		
	Reflectance		Solar Reflectance Coefficient
	Transmittance		
	Emittance		Emissivity
	ImageTexture		
	R-value	R-value	
	Thickness	Thickness	
	Conductivity	Conductivity	
	Density	Density	
	SpecificHeat	SpecificHeat	
	Permeance		
	Porosity		
	RecycledContent		recycled content
	Fire		
	Cost		cost
	IndoorAirQuality		
	CADMaterialId		
	Reference		
			Origin
			IsRenewable
			volume
			weight
Construction	Name	Id	
	Description		
	U-value	U-value	U-value
	Absorptance		Absorption Coefficient
	Roughness		Roughness
	Albedo		
	Reflectance		Solar Reflectance Coefficient
	Transmittance		
	Emittance		Emissivity

	Cost		
	PercentExisting		percent exist
	FireFace		
	LayerId	LayerId	
	ExtEquip		
	LoadCalcInputParameters		
Surface	id	Id	
	surfaceType	surfaceType	Surface Type
	constructionIdRef	constructionIdRef	
	scheduleShadeIdRef		
	exposedToSun		
	ifcGUID		
	Name	Name	
	Description		
	FamilyName		
	AdjacentSpaceId	AdjacentSpaceId	
	RectangularGeometry	RectangularGeometry	
	PlannerGeometry	PlannerGeometry	
	Opening		
	CADObjectId	CADObjectId	
RectangularGeometry	id		
	unit		
	Azimuth		Azimuth
	CartesianPoint		
	Tilt		Tilt Angle
	Height		
	Width		
	PolyLoop		
			Area
			(WWR)
Layer	id	Id	
	DOELibIdRef		
	Name		
	Description		
	Cost		
	InsideAirFilmResistance		
	MaterialId	MaterialId	
	HOutSide		
			Insulation Location
WindowType	id	Id	
	DOELibIdRef		
	programId		
	Name	Name	
	Description		
	U-value	U-value	U-value
	ShadingCoeff		Shading Coefficient
	SolarHeatGainCoeff	SloarHeatGainCoeff	SolarHeatGainCoeff
	Transmittance	Transmittance	Visual Transmittance
	Reflectance		
	Emittance		
	Blind		
	Frame		
	Gap		
	Glaze		
	Cost		
	ExtEquipId		

Opening	id	id	
	coordinatesAbsolute		
	interiorShadeType		
	exteriorShadeType		ExteriorShading Type
	windowTypeIdRef		
	constructionidRef	constructionIdRef	
	openingType	OpeningType	Opening Type
	ifcGUID		
	Name	Name	
	Description		
	ShadeControl		
	U-value		U-value
	ShadingCoeff		Shading Coefficient
	SolarHeatGainCoeff		Solar Heat Gain Coefficient
	Transmittance		Visual Transmittance
	Reflectance		
	GlazeConductivity		
	Emittance		
	Setback		
	NaturalVentHiTemp		
	NaturalVentLoTemp		
	NaturalVentOccDep		
	RectangularGeometry	RectangularGeometry	
	PlannerGeometry	PlannerGeometry	
	CADObjectId	CADObjectId	
			Area
Equipment	id		Renewable Energy
	shceduleIdRef		Elevators
	waterTempScheduleIdRef		Escalators
	hydronicLoopIdRef		
	waterScheduleIdRef		
	waterMeterIdRef		
	type		PV/Pump/Elevators/Escalators/Pool/Freezer/GeneralPlugLoad/Refrigerator/Motors
	airLoopIdRef		
	programId		
	Name		
	Description		
	Manufacturer		
	Model		
	ElecLoad		
	FuelLoad		
	LatentLoad		
	WindSpeed		
	Efficiency		
	Performance		
	Cost		
	Weight		
	WasteWaterHREFF		
	WaterUsePerCycle		
	RatedFlow		
	Power		
	CyclePerWeek		
	Energy		
	GeneralGeometry		
	ShellGeometry		

	IndoorAirQuality	
	Age	
	Reference	
	CAADobjectId	
LightingControl		lighting control
	id	
	type (Continous, OnOff, Stepped, ContinousOff,MotionSensor,Photocell)	Intensity Sensor, Automatic Control, Occupancy Sensor, Motion Sensor
	lightingSystemIdRef	
	programId	
	GeneralGeometry	
	ShellGeometry	
	Illuminance	
	CartesianPoint	
	MinPowerFrac	
	MinLightFrac	
	PercentAreaDaylitControlled	
LightingSystem		lighting system
	id	
	programId	
	Manufacturer	
	NumberOfLAmps	
	LumensPerLamp	Lumens
	Dimensions	
	InputWatts	Watts
	Ballast	
	Lamp	
	Luminaire	
	Photometry	
	CoefficientOfUtilization	
	Cost	
	GeneralGeometry	
	ShellGeometry	
	Refrence	
AirLoopEquipment		Fans, HVAC, AC, Economizer, HVAC systems Balance
	id	
	controlZoneIdRef	
	systemType (SingleZoneReheat, ReheatFan, MultiZone, VariableAirVolume, FanCoil, etc.)	
	programId	
	Name	
	Description	
	Reference	
	AirLoopEquipment	
	TemperatureControl	
	PressureControl	
AirLoopEquipment		Fans, HVAC, AC, Economizer, HVAC systems Balance
	id	
	equipmentType (Economizer, SplitAC, Fan, Coil, Radiant, etc.)	
	programId	
	Name	
	Description	
	Model	
	Manufacturer	

RatedFlow	system fan speed
MinFlow	system fan speed
MaximumFlow	system fan speed
MaximumFlowFractionDuringReheat	system fan speed
OperationSchedule	system operation schedule
MotorInAirstream	
Temp	temperature
Enthalpy	
EconomiserLockout	
ResetTemperature	
DeltaP	
DeltaT	
MinRelativeHumidity	
MaxRelativeHumidity	
Power	system power
Capacity	system capacity
Contol	System Control
Efficiency	system efficiency
AirStreamFraction	
Performance	system performance
Cost	
Weight	
Life	
WaterLoss	
Energy	
HydronicLoopId	
Reference	
RefrigerantType	
GeneralGeometry	
ShellGeometry	
FlowType	
ParallelFanOnFlowFraction	
NightCycleControl	
HeatRecoveryType	
SensibleHeatRecoveryEffectiveness	
LatentHeatRecoveryEffectiveness	
CoolingCoilSetpointResetType	
HeatingCoilSetpointResetType	
DamperHeatingAction	
HeatPumpDefrostControl	
HeatPumpDefrostStrategy	
SupplementalHeatingCoilType	
SupplementalHeatingCoilCapacity	
SupplementalGasHeatingCoilEfficiency	
SupplementalGasHeatingCoilParasiticElectricLoad	
CyclingRateMax	
HeatPumpTimeConstant	
FractionOnCyclePowerUse	
HeatPumpFanDelayTime	
CoolingCoilType	
PreheatCoilType	
GasPreheatCoilEfficiency	
GasPreheatCoilParasiticElectricLoad	