

Article

Utilization of an Automatic Tool for Building Material Selection by Integrating Life Cycle Sustainability Assessment in the Early Design Stages in BIM

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Abstract: Recent international scientific studies have described the current situation regarding CO₂ emissions and have provided evidence of its catastrophic short- and medium-term consequences. The implementation of solutions of a more sustainable nature to reduce and mitigate this situation is becoming increasingly urgent. To this end, the integration of multi-dimension and life cycle assessment into the design process of buildings can help and support decision making. Life Cycle Sustainability Assessment (LCSA) is one of the scientific community's most widely recognized methodologies for this purpose, combining the evaluation of the social, economic, and social dimensions (Triple Bottom Line). One of the main obstacles to implementing this methodology lies in the difficulties in automatically comparing alternative design options for the selection of different materials. To overcome this limitation, the authors developed the BIM3LCA (Building Information Modelling Three Life Cycle Assessment) tool conceived to guide the decision-making process during the early design steps. This study introduces a Building Information Modelling (BIM) plug-in development and validates its application in a case study to support the multi-criteria building material selection based on the LCSA implementation at the early design stage. Three building material alternatives for the structural system of a multi-family residential building are employed to validate this plug-in. The results show the viability of using this tool during the early design stages and demonstrates the consistency of the results regarding the use of the BIM model to conduct the LCSA. The study discusses the benefits and limitations of the BIM3LCA tool. This research contributes towards the integration of multi-dimension real-time assessment in the building design process by using semantically rich BIM models.

Keywords: sustainability; life cycle sustainability assessment; building information modelling; tool development; building early design steps



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1. Introduction

Recent international scientific studies have described the current situation with regard to CO₂ emissions, and have provided evidence of its catastrophic short- and medium-term consequences [1]. In this respect, the built environment plays a crucial role, since it is responsible for 40% of greenhouse gas emissions [1] and constitutes one of the largest consumers of natural resources [2]. Given the environmental, economic, and social impact [3] that buildings produce throughout their life cycle, society demands an increase in the sustainability of buildings [4–6]. In order to overcome this situation, current international sustainability strategies such as the United Nations Sustainable Development Goals [7] and European strategies such as Green Deal [8] and Circular Economy Action Plan [9] propose radical changes in our development model, such as decarbonization. Moreover, the predictions and scientific evidence regarding the effects of climate change [1,10] necessitate the implementation of measures of a more effective and innovative nature to produce drastic changes. Indeed, the scenario for the improvement of energy efficiency in the

building sector terminates when, for example, near-zero energy consumption standards are reached [11], or when the use of renewable sources for energy supply in the operational phase are fully achieved. However, the embodied impacts related to materials and products included in buildings have yet to be reduced. Hence, due to the complexity of existing problems, potential solutions demand that the sustainability of buildings is addressed from a holistic perspective that integrates the three fundamental dimensions (environmental, economic, and social) for their whole life cycle [11,12].

The Building Information Modelling methodology is the “construction of a model that contains the information about a building from all phases of the building life cycle” [13]. Currently, an increasing number of studies demonstrate the potential of the use of BIM methodology in supporting sustainable construction [14] and in the integration of tools based on LCA [15,16]. Furthermore, the use of BIM in current practice in AECO (Architecture, Engineering, Construction, and Operation) has been mandatory for the tendering of public buildings in the EU since the end of 2018 [14]. Indeed, the use of BIM constitutes a digital revolution in the construction sector, and the scientific community has highlighted its potential in improving the sustainability of buildings [17–20]. However, its effective implementation in the building sector, which requires tools adapted to each context and integrated into the design workflow, remains insufficiently mature [15].

The design process is crucial for the reduction of the impact of the building during its life cycle [11,12]. Consequently, Life Cycle Assessment (LCA) constitutes the most objective and widely employed method [13,14] for the assessment of the environmental impact of building projects, and it plays a crucial role in achieving decarbonization objectives [21]. In recent decades, the use of the LCA method has been largely focused on scientific research by the academia sector [22,23]. The results from a survey of 500 practitioners in the construction sector point out the lack of quantitative life cycle assessment in the early design stages [23], and provide evidence of its limited implementation in practice. However, recent developments are helping to turn this situation around. Indeed, the sustainability assessment in the design process is moving from qualitative to quantitative metrics [24]. The use of LCA-based methods in sustainability assessment and sustainability certification has increased in recent years. For example, the Level(s) [25] (European Commission) framework for the assessment of building sustainability, and the DGNB (German Sustainable Building Council) [26] and Verde (Spain) [27] Green Building Rating System (GBRS), use simplified LCA and LCC methods in the evaluation process. Moreover, they have integrated both methods into their evaluation requirements [26,28]. Nevertheless, the reduction of the environmental impact of the built environment goes beyond traditional unidimensional approaches [29]. Life Cycle Sustainability Assessment (LCSA) provides a more comprehensive approach than do the LCA and LCC techniques. The methodology combines three methods based on the quantification of the life cycle impacts: (environmental) LCA, Life Cycle Costing (LCC), and Social-Life Cycle Assessment (S-LCA) [18]. It, therefore, conducts the so-called Triple Bottom Line (TBL) sustainability assessment. Nonetheless, the integration of the Social-Life Cycle Assessment (S-LCA) is not yet specifically required in this certification or assessment framework [30], since it is only starting to be considered as a relevant method for its integration into future developments of the sustainability certifications [21], in order to provide a more quantitative assessment of sustainability. One of the main obstacles therein involves the limited data availability and the limited development of indicators adapted to the BIM workflow and design process [30]. The potential of using the LCSA to assess the embodied impacts (environmental, economic, and social) of those directly related to the materials that compose the building from a life cycle perspective is demonstrated in the literature [31].

Recent studies highlight that the integration of LCSA-based sustainability assessment in the building sector is scarce [32,33], as its implementation in BIM [33]. The authors' recent development [31] constitutes one of the first to propose an interoperable framework. This study develops an Autodesk Revit Dynamo Script [34] and defines the main steps for real-time LCSA calculations to be conducted in BIM. It is based on the

enrichment of the parameters of the BIM model, that was previously implemented by Santos et al. [35–37] to conduct LCA and LCC. Similar principles are implemented in Röck et al. [38], Bueno et al. [39], Giaveno et al. [40], and Santos et al. [37,41] that insert new parameters in the BIM objects (environmental impact categories), which have previously been defined in an Excel file. Zhaon et al. [42] propose a plug-in implemented in BIM to low-carbon building design optimization, which focuses on operational aspects such as energy consumption and daylighting performance, but embodied impacts are not included in the assessment. Filho et al. [43] conducted the LCSA based on a BIM model integrating a multi-criteria decision-making technique (Fuzzy Analytical Hierarchy Process (AHP)), nevertheless the work proposes a manual workflow, which lacks in the automation of the LCSA implementation in BIM using a single plug-in. In this vein, the existing literature [37–41] provides evidence of limitations in the use of the data sources along the design stages. It means that for the early design, step generic data from ecoinvent [44] is mainly used, and for the detailed design steps, specific data from EPDs (Environmental Product Declaration) are used. One of the limitations of this approach involves the risk of data inconsistency in the simultaneous implementation of the LCA techniques, which include various inventories (and data structures for the economic and environmental dimensions) and data sources depending on the dimension (e.g., ecoinvent [44] for the environmental dimension and CYPE for the economic dimension). This gap was recently explored in this research [45], which demonstrates the potential of the method and its consistency throughout the design process. The study uses a Triple Bottom Line (TBL) database to integrate the environmental, economic, and social dimension, which means a sustainability assessment based on a triple dimension. The TBL database is developed to fill the information gaps in the early design steps [45] and to provide and harmonize the data structure for the triple-dimension assessment. Another limitation detected in the existing studies [31] involves the automatic comparison of various design options, modelled in different BIM folders, and also the difficulties in detecting model errors and the user interface limitations of the prototype developments [31]. The lack of a stable and user-friendly interface is a limitation in this existing development [31]. Using the plug-in requires a basic knowledge of Dynamo Autodesk Revit and the plug-in mainly depends on pre-developed packages for Dynamo Autodesk Revit to complete several functions (such as data visualization). In addition, there are limitations on the results of the data visualization, which depend on a predefined layout and existing functionalities. Moreover, the use of the outputs is limited to the format and visualization charts that the packages are including. Hence, knowledge gaps are detected so that these shortcomings are addressed in this present study.

Given that the authors' previous studies are based on the development of a prototype tool [31] and on the demonstration of the data consistency of the LCSA framework throughout the design process [45], this present study proceeds with the improvement of the latter's development, and explores its potential for the selection of building material based on multi-criteria decision-making techniques, which are discussed for the first time in this work.

Therefore, unlike the previous three articles [31,33,45] and in order to fill the detected knowledge gaps, this present paper aims to answer the following research questions (RQ):

- RQ1: Is it possible to conduct an automatic calculation of the environmental, economic, and social impacts based on the LCSA method in real time using specific (improving the usability and data visualization) software integrated into the BIM environment?
- RQ2: Is it possible to implement an automatic multi-model assessment to support the building material selection within the BIM environment?

To this end, the BIM3LCA tool has been developed: a BIM-based Sustainability Life Cycle Assessment plug-in to support the integration of environmental, economic, and social information into the BIM objects, as described in Section 2. Section 3 includes the tool validation with a case study application to evaluate three alternative building materials for a multi-family residential building located in Seville. Section 4 discusses the advantages and limitations of the developed tool, while Section 5 focuses on the conclusions of the research.

2. Materials and Methods

This research aims to develop a BIM-based application to support both an automatic LCSA and the multi-dimension material assessment within the BIM environment. This study is supported by previous studies in this field [31,33,45] that propose the methodological framework to conduct the LCSA in BIM [33]. Hence, the initial prototype tool (LCSA Dynamo Autodesk Revit Script) described in Llatas et al. [31,45], has been further explored (upgraded) in this article, employed to develop the BIM3LCA tool, and then validated on a case study application (see Figure 1). To address the research questions, the methodology applied in this study focuses on the operative implementation of the approach of previous studies towards validating the tool developed. Therefore, the in-depth analysis of the LCSA results lies outside of the scope of this study.

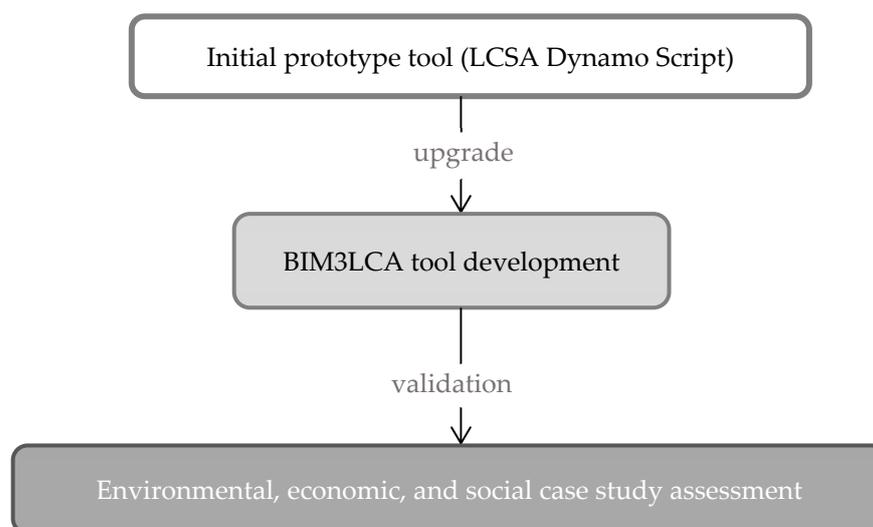


Figure 1. Schema of the methodology developed in this work.

The selected BIM-based environment software is that of Autodesk Revit, one of the most widely used, both for BIM tools in the international market and for sustainability-related simulations [46] through the Revit Application Programming Interface (API) based on the Microsoft.NET environment. The programming language C# was selected to develop the BIM3LCA tool (including BIM model data management, LCSA calculation, and visualization of the LCSA results), mainly since the most readily available Revit API user's guide information is based on this language [34]. Furthermore, Windows Form (WinForms) classes were needed to generate the Graphic User Interface (GUI) which acts as a connection between the database and the user.

2.1. LCSA Implementation in BIM

The LCSA implementation was based on the ISO 21931-1 [47] standard. It proposed the organization of the information according to the modularity principle. Table 1 shows a possible organization of the embodied (E) and operational (O) aspects involved in the LCSA based on [31,47], and indicates the information modules included (marked with X) in this study. The incorporation of information modules was based on the data availability and the scope of the study, with the aim of covering as many modules as possible. However, several omissions were assumed and justified in [31]. The scope of the LCSA was focused on the building structure system. Hence, the study only included the building elements that compose the structure (including beam, column, foundation, slab, wall). The service life of those building elements was 50 years (the same as the building life span), which was based on Spanish regulations [48] about the building structure life span.

Table 1. Information modules according to ISO 21931-1 [47].

		A0	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	C1	C2	C3	C4	D
Environmental LCA	E		X		X									X	X			X
	O																	
Economic LCC	E		X		X									X				
	O																	
Social S-LCA	E				X									X	X			X
	O																	

A0: Land and associated fees/advice; A1: Raw material supply; A2: Transport and all upstream process from cradle to gate; A3: Manufacturing of products; A4: Transportation to the site; A5: Construction of the building, B1: Use; B2: Maintenance; B3: Repair; B4: Replacement; B5: Refurbishment; B6 to B8: Use of energy resources, use of material resources, use of water and building user's activities not covered in B1-B7, C1: Deconstruction/Demolition; C2: Transport waste processing of disposal; C3: Waste processing; C4: Disposal; D: Potential net benefits from reuse, recycling and or energy recovery, beyond the system boundary. Fuente: ISO 21931-1 (ISO, 2022).

The LCSA data input (Table 2) refers to the type of information that should be prepared before the plug-in is run. Considering the geometric information about the building elements that composed the building, the BIM model was modeled in a 200 LOD (Level of Development). At that LOD, the “model element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation” [48].

Table 2. Description of the data input and output for the plug-in application.

Data input		LCA	LCC	S-LCA
BIM model TBL database		Building elements volumes	Building elements volumes	Building elements volumes
Data output		LCA	LCC	S-LCA
Impact category and indicator		CO ₂ eq. emissions	Euros	Working hours

The LCSA data output (Table 2) refers to the type of information that will be calculated with the plug-in. This study includes the following impact categories and indicators: Global Warming Potential (GWP) in kg. CO₂ eq. (environmental); costs in Euros (economic); and labor in working hours (social). The selection of the impact categories and indicators: GWP in kg. CO₂ eq. (LCA) was based on its relevance in achieving the decarbonization objectives [8]. The selection of the inventory indicators of costs (LCC) and working hours (S-LCA) was based on the existing systematic data sources such as BCCA [49]. The “Working hours” inventory indicator [50] is referenced in the UNEP S-LCA guidelines [50] as the most frequently used activity variable, and it has previously been used in other S-LCA studies [31,45,51,52].

2.2. Case Study Description

The case study is the La María multi-family residential building located in Seville, Spain. The building was promoted by EMVISESA, a public enterprise dedicated to the

construction of public housing. The building total area is 2119.24 square meters, distributed across 5 levels (including the ground floor), and 16 apartments. Even though the structure is mainly composed of reinforced concrete and the foundations are composed of slab concrete, this study compares three alternative materials for the structure: timber (CLT), reinforced concrete, and steel (see Figure 2 and Table 3). The complete list of materials is included in the Supplementary Data.

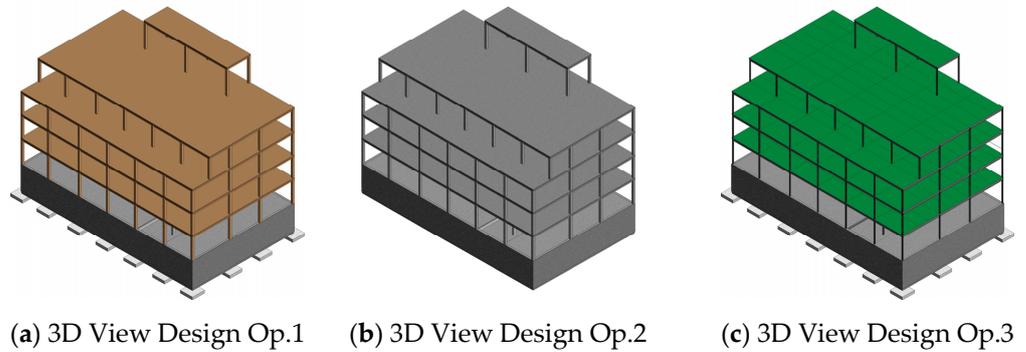


Figure 2. 3D View of the material alternatives BIM model.

Table 3. Description of the main materials included in the design options.

	Design Option 1	Design Option 2	Design Option 3
Foundations	Reinforced Concrete H25	Reinforced Concrete H25	Reinforced Concrete H25
Retaining walls	Reinforced Concrete H25	Reinforced Concrete H25	Reinforced Concrete H25
Beams	Wood M24	Reinforced Concrete H25	Steel
Columns	Wood M24	Reinforced Concrete H25	Steel
Slabs	Wood CLT	Reinforced Concrete H25	Collaborating and (collaborating) metal sheet

2.3. Tool Development

The tool assumes that the BIM model and the objects contained in the BIM model include insufficient environmental, economic, and social data to conduct an automatic LCSA. To this end, it is necessary to enrich the BIM model. The tool integrates a predefined library of BIM objects (TBL database [31,45]) that are linked to the objects included in the model (Figure 3).

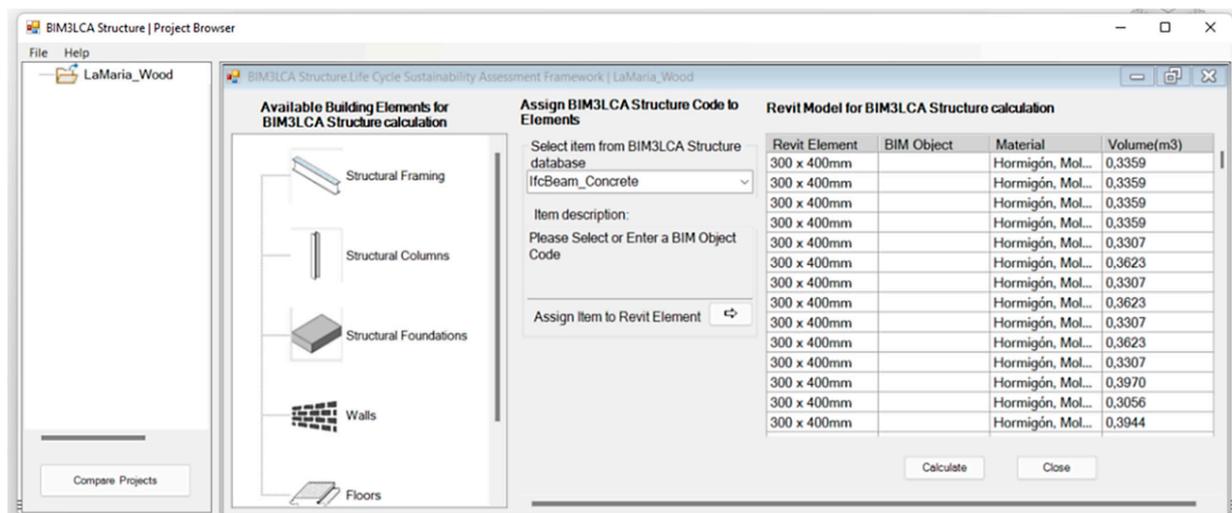


Figure 3. BIM3LCA User Interface.

In this study, only the main structural elements are considered in the contribution to the environmental, economic, and social impacts of the project: mechanical, electrical, and MEP elements are excluded from the assessment. The LCSA calculation procedure consists of the multiplication of the bill of material quantities of each building element (from the BIM model) and the impact factor extracted from the TBL database. This procedure and the methodology assumed to conduct the LCSA has been described in previous studies [31,45]. Following the main steps to conduct the LCSA in BIM previously defined in Llatas et al. [31], (parameters assignment, material code assignment, LCSA calculation, and results visualization), this study focuses on developing a more stable and reproducible workflow to conduct reliable LCSA. Thus, it focuses on improving the user interface and the detection of errors in the BIM model, the usability and the materials assignment to the BIM model, the visualization of the LCSA results, and adding more flexibility to the values obtained (different formats). To improve the user interface, the BIM3LCA software creates a single shared parameter (BIM3LCA code) which is automatically assigned to the project's general information together with elements from the BIM Model: foundations, columns, beams, floors, and walls. The user interface subsequently appears, thereby allowing us to find useful information regarding the BIM model: the different categories, element names, material, and volume information, and the BIM3LCA code to each element can be easily assigned.

The upgrade and optimization of previous developments [31] focuses on increasing the interaction between the model and the plug-in, to support the selection of the building elements.

To this end, and to improve in the detection of errors, the tool enables several verifications to be conducted to detect erratic elements (i.e., due to wrong imports from external models into Autodesk Revit) and to allow for the deletion of these elements and the correction of the imported BIM Model (Figures 4 and 5) before the main user interface appears.

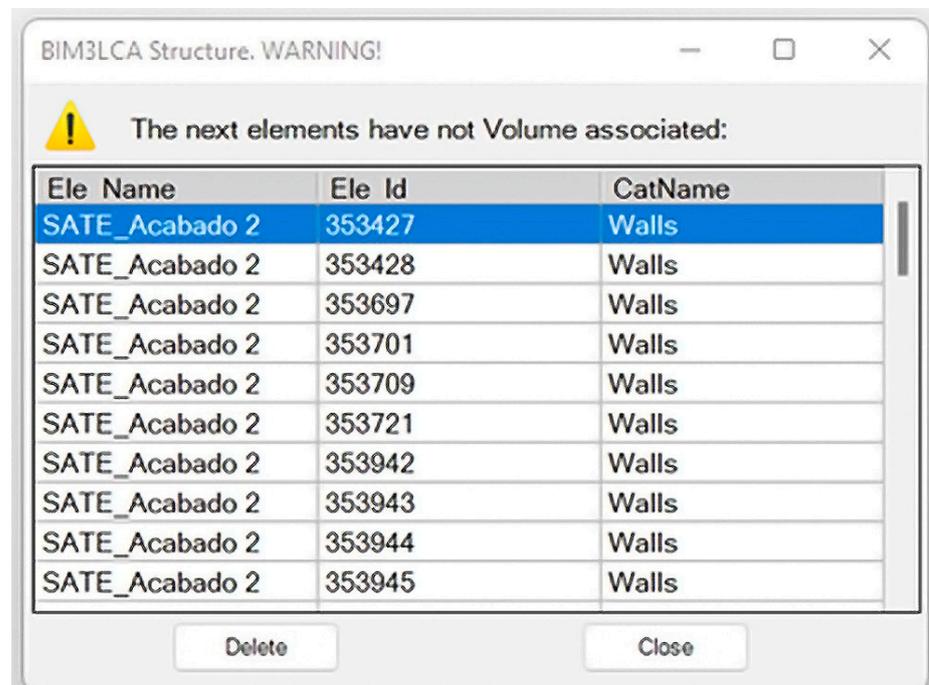


Figure 4. BIM3LCA. Null Element Volume Detection.

To improve the usability and the materials assignment to the BIM model, the user interface contained the items from the BIM3LCA TBL database which contained all the information required for the LCA, LCC, and S-LCA implementation (see Figure 6). This task can be performed in a single step using the box menu, which enabled automatic filters

to detect the category of the elements selected (e.g., on selecting columns, all the items related to the element ‘Structural Columns’ were shown). To facilitate the assignment, the process of a table with all the filtered elements from the BIM Model were shown, displaying the name, BIM object code assigned, material names, and volumes of those elements.

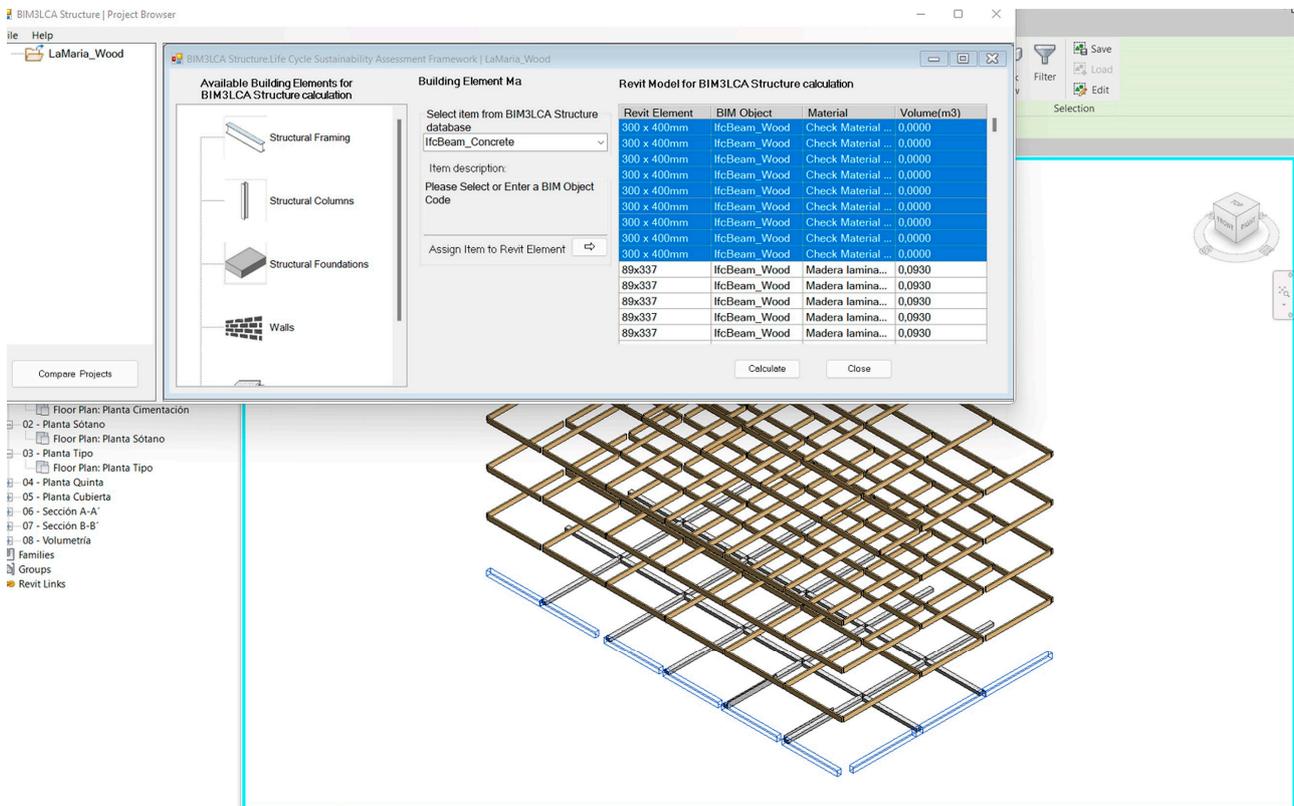


Figure 5. BIM3LCA. Null Element Material Volume Detection.

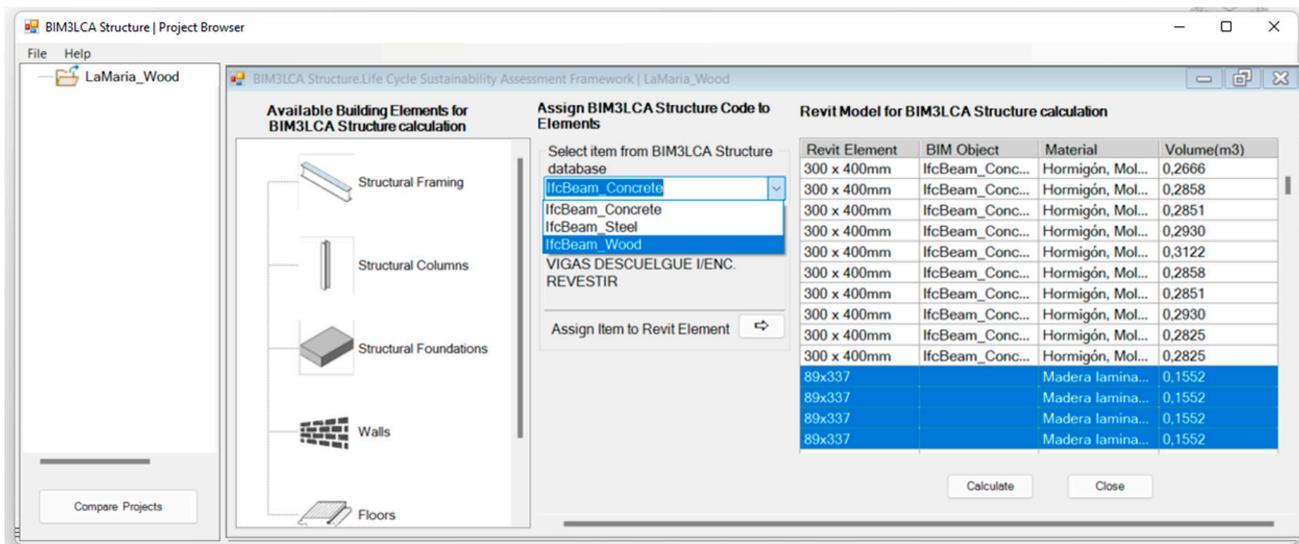


Figure 6. BIM3LCA. Item category assignment.

To facilitate the LCSA implementation of the BIM Model, the BIM code from the dropdown list was used. This code related the name of the possible materials from the TBL database with the environmental, economic, and social values for the functional unit

(1 cubic meter) of the different materials of the building elements. The window displayed the existing building elements of the selected type (e.g., column, slab, beam, foundation, and wall). Thus, once the code was selected, the 'Assign Item to Revit Element' button was used to confirm it. As a result, this information was saved into the selected elements of the BIM model.

To confirm the information added into the corresponding building elements, it was possible to verify whether the information has been successfully saved in the BIM model, which allows them to check the element's properties in the Revit GUI (Figure 7).

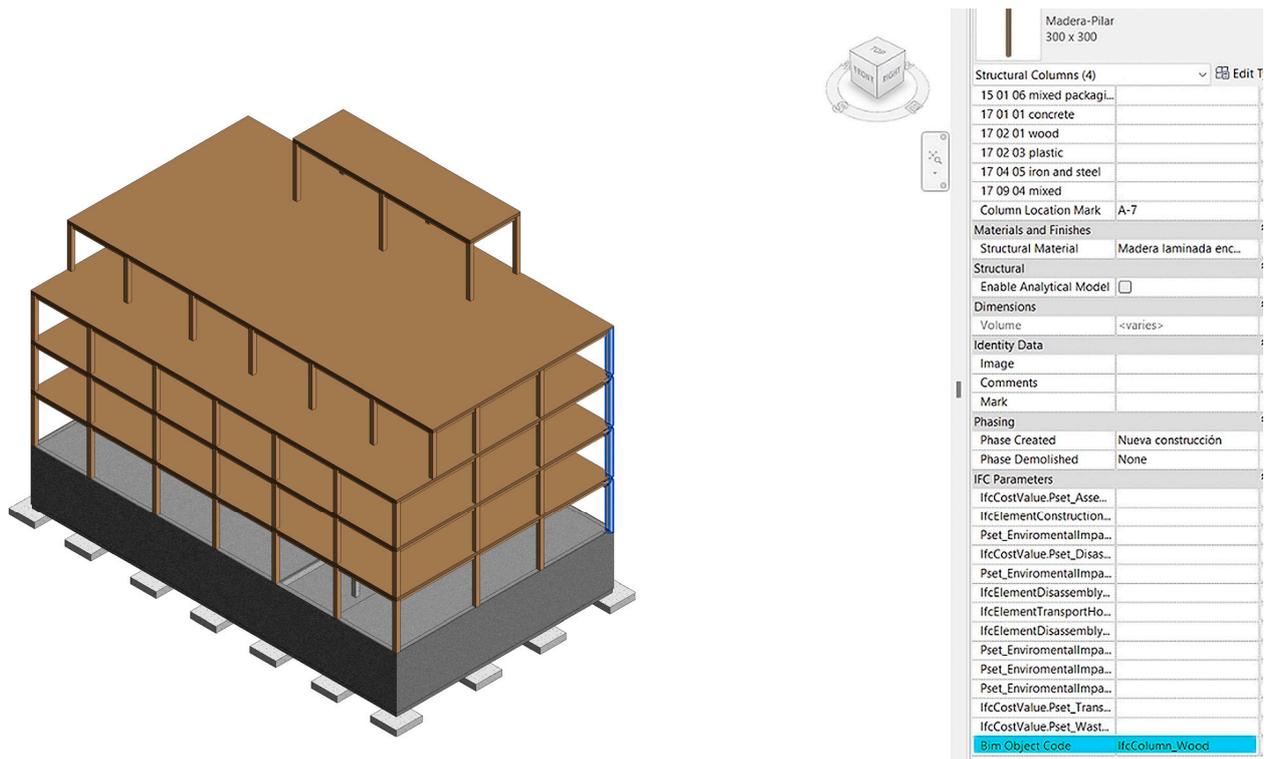


Figure 7. BIM3LCA. Item assignment verification.

Once the items were assigned with a BIM object code, the calculate button was pressed (Figure 6), the BIM3LCA plugin performed the LCSA calculation automatically and displayed the result in a pop-up window (Figure 8). This window displayed the triple dimension assessment based on the LCA, the LCC, and the S-LCA, of the different building life cycle stages (product, construction, and deconstruction) and life cycle information module (e.g., A1–A3, A5, C1, C2, C4), grouped into building element type (e.g., beam, column, foundation, slab, wall), and the global impact of those stages per dimension on the studied BIM model. This enhancement enables us to visualize the impacts of each of the building elements, life cycle stages, and total results per dimension, in order to implement measures for their potential reduction.

To add more flexibility to the values obtained and to enable their use in other formats, the plug-in not only enables us to visualize the charts (Figure 8), but also the Environmental, Economic and Social tabs can be exported to Microsoft Excel files, in order to extract new customized information (Figure 9).



Figure 8. BIM3LCA. Pop-up window of the LCSA results.

elem_Name	elem_Id	BIM Object Code	Structural_Material	elem_Vol	Sum_rows_IFCvV_perElement
300 x 400mm	422162	IfcBeam_Concrete	Hormigón, Moldeado in situ, gris	0.33594000000005581	146.06671200002427
300 x 400mm	422228	IfcBeam_Concrete	Hormigón, Moldeado in situ, gris	0.33594000000005708	146.06671200002481
300 x 400mm	422271	IfcBeam_Concrete	Hormigón, Moldeado in situ, gris	0.33594000000005836	146.06671200002538
300 x 400mm	422299	IfcBeam_Concrete	Hormigón, Moldeado in situ, gris	0.33594000000005758	146.06671200002503
300 x 400mm	423022	IfcBeam_Concrete	Hormigón, Moldeado in situ, gris	0.33066000000005158	143.77096800002244
300 x 400mm	423022	IfcBeam_Concrete	Hormigón, Moldeado in situ, gris	0.36234000000003724	157.54543200001621
300 x 400mm	423047	IfcBeam_Concrete	Hormigón, Moldeado in situ, gris	0.33066000000005419	143.77096800002354
300 x 400mm	423049	IfcBeam_Concrete	Hormigón, Moldeado in situ, gris	0.36234000000005717	157.54543200002485
300 x 300	420030	IfcColumn_Concrete	03HRZ80010	0.33300000000000335	228.46464000000223
300 x 300	420099	IfcColumn_Concrete	03HRZ80010	0.33300000000000335	228.46464000000223
300 x 300	420126	IfcColumn_Concrete	03HRZ80010	0.33300000000000485	228.46464000000333
300 x 300	420157	IfcColumn_Concrete	03HRZ80010	0.33300000000000252	228.46464000000171
300 x 300	420177	IfcColumn_Concrete	03HRZ80010	0.3330000000000059	228.46464000000267
300 x 300	420218	IfcColumn_Concrete	03HRZ80010	0.33300000000000335	228.46464000000223
300 x 300	420218	IfcColumn_Concrete	03HRZ80010	0.33300000000000496	228.46464000000339
300 x 300	420220	IfcColumn_Concrete	03HRZ80010	0.33300000000000324	228.46464000000219
2000 x 2000 x...	437868	IfcPlate_Concrete	Layer 0 : 03HRL80090 Layer thickness:300 mm	140.899980000000058	675.16423846200283
2000 x 2000 x...	438885	IfcPlate_Concrete	03HRZ80010	1.7999999999999992	862.54199999999992
2000 x 2000 x...	439157	IfcPlate_Concrete	03HRZ80010	1.7999999999999992	862.54199999999992
2000 x 2000 x...	439202	IfcPlate_Concrete	03HRZ80010	1.7999999999999996	862.54199999999992
2000 x 2000 x...	439281	IfcPlate_Concrete	03HRZ80010	1.7999999999999996	862.54199999999992
2000 x 2000 x...	439366	IfcPlate_Concrete	03HRZ80010	1.7999999999999992	862.54199999999992
2000 x 2000 x...	439409	IfcPlate_Concrete	03HRZ80010	1.7999999999999996	862.54199999999992
2000 x 2000 x...	439496	IfcPlate_Concrete	03HRZ80010	1.7999999999999996	862.54199999999992
Muro cimenta...	442750	IfcWall_Concrete	Layer 0 : 03HRM80080 Layer thickness:300 mm Vol:33.888 m3	33.888000000000169	14652.154560000072
Muro cimenta...	442839	IfcWall_Concrete	Layer 0 : 03HRM80080 Layer thickness:300 mm Vol:19.428 m3	19.428000000000047	8400.0843600002027
Muro cimenta...	442942	IfcWall_Concrete	Layer 0 : 03HRM80080 Layer thickness:300 mm Vol:33.888 m3	33.888000000000162	14652.154560000072
Muro cimenta...	443043	IfcWall_Concrete	Layer 0 : 03HRM80080 Layer thickness:300 mm Vol:19.428 m3	19.427999999999925	8400.0843599997934
Losas de CLT...	432597	IfcSlab_Concrete 30cm	Layer 0 : 05WC490110 Layer thickness:300 mm Vol:135.362 m3	135.3619600000007	46375.014348000244
Losas de CLT...	432678	IfcSlab_Wood_22cm	Layer 0 : Losa de CLT Layer thickness:220 mm Vol:103.324 m3	103.32445200000049	20029.445020200095
Losas de CLT...	432720	IfcSlab_Wood_22cm	Layer 0 : Losa de CLT Layer thickness:220 mm Vol:103.324 m3	103.32445200000049	20029.445020200095
Losas de CLT...	432762	IfcSlab_Wood_22cm	Layer 0 : Losa de CLT Layer thickness:220 mm Vol:103.324 m3	103.32445200000049	20029.445020200095
Losas de CLT...	435580	IfcSlab_Wood_22cm	Layer 0 : Losa de CLT Layer thickness:220 mm Vol:85.866 m3	85.866390000000492	16645.200864000094
Losas de CLT...	436958	IfcSlab_Wood_22cm	Layer 0 : Losa de CLT Layer thickness:220 mm Vol:11.435 m3	11.435116000000111	2216.6972366000214

Figure 9. BIM3LCA. Pop-up window to export to Excel the LCSA results.

3. Results

The tool validation was conducted on a case study where three building material alternatives were evaluated. To that end, three different BIM models that include different material (steel, concrete, and wood) for the structure were compared. The plug-in was executed in a few seconds and the results were displayed, and this enabled us to obtain a global perspective of the applied options, and to view which categories and stages have

the most critical impact, which led us to decide which alternative is the optimal material for the BIM model.

Validation of the Tool in the Case Study Application

After the tool application to the case study alternative materials, the results for the LCSA were obtained. Figures 10–12 show the screenshots of the values obtained considering the building elements, the LCSA stages, and the total value for each dimension.

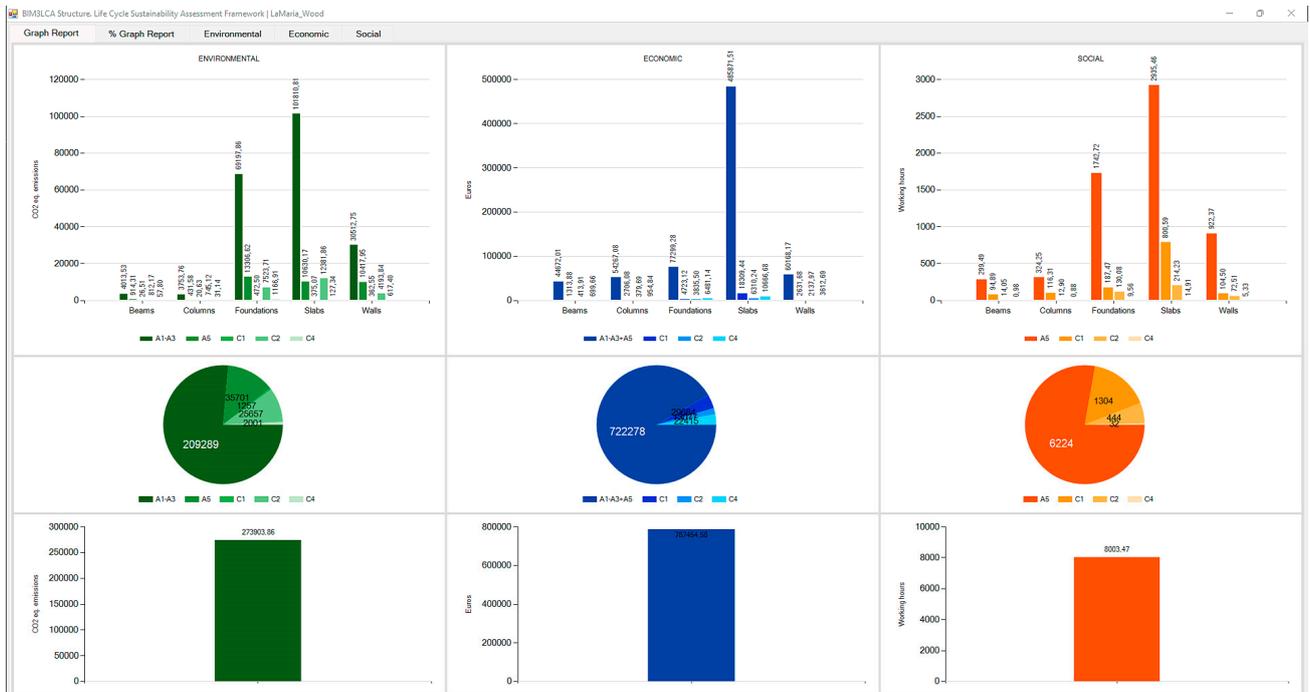


Figure 10. Results for Design option 1 (timber and reinforced concrete).



Figure 11. Results for Design option 2 (reinforced concrete).

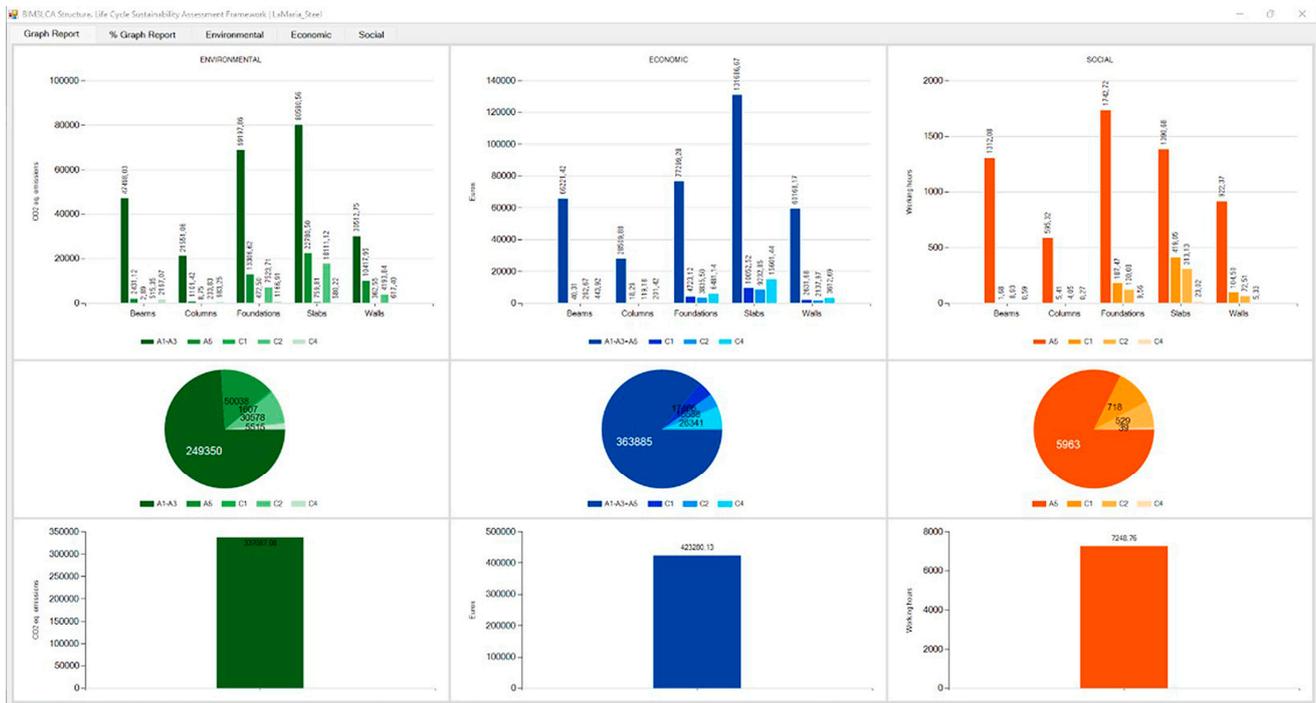


Figure 12. Results for Design option 3 (steel and reinforced concrete).

It can be inferred from the evaluation of the different design solutions (Table 4), whereas Design Option 1 (timber) had the lowest in CO₂ emissions, it had, on the other hand, the highest economic costs. However, Design Option 3 (steel) presented the lowest LCC and S-LCA with an intermediate environmental impact. This fact will be further discussed in Point 4.

Table 4. Summary of the results for the three material alternatives.

	Environmental (Kg. CO ₂ eq.)	Economic (Euros)	Social (Working Hours)
Timber	273,904	787,455	8003
Concrete	474,249	569,867	10,423
Steel	337,087	423,280	7249

4. Discussion

4.1. Lessons Learnt from the Tool Development

The results provide evidence that it is possible to conduct environmental, economic, and social impact calculations based on the LCSA method in real time within the BIM environment (RQ1) using a plug-in. The BIM3LCA structure development enables the simultaneous assessment of different BIM models (and files) and the visualization of the results within the BIM environment (native software where the building was modelled). This enables the designer to speed up the implementation of changes and modifications in real time without any other further steps (such as for the material quantities take-off process in the BIM model). This implies an improvement in aspects such as usability and data visualization compared to previous studies [31]. This study also provides evidence that the BIM3LCA structure tool enables an automatic multi-model assessment to be conducted to support the building material selection within the BIM environment (RQ2). In this vein, the use of the TBL database reduced the effort in the environmental, economic, and social data preparation and BIM workflow adaptation, compared to previous works in this field [43,53]. The authors demonstrate that the plug-in can develop automatic LCSA calculations and

support designers in the decision-making process, thereby integrating a straightforward user interface and methods to simplify the detection of the modelling errors.

The selection of the best option was conducted using the real-time calculation of the LCSA to obtain the embodied carbon footprint, economic costs, and the working hours (for the assessment of the social impact).

This development demonstrates that the tool can identify the best option in the three assessed categories and dimensions and shows the greatest building elements (Ifc Building Element Class) contributors (such as IfcBeam, IfcColumn, IfcFoundation, IfcSlab, IfcWall), and LCA stages (such as Product and Construction, Use and End-of-Life).

Due to the relevance of the Life Cycle Inventory (LCI) [45] and the material quantity take-off in the LCSA implementation in BIM [54], the results for the manual and automatic material quantity were compared. Thus, to validate the consistency of the BIM3LCA results, a manual material quantity take-off is compared with that conducted by the plug-in of the existing materials in the BIM model. Table 3 shows that the material quantities extracted from the manual quantity take-off and the plug-in are very similar and that the variation is related to the digits considered after the decimal point. Given that the only possible variations are related to the material quantity take-off values, the results shown in Table 3 demonstrate the validation of the plug-in development using the LCSA-based method.

It is, therefore, demonstrated that by manually extracting the material quantities of the BIM objects and the material quantities used by the plug-in, similar values are obtained and those values are subsequently multiplied with the data from the TBL database (see Table 5). The timber option produces the least CO₂ eq. emissions, the steel option is the cheapest, and the concrete option is the best in terms of its contribution to local employment in the construction sector. The results obtained are also aligned with other studies in this field [54,55] that compare the steel, concrete, and timber of the environmental impacts produced by building structure materials.

Table 5. Description of the main materials (Material Volume in m³) included in the design options.

	Design Option 1		Design Option 2		Design Option 3	
	Manual Extraction	Plug-In	Manual Extraction	Plug-In	Manual Extraction	Plug-In
Foundations	191.30	191.2970	291.14	291.1433	191.30	191.2970
Retaining walls	106.63	106.6320	163.54	163.5176	106.63	106.6320
Beams	35.90	35.9006	25.88	25.8787	4.19	4.1946
Columns	38.77	38.7684	52.14	52.1991	1.90	1.9032
Slabs	542.64	542.6368	633.31	633.3076	460.49	460.4912

4.2. Limitations and Future Developments

From the current development, several limitations and future improvements have been detected. This present study identifies and focuses on the sustainability assessment in real-time, automatic assessment of different alternatives and materials, and using the plug-in to visualize the best option. However, what if a set of guidance quantitative values, such as the results for unit impacts (e.g., a cubic meter of a column or a square meter of a wall) for environmental, economic, and social impacts of different materials and building elements, are shown to the designer before deciding which material to use? Indeed, this type of information can help reduce the effort and time required in the modelling process, as well as raise awareness regarding the impacts and consequences of design decisions. Hence, user-centered decision tools not only focus on the assessment process and LCSA results, but also integrate quick and short paths towards identifying the best material (regarding diverse environmental, economic, and social dimensions) so that the required function can be considered for implementation in the future. Furthermore, feedback from designers, policy makers, and various stakeholders can use the tool to test the development and utility of this information in current practice [56].

The present study demonstrates the utility of the tool to conduct a Triple Bottom Line (TBL) sustainability assessment and to compare different materials in real time using a BIM model. However, the results obtained provide evidence of the discrepancy of the values for each of the dimensions and of the existing limitation in the weighting and multi-dimension decision making in the LCSA implementation [57]. The automatic integration of multi-criteria assessment using methods such as TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) [58–60] and AHP (Analytic Hierarchy Process) [61–63] can help the designer to select the most sustainable option by integrating a variety of categories.

Given the limitation of this development in conducting a whole life cycle building assessment, specifically in the modelling of the distances of transport, future research can focus on modelling transport distances from product manufacturer to site and from site to final disposal points (modules A4 and C2) using GIS (Geographic Information System) and automatic geolocation, such as in [64]. For the integration of other building systems to conduct a whole building LCSA, the main obstacle is the data availability, which means that the development of regionally representative data (environmental, economic, and social) needs to be increased. This plug-in uses manually created BIM objects (data collection and systematization); hence, future developments can focus on improving the automatic and semi-automatic BIM-object creation to enrich the existing database (BIM-TBL).

To increase the tool maturity level, this plug-in should be tested under a variety of case studies, thereby enriching the TBL database and testing different contexts (e.g., adjusting the tool development to different file format exchanges and building elements). This type of test can also help to define the most accurate material quantity take-off unit (e.g., volume and area) for each building element, whereby the lowest number of possible changes in the BIM model are included in the assessment of different material solutions. Moreover, different approaches to the quantity take-off variability can be verified that depend on the building elements, the functional units (for environmental, economic, and social data), and the possible variation of the design parameters (e.g., volume, thickness, and area).

5. Conclusions

There is a relatively new approach to the evaluation of building sustainability through the integration of environmental, economic, and social dimensions using a life cycle perspective (LCSA) and a quantitative assessment. This study aims to contribute to this field by developing the BIM3LCA structure tool to support the material selection during the design process. The case study validation demonstrates the consistency of the tool concerning the material quantity take-off and the building material assessment. The tool is developed in native BIM software to enable real-time LCSA calculations.

The main contribution of this approach involves the development and validation of the BIM3LCA plug-in, an automatic tool to conduct building LCSA in the early design stages and support the selection of the building materials. Given that most of the existing LCSA-based tools are focused on detailed design stages, this tool can help designers increase the consistency of LCSA results throughout the design process. Future research should be focused on improving the development of the tool in order to increase the decision-making potential in the early design steps. Moreover, the verification of further case studies should consider different technical solutions, typologies, and contexts.

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Abbreviations

AHP	Analytic Hierarchy Process
API	Application Programming Interface
BIM	Building Information Modelling
DGNB	German Sustainable Building Council
EMVISESA	Empresa Municipal de Vivienda, Suelo y Equipamiento de Sevilla, S.A.
EPD	Environmental Product Declaration
IFC	Industry Foundation Classes
GBRS	Green Building Rating System
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCSA	Life Cycle Sustainability Assessment
LCC	Life Cycle Costing
LOD	Level Of Development
GIS	Geographic Information System
GUI	Graphic User Interface
GWP	Global Warming Potential
S-LCA	Social Life Cycle Assessment
TBL	Triple Bottom Line
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
WinForms	Windows Form

References

1. IEA. *International Energy Agency (IEA) Global Status Report for Buildings and Construction 2019*; IEA: Paris, France, 2019.
2. European Commission. *European Commission COM(2011) 571 Final*; European Commission: Brussels, Belgium, 2011.
3. Alwan, Z.; Jones, P.; Holgate, P. Strategic sustainable development in the UK construction industry, through the framework for strategic sustainable development, using Building Information Modelling. *J. Clean. Prod.* **2017**, *140*, 349–358. [CrossRef]
4. Mc Graw-Hill construction World Green Building Trends. 2013. Available online: https://sftool.gov/Content/attachments/World_Green_Building_Trends_SmartMarket_Report_2013.pdf (accessed on 1 November 2022).
5. Parker, J. *The Value of BREEAM, A BSRIA Report*; BSRIA: Bracknell, UK, 2012; Available online: <https://www.bsria.com/doc/rMwG2D> (accessed on 1 November 2022).
6. World Green Building Council. *The Business Case for Green Building*; World Green Building Council: Toronto, ON, Canada, 2013.
7. UN—United Nations. *The Sustainable Development Goals Report 2019*; United Nations: New York, NY, USA, 2019.
8. European Commission. European Parliament The European Green Deal. *Eur. Comm.* 2019. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed on 1 November 2022).
9. European Commission. *Circular Economy Action Plan*; European Commission: Brussels, Belgium, 2020. [CrossRef]
10. IPCC. *IPCC Working Group I Contribution to the IPCC Fifth Assessment Report, Climate Change 2013: The Physical Science Basis*; IPCC: Geneva, Switzerland, 2013.
11. Tschetwertak, J.; Schneider, S.; Hollberg, A.; Donath, D.; Ruth, J. A Matter of Sequence: Investigating the Impact of the Order of Design Decisions in Multi-Stage Design Processes. *Proc. Commun. Comput. Inf. Sci.* **2017**, *724*, 100–120.
12. Meex, E.; Hollberg, A.; Knapen, E.; Hildebrand, L.; Verbeeck, G. Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. *Build. Environ.* **2018**, *133*, 228–236. [CrossRef]

13. ISO 16757-1:2015; Data Structures for Electronic Product Catalogues for Building Services—Part 1: Concepts, Architecture and Model. ISO: Geneva, Switzerland, 2015.
14. Cao, Y.; Kamaruzzaman, S.N.; Aziz, N.M. Building Information Modeling (BIM) Capabilities in the Operation and Maintenance Phase of Green Buildings: A Systematic Review. *Buildings* **2022**, *12*, 830. [CrossRef]
15. Obrecht, T.P.; Röck, M.; Hoxha, E.; Passer, A. BIM and LCA Integration: A Systematic Literature Review. *Sustainability* **2020**, *12*, 5534. [CrossRef]
16. Soust-Verdaguer, B.; Llatas, C.; García-Martínez, A. Critical review of bim-based LCA method to buildings. *Energy Build.* **2017**, *136*, 110–120. [CrossRef]
17. Naderi, H.; Shojaei, A. Civil Infrastructure Digital Twins: Multi-Level Knowledge Map, Research Gaps, and Future Directions. *IEEE Access* **2022**, *10*, 122022–122037. [CrossRef]
18. Rajabi, M.S.; Rezaeiashtiani, M.; Radzi, A.R.; Famili, A.; Rezaeiashtiani, A.; Rahman, R.A. Underlying Factors and Strategies for Organizational BIM Capabilities: The Case of Iran. *Appl. Syst. Innov.* **2022**, *5*, 109. [CrossRef]
19. Omer, M.M.; Mohd-Ezazee, N.M.A.; Lee, Y.S.; Rajabi, M.S.; Rahman, R.A. Constructive and Destructive Leadership Behaviors, Skills, Styles and Traits in BIM-Based Construction Projects. *Buildings* **2022**, *12*, 2068. [CrossRef]
20. Rajabi, M.S.; Radzi, A.R.; Rezaeiashtiani, M.; Famili, A.; Rashidi, M.E.; Rahman, R.A. Key Assessment Criteria for Organizational BIM Capabilities: A Cross-Regional Study. *Buildings* **2022**, *12*, 1013. [CrossRef]
21. WGBC. *WGBC Building Life*; WGBC: Toronto, ON, Canada. Available online: <https://worldgbc.org/buildinglife/> (accessed on 1 November 2022).
22. Bahramian, M.; Yetilmezsoy, K. Life cycle assessment of the building industry: An overview of two decades of research (1995–2018). *Energy Build.* **2020**, *219*, 109917. [CrossRef]
23. Jusselme, T.; Rey, E.; Andersen, M. Surveying the environmental life-cycle performance assessments: Practice and context at early building design stages. *Sustain. Cities Soc.* **2019**, *52*, 101879. [CrossRef]
24. Sartori, T.; Drogemuller, R.; Omrani, S.; Lamari, F. An integrative Whole Building Life Cycle Assessment (WBLCA) framework: A survey of software developers' perspective. *Build. Environ.* **2022**, *223*, 109475. [CrossRef]
25. European Commission Level(S). Available online: https://ec.europa.eu/environment/topics/circular-economy/levels_en (accessed on 1 November 2022).
26. German Sustainable Building Council. *Certificate for Sustainable and Green Building*; DGNB GmbH: Stuttgart, Germany, 2019.
27. Green Building Council España. Herramienta VERDE. Available online: <http://www.gbce.es/pagina/certificacion-verde> (accessed on 1 November 2022).
28. Dodd, N.; Cordella, M.; Traverso, M.; Donatello, S. Level(s)-A Common EU Framework of Core Sustainability Indicators for Office and Residential Buildings Part 3: How to Make Performance Assessments Using Level(s) (Draft Beta v1.0). 2017.
29. Ciroth, A.; Finkbeiner, M.; Traverso, M.; Hildenbrand, J.; Kloepffer, W.; Mazijn, B.; Prakash, S.; Sonnemann, G.; Valdivia, S.; Ugaya, C.M.L.; et al. *Towards a Life Cycle Sustainability Assessment: Making Informed Choices on Products*; Valdivia, S., Ugaya, C., Sonnemann, G., Hildenbrand, J., Eds.; UNEP/SETAC Life Cycle Initiative: Paris, France, 2011; ISBN 978-92-807-3175-0. Available online: <https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2011%20-%20Towards%20LCSA.pdf> (accessed on 1 November 2022).
30. Somanath, S.; Hollberg, A.; Beemsterboer, S.; Wallbaum, H. The Relation between Social Life Cycle Assessment and Green Building Certification Systems. In Proceedings of the 7th Social LCA Conference, Gothenburg, Sweden, 14–17 June 2020; p. 198.
31. Llatas, C.; Soust-Verdaguer, B.; Hollberg, A.; Palumbo, E.; Quiñones, R. BIM-based LCSA application in early design stages using IFC. *Autom. Constr.* **2022**, *138*, 104259. [CrossRef]
32. Backes, J.G.; Traverso, M. Application of Life Cycle Sustainability Assessment in the Construction Sector: A Systematic Literature Review. *Processes* **2021**, *9*, 1248. [CrossRef]
33. Llatas, C.; Soust-Verdaguer, B.; Passer, A. Implementing Life Cycle Sustainability Assessment during design stages in Building Information Modelling: From systematic literature review to a methodological approach. *Build. Environ.* **2020**, *182*, 107164. [CrossRef]
34. Autodesk Revit. *Architecture* **2021**, *1*. Available online: <https://www.autodesk.com/> (accessed on 1 November 2022).
35. Santos, R.; Costa, A.A.; Silvestre, J.D.; Vandenbergh, T.; Pyl, L. BIM-based life cycle assessment and life cycle costing of an office building in Western Europe. *Build. Environ.* **2019**, *169*, 106568. [CrossRef]
36. Santos, R.; Costa, A.A.; Silvestre, J.D.; Pyl, L. Informetric analysis and review of literature on the role of BIM in sustainable construction. *Autom. Constr.* **2019**, *103*, 221–234. [CrossRef]
37. Santos, R.; Costa, A.A.; Silvestre, J.D.; Pyl, L. Development of a BIM-based Environmental and Economic Life Cycle Assessment tool. *J. Clean. Prod.* **2020**, *265*, 121705. [CrossRef]
38. Röck, M.; Hollberg, A.; Habert, G.; Passer, A. LCA and BIM: Visualization of environmental potentials in building construction at early design stages. *Build. Environ.* **2018**, *140*, 153–161. [CrossRef]
39. Bueno, C.; Pereira, L.M.; Fabrício, M. Life cycle assessment and environmental-based choices at the early design stages: An application using building information modelling. *Arch. Eng. Des. Manag.* **2017**, *14*, 332–346. [CrossRef]
40. Giaveno, S.; Osello, A.; Garufi, D.; Razo, D.S. Embodied Carbon and Embodied Energy Scenarios in the Built Environment. *Computational Design Meets EPDs. Sustainability* **2021**, *13*, 11974. [CrossRef]

41. Santos, R.; Costa, A.A.; Silvestre, J.D.; Pyl, L. Integration of LCA and LCC analysis within a BIM-based environment. *Autom. Constr.* **2019**, *103*, 127–149. [CrossRef]
42. Zhao, L.; Zhang, W.; Wang, W. BIM-Based Multi-Objective Optimization of Low-Carbon and Energy-Saving Buildings. *Sustainability* **2022**, *14*, 13064. [CrossRef]
43. Filho, M.V.A.P.M.; da Costa, B.B.F.; Najjar, M.; Figueiredo, K.V.; de Mendonça, M.B.; Haddad, A.N. Sustainability Assessment of a Low-Income Building: A BIM-LCSA-FAHP-Based Analysis. *Buildings* **2022**, *12*, 181. [CrossRef]
44. Ecoinvent. Database. 2019. Available online: <https://www.ecoinvent.org/> (accessed on 1 November 2022).
45. Soust-Verdaguer, B.; Galeana, I.B.; Llatas, C.; Montes, M.; Hoxha, E.; Passer, A. How to conduct consistent environmental, economic, and social assessment during the building design process. A BIM-based Life Cycle Sustainability Assessment method. *J. Build. Eng.* **2021**, *45*, 103516. [CrossRef]
46. Kamel, E.; Memari, A.M. Review of BIM's Application in Energy Simulation: Tools, Issues, and Solutions. *Autom. Constr.* **2019**, *97*, 164–180. [CrossRef]
47. ISO. ISO 21931-1:2022. *Sustainability in Building Construction—Framework for Methods of Assessment of the Environmental, Economic and Social Performance of Construction Works—Part 1: Buildings*; ISO: Geneva, Switzerland, 2022.
48. CTE. Spanish Building Technical Code. Real Decreto 314/2006 17 marzo 2006. Available online: <https://www.codigotecnico.org/> (accessed on 1 November 2022).
49. Andalusian Government BCCA. *Base de Costes de La Construcción de Andalucía, Clasificación Sistemática de Precios Básicos, Auxiliares y Unitarios*; Andalusian Government BCCA: Andalusia, Spain, 2021. Available online: <https://www.juntadeandalucia.es/organismos/fomentoarticulaciondelterritorioyvivienda/areas/vivienda-rehabilitacion/planes-instrumentos/paginas/vivienda-bcca.html> (accessed on 1 November 2022).
50. Benoît Norris, C.; Traverso, M.; Neugebauer, S.; Ekener, E.; Schaubroeck, T.; Russo Garrido, S.; Berger, M.; Valdivia, S.; Lehmann, A.; Finkbeiner, M.; et al. *Guidelines for Social Life Cycle Assessment of Products and Organizations*; UNEP: Nairobi, Kenya, 2020.
51. Traverso, M.; Asdrubali, F.; Francia, A.; Finkbeiner, M. Towards life cycle sustainability assessment: An implementation to photovoltaic modules. *Int. J. Life Cycle Assess.* **2012**, *17*, 1068–1079. [CrossRef]
52. Zheng, X.; Easa, S.M.; Yang, Z.; Ji, T.; Jiang, Z. Life-cycle sustainability assessment of pavement maintenance alternatives: Methodology and case study. *J. Clean. Prod.* **2018**, *213*, 659–672. [CrossRef]
53. Figueiredo, K.; Pierott, R.; Hammad, A.W.; Haddad, A. Sustainable material choice for construction projects: A Life Cycle Sustainability Assessment framework based on BIM and Fuzzy-AHP. *Build. Environ.* **2021**, *196*, 107805. [CrossRef]
54. Li, S.; Altan, H. Environmental Impact Balance of Building Structures and Substitution Effect of Wood Structure in Taiwan. *Int. J. Environ. Prot.* **2012**, *2*, 1–7. [CrossRef]
55. Zeitz, A.; Griffin, C.; Dusicka, P. Comparing the embodied carbon and energy of a mass timber structure system to typical steel and concrete alternatives for parking garages. *Energy Build.* **2019**, *199*, 126–133. [CrossRef]
56. Hollberg, A.; Tjäder, M.; Ingelhart, G.; Wallbaum, H. A Framework for User Centric LCA Tool Development for Early Planning Stages of Buildings. *Front. Built Environ.* **2022**, *8*, 744946. [CrossRef]
57. Kalbar, P.P.; Das, D. Introduction. Life cycle thinking. In *Life Cycle Sustainability Assessment for Decision-Making: Methodologies and Case Studies*; Elsevier: Amsterdam, The Netherlands, 2020; ISBN 9780128183557.
58. Balasbaneh, A.T.; Yeoh, D.; Abidin, A.R.Z. Life cycle sustainability assessment of window renovations in schools against noise pollution in tropical climates. *J. Build. Eng.* **2020**, *32*, 101784. [CrossRef]
59. Ren, J. Multi-criteria decision making for the prioritization of energy systems under uncertainties after life cycle sustainability assessment. *Sustain. Prod. Consum.* **2018**, *16*, 45–57. [CrossRef]
60. Fazeli, A.; Jalaee, F.; Khanzadi, M.; Banihashemi, S. BIM-Integrated TOPSIS-Fuzzy Framework to Optimize Selection of Sustainable Building Components. *Int. J. Constr. Manag.* **2022**, *22*, 1240–1259. [CrossRef]
61. Hosseinijou, S.A.; Mansour, S.; Shirazi, M.A. Social life cycle assessment for material selection: A case study of building materials. *Int. J. Life Cycle Assess.* **2013**, *19*, 620–645. [CrossRef]
62. Ren, J.; Ren, X.; Liang, H.; Dong, L.; Zhang, L.; Luo, X.; Yang, Y.; Gao, Z. Multi-actor multi-criteria sustainability assessment framework for energy and industrial systems in life cycle perspective under uncertainties. Part 2: Improved extension theory. *Int. J. Life Cycle Assess.* **2016**, *22*, 1406–1417. [CrossRef]
63. Díaz-López, C.; Carpio, M.; Martín-Morales, M.; Zamorano, M. Defining strategies to adopt Level(s) for bringing buildings into the circular economy. *A case study of Spain. J. Clean. Prod.* **2021**, *287*, 125048. [CrossRef]
64. Shadram, F.; Johansson, T.D.; Lu, W.; Schade, J.; Olofsson, T. An integrated BIM-based framework for minimizing embodied energy during building design. *Energy Build.* **2016**, *128*, 592–604. [CrossRef]

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