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BIM-based LCSA application in early design stages using IFC

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ABSTRACT

Life Cycle Sustainability Assessment (LCSA) is an integrated method that combines environmental, economic, and social assessments. Its methodological development remains under discussion, mainly regarding the building design. This paper aims to provide a systematic, interoperable, and open-source approach towards implementing LCSA in Building Information Modelling (BIM) in five steps. A harmonized data structure that enriches BIM objects is proposed. Automation in the principal evaluation step is provided by integrating new parameters into the current Industry Foundation Classes (IFC4). A Dynamo script verifies its utility in a case study in Spain using real-time calculations and visualizations. Two alternative structural systems are assessed, and identification is made of the lowest CO_2 emitter, the lowest cost, and the most beneficial system for local employment. The approach can be employed to evaluate other indicators and building systems in other countries. Challenges and limitations in the standardization and harmonization of the three dimensions are identified.

1. Introduction

1.1. Context

The building sector is recognized as one of the main consumers of resources and energy (35% of final energy use). At the same time, it is one of the greatest emitters of greenhouse gases (GHG) (38% of energy and process-related) [1] and waste producers (30% of all waste in the EU) [2]. The need for rapid decarbonization of the building and construction sector requires new strategies to reduce impacts and the early design stages have a high potential to implement these [3,4].

Currently, Life Cycle Assessment (LCA) is considered the most scientifically accepted method for environmental assessment, albeit being complex [5]. However, sustainable development requires a holistic perspective that integrates the three dimensions (environmental, economic, and social) throughout the product's life cycle [6]. Hence, Life Cycle Sustainability Assessment (LCSA) is conceived as one of the most complete methods to encourage this Triple Bottom Line (TBL) assessment of sustainability of buildings [7]. This assessment is defined as the sum of LCA, Life Cycle Costing (LCC), and Social-Life Cycle Assessment (S-LCA) [8]. However, several differences between the three methods are detected, mainly in areas such as communication, qualitative/quantitative data, goals and scopes, and interpretation of results [9]. For example, LCA only considers human injury to people (derived from environmental impacts), while S-LCA considers all social impacts and human injury, and includes both positive and negative impacts [10]. These impacts, in S-LCA are related to local (geographical) conditions and organizational behavior in the company, while in LCA, these are only related to processes that can be similarly implanted in different locations [11]. When comparing LCA and LCC, although the economic

Abbreviations: ADP-fossil, Abiotic Depletion Potential for fossil fuels; ADP-minerals & metals, Abiotic Depletion Potential of Materials; AP, Acidification Potential; BCCA, Base de Costes de la Construcción de Andalucía; BIM, Building Information Modelling; BP, Basic Project; CTE, Código Técnico de la Edificación; E, Embodied; EN, European Standard; EP, Execution Project; EP[1], Eutrophication potential; EPD, Environmental Product Declaration; EU, European Union; GHG, Greenhouse Gas; GWP, Global Warming Potential; IDM, Information Delivery Manual; IEA, International Energy Agency; IFC, Industry Foundation Classes; ISO, International Organization for Standardization; LC, Life Cycle; LCA, Life Cycle Assessment; LCC, Life Cycle Costing; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; LCSA, Life Cycle Sustainability Assessment; LOD, Level of Development; LOI, Level of Information; MVD, Model View Definitions; O, Operational; ODP, Ozone Depletion Potential; PE-NRe, Non-Renewable Energy; PE-Re, Renewable Energy; POCP, Photochemical Ozone Creation Potential; RQ, Research Question; S-LCA, Social-Life Cycle Assessment; SPD, Sustainable Product Declaration; TBL, Triple Bottom Line..

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and environmental results may be complementary, they may still differ and evolve into disparate actions. Moreover, LCC uses a dynamic approach (using discounting) while LCA uses a static methodology where the weight of the impacts remains either totally or largely unchanged over time [10].

LCA is described in the ISO standards 14,040 [12] and 14,044 [13], whose methodological approach can also be applied to economic and social issues [14]. However, the application of LCSA in the building and construction sector remains scarce [15]. Sustainability assessment frameworks, such as EN 15643 [16], have been developed to support designers in evaluating the performance of a building in a standardized and systematic way. The standard for the calculation of the environmental performance based on LCA, EN 15978 [17], has been adopted by practitioners. LCC-based EN 16627 [18] and ISO 15686-5 [19] are commonly used as part of certification systems, such as DGNB. In contrast, the standard EN 16309 [20] for social performance assessment is not currently used in practice [21]. Only very few studies have attempted to apply S-LCA to building products or buildings [21,22], which shows the difference in the level of maturity of the three methods (LCA, LCC, S-LCA) for the application to buildings.

1.2. The challenges in integrating LCA-based techniques in BIM

Although LCSA is considered a valuable support in the assessment of environmental, economic, and social dimensions considering a life cycle perspective [15], the combination with Building Information Modelling (BIM) has yet to be verified and implemented in case studies [15]. One of the main obstacles is that current BIM structures hold only limited information, sufficient to conduct LCA-based methods [23], and hence for LCSA, this needs to be enriched. To this end, the most frequently used method for conducting LCA in BIM is the exchange of manual data [24,25]. Moreover, the data acquisition and calculation procedure can prove complex for non-LCA experts. This limits its use to detailed design stages when the completeness of information is high. However, the most relevant design decisions have already been made, thereby leaving little room for optimization [23,26].

From the practical point of view, when conducting LCA-based techniques in BIM, five possible strategies can be identified [25,27]. Strategy 1 exports the Bill of Material Quantities (BoMQ) from the BIM environment and uses this information in other LCA-specific tools. This strategy is used, for example, to analyze envelope alternatives [28]. Strategy 2 imports areas using the IFC format, with predefined LCA profiles, such as those in [29]. In the third, information extracted from a BIM model is enriched in a BIM viewer tool and then transferred into an LCA software, as in [30]. The fourth strategy uses plug-ins to conduct the LCA in BIM, as in [31]. Strategy 5 uses BIM objects to include environmental properties (LCA information) and implement the LCA by using a plug-in or LCA software such as in [32]. This strategy is one of the least implemented [24,25] due to a lack of available BIM objects with LCA data and to a lack of consensus on how to structure LCA data and profiles [27]. The main benefit of using BIM for LCA is that the calculation can be performed with little effort for data acquisition, which is one of the most time-consuming stages in LCA [25]. Moreover, including information within the BIM model was identified as one of the three main approaches for BIM integrated LCA and LCC [33].

The use of predefined BIM objects provided by the construction industry is growing considerably, and is mainly promoted by manufacturers of building products [23]. The specific integration of environmental information in the BIM model is being addressed by the [34], which aims to provide a framework to standardize the integration of environmental information, such as Environmental Product Declarations (EPDs) in BIM objects. However, the LCSA approach requires a high level of complexity in the data and information collection compared to LCA [35]. To overcome this problem, similar to the use of EPDs in LCA, previous studies in this field [15] propose the use of *Sustainable Product Declarations* (SPDs). SPDs can be used as a data source to support the integration of environmental, economic, and social data when conducting LCSA, but they have yet to be verified in case studies. The potential of using this approach is given by conducting real-time assessment based on the LCSA method. Thus, the designer can focus on the building shape and geometry of the building elements, instead of spending time on data acquisition. Other BIM-based LCSA studies [36] are more focused on the LCSA result itself and do not address the possibility of simplifying and conducting real-time simulations. The present study therefore identifies the opportunity to address the use of SPDs as a data source to implement real-time LCSA in the design process.

1.3. The relevance of the IFC format in conducting LCA-based techniques

The enrichment of the information contained in the BIM model to implement LCA-based methods can be performed using a variety of strategies. Hollberg et al. [23] underlined that one possible path is based on the development of predefined libraries, such as the H\B: ERT tool [37]. However, this approach does entail several limitations, such as the exclusive use of predefined materials for specific BIM software (e.g., Autodesk Revit [38]). To be independent of specific commercial software and to focus on the LCA and LCC implementation, Santos et al. [32] propose the use of BIM objects based on the enrichment of the Industry Foundation Classes (IFC) schema. They have developed a systematic approach to integrate environmental and economic parameters into the IFC4 schema. The study includes 9 environmental impact categories: acidification potential (AP); global warming potential (GWP); eutrophication potential (EP[1]); abiotic depletion potential of materials (ADP-minerals & metals); abiotic depletion potential for fossil fuels (ADP-fossil); photochemical ozone creation potential (POCP); ozone depletion potential (ODP); renewable energy (PE-Re); and non-renewable energy (PE-NRe).

IFC is an object-oriented open standard promoted by buildingSMART [39] and formally registered by ISO 16739-1 [40]. The IFC schema enables the interoperability between different native BIM software tools, (e.g., Revit, ArchiCAD, AllPlan), and file versions [40]. It also supports the development of new parameters or properties. Semantic enrichment of the IFC schema has been conducted for various purposes. For instance, Park et al. [41] added IFC entities to manage information for bridge structures. Andriamamonjy et al. [42] used IFC to simulate the energy performance of buildings. Theißen et al. [43] compared different approaches towards the inclusion of building services by using open BIM and IFC. However, Llatas et al. [15] provide evidence that a BIM-IFC-based LCSA case study validation has yet to be addressed**.** One of the main challenges therein involves the definition of the data requirements for the implementation of LCSA in BIM of buildings following an interoperable and open-source schema.

In summary, the main research gap arises from the lack of studies that have addressed the problem of the LCSA application in the building design process that are supported by the IFC schema and that enable an automatic and real-time LCSA calculation. Furthermore, the use of SPDs to conduct the LCSA in BIM remains to be verified in a case study application.

1.4. Goals of the study

This study proposes a possible path to answer the following research questions (RQ):

RQ1. Which strategy and workflow supported by the IFC schema can reduce the effort required to conduct LCSA during the design process?

RQ2. Which IFC properties and calculation processes are needed for LCSA to be conducted in BIM in the early design stages?**RQ3.** How can LCSA be applied automatically to a case study and how can the obtained results be visualized in real-time?

The present paper proposes a schema to manage environmental, economic, and social data of a building to perform an LCSA during the design stages in BIM. The study identifies both the IFC attributes and properties and the variables and equations necessary to conduct a building LCSA. Subsequently, the verification of the consistency of the proposed schema in a case study is performed in an Autodesk Revit Dynamo script [38]. The schema can be used to enrich BIM objects and materials in IFC format, organized, for example, in a library to support BIM methodology.

2. Method

The method is based on the *Strategy 5,* defined by Wastiels and Decuypere [27], which is focused on using the enriched BIM objects to conduct the LCA. The novelty of the present approach is going beyond the LCA method and exploring the possibility of simultaneously LCA, LCC, and S-LCA. It uses BIM objects that are enriched with data and creates a plug-in to the data in BIM. Based on previous methodological approach of the LCSA implementation in BIM [15] systematic IFC schema enrichment is proposed and validated using a case study. Regarding the LCSA implementation in BIM and the potential of SPDs to simplify the data collection [15], the innovation of the present study lies in the proposal of a systematic approach to integrate the information in the IFC schema that enables automatic and real-time LCSA calculations. The method consists of five steps. It starts by identifying the main properties and attributes that should be used and added in the current IFC4 schema (IFC4.1.0.0). Furthermore, the necessary equations to calculate the LCSA result are developed (see Supplementary data). Finally, the method is validated in a case study application. An Autodesk Revit Dynamo script [38] is developed to automatically compare two alternative designs based on BIM models. The five steps are defined below (see Fig. 1). The Dynamo script is a trial of the method that can be transferred to other types of BIM authoring software and programming languages, such as plug-ins developed using the Revit API.

2.1. Step 1: Definition of the design stages and data requirements to conduct LCSA in BIM

This step identifies the main decisions considered in each design stage for the integration of their respective information requirements to conduct an LCSA throughout the project development, in a user-friendly way. Therefore, the building design stages as defined by the *Ministerio de la Vivienda de España* [44], are related to the requirements of BIM defined by buildingSMART Spain [45]. Table 1 shows the correlation between the design stages and the Level of Information (LOI) and the Level of Development/Detail (LOD) of the BIM objects [46], to meet the minimum information requirements in each design stage.

The present approach focuses on the early stages of the design process. In the detailed stages, the project holds more information which, on the one hand, entails less uncertainty and errors in LCSA results. On the other hand, it implies a greater effort and more time in its development and data acquisition, which limits its use [23,25]. In the early stages, most of the design decisions are taken [15], such as the selection of the main materials in the building systems, which have major influences on the final impacts. Therefore, the interval between the Basic Project (BP) and the Execution Project (EP) is considered ideal to conduct an LCSA. The aim is to assess alternative design decisions before selecting those with the least impact and delving into higher specification at the detailed stage EP. However, a disadvantage of applying the method in the early design stage is the lack of information, since the LOD in the BP is 200 (see Table 1). It falls short of LOD 300, the minimum recommended LOD for conducting an LCA [47]. To overcome this limitation, the following strategy is proposed. The data necessary to conduct the LCSA that is inexistent in the BP is estimated and extracted from existing regional databases. It helps to include the most frequent and representative scenarios in the context of the building typology under study. Data extraction is a manual process since it needs to be verified previous to the LCSA implementation.

To define the building model, a decomposition of the building systems (foundation, structure, roofs, etc.) into building elements (pillars,

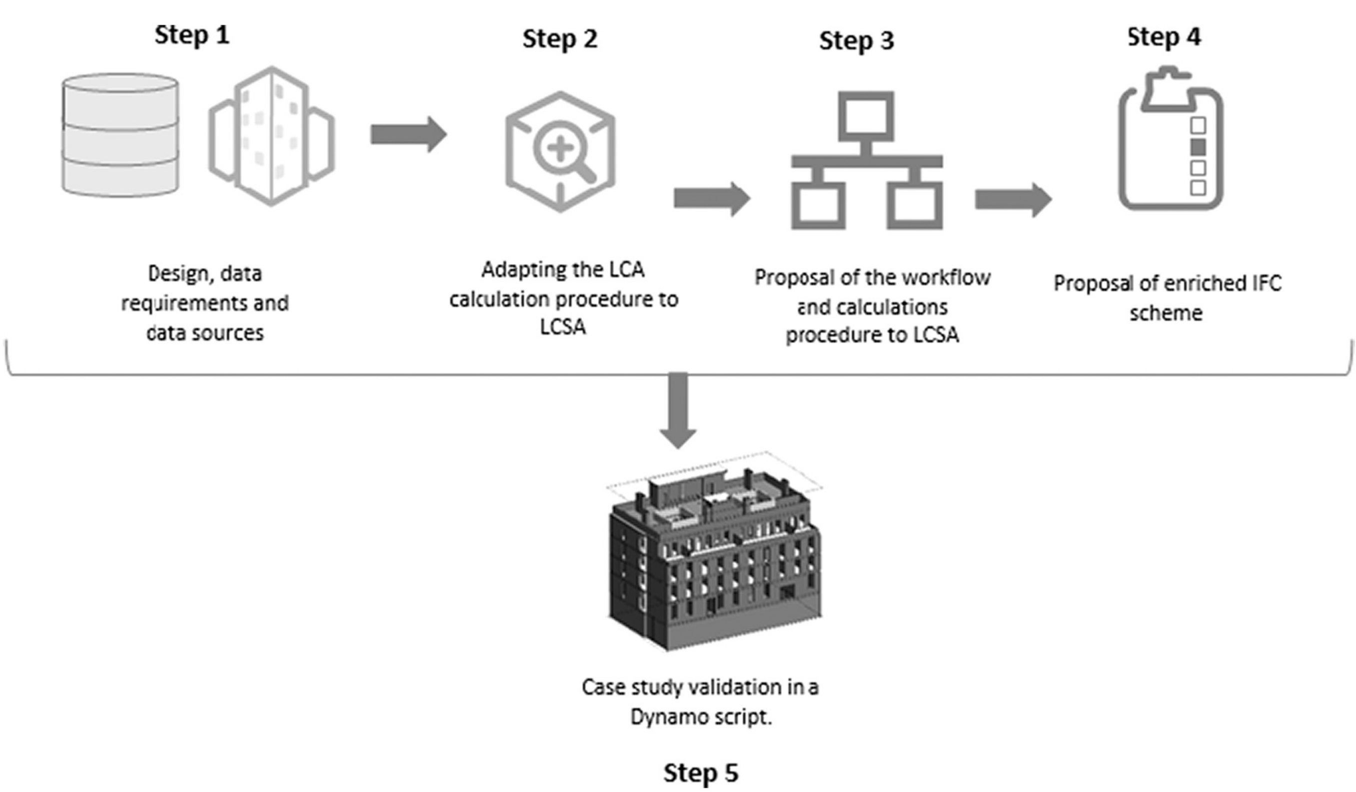


Fig. 1. 5-step method proposed for the implementation of the LCSA.

Table 1
Correlation between the design stages of the Project (Spain) and the BIM design stages.

Design stage		BIM Object		Information requirements*
"Ministerio de la Vivienda de España" [44]	BIM Guide Spain [45]	LOI	LOD	
"Anteproyecto" Preliminary Project	Preliminary	0/1	100	1. Estimated built area 2. Volume 3. Main building characteristics
"Proyecto Básico" Basic Project (BP)	General	1	200	1. Description of the building 2. Constructive description of the building 3. Drawings (Plans, Sections, Façades) 3. Compliance with the CTE (Basic) 4. Estimated budget
"Proyecto de Ejecución" Execution Project (EP)	Detailed	2	300 /350/ 400	BP documents 1, to 4 5. Calculation annexes 6. Drawings for the execution (Plans, Sections, Façades, Details) 7. Technical Specifications Document 8. Measurements and detailed budget 9. Manual of use and maintenance.

* According to [44] for the Preliminary Project, and according to [45] for the BP and EP.

slabs, beams, etc.) is structured in accordance with BCCA [48]. It is a regional database frequently used to organize the cost estimation of the buildings in Andalusia. The building elements are modeled using BIM objects, which provide the information required to conduct the LCSA. For example, information related to the material (e.g., concrete) is extracted from the BP. Other additional information needed (e.g., type of concrete) is extracted from existing Spanish databases (see 2.2.2. Data sources). This element breakdown implies the use of a systematic approach for the classification of elements, and is frequently used to conduct cost estimation in BIM [49].

2.2. Step 2: Adapting the LCA calculation procedure to the LCSA and definition of data sources

2.2.1. Adapting the LCA calculation procedure to LCSA

The standard EN 15978 [17] proposes an LCA calculation procedure based on the total sum of the products from the bill of quantities and the impact factor per product/process. The impact factors are extracted from EPDs of the product/material/process. Here, the relevance of SPDs for the implementation of the LCSA is assumed to be similar to EPDs for the implementation of the LCA to buildings [15].

The present approach follows the modularity principles developed by the ISO 21931-2 standard [50] to assess the sustainability of construction work, as shown Fig. 2. The structure aims to cover as many modules of information as possible. However, during its implementation, several omissions can be assumed and justified, as can slight differences in the modules of the three dimensions. For example, the information regarding several modules, such as B6, can be omitted in the case of the assessment of building systems if the aim is to focus on embodied impacts, or B7, due to the low influence of the building geometry during the design stage on the water demand.

The LCA phases can contribute either directly or indirectly to the operational and embodied impacts [51]. Thus, in accordance with Annex 57 [51], it is assumed that the embodied aspects are more closely related to the material and element definition of the building and that the operational aspects remain more closely related to other aspects, such as the climate, scenarios of use, and the material definition of the complete building. In Fig. 2, based on the modular set up developed by the ISO 21931-2 [50] a possible organization of the embodied and operational aspects involved in the LCSA is proposed. This definition enables two levels of data granularity to be identified in the early design stage (BP). The first is at the level of the building element (embodied aspects) and the second is at the level of the complete building (operational aspects), which affects the organization of the information to conduct the LCSA. Module D can include the account of the benefits related to the production of energy (operational) and to the recycling and recovery of materials and products (embodied).

2.2.2. Data sources

The LCSA implementation in BIM requires not only a methodological

		Sustainability assessment information modules																	
		A0	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	C1	C2	C3	C4	C5	D
Environmental LCA	E	X	X̲	X	X̲	X	X	X	X	X				X̲	X̲	X	X̲	X	X
	O										X	X	X						X
Economic LCC	E	X	X̲	X	X̲	X	X	X	X	X				X̲	X̲	X	X̲	X	X
	O										X	X	X						X
Social S-LCA	E	X	X	X	X̲	X	X	X	X	X				X̲	X̲	X	X̲	X	X
	O										X	X	X						X

A0: Land and asscciated 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 waste management from the operation of the building, C1: Deconstruction/Demolition; C2: Transport waste processing of disposal; C3: Waste processing; C4: Disposal; C5: Re-landscaping; D: Potential net benefits from reuse, recycling and or energy recovery, beyond the system boundary. Source: ISO 21931-2[50].
X̲ Module analyzed in the case study

Fig. 2. Proposal of Embodied (E) and Operational (O) modules according to the ISO 21931-2 [50], which can be included in the LCA, LCC, and S-LCA.

basis but also data sources that are compatible and adapted to the BIM workflow. The inventory is developed by using a TBL library which compiles the SPD of the main building elements (see Fig. 3).

Three selected indicators are included in the assessment: CO_2 eq. (LCA), Euros (LCC), and working hours of local employment (S-LCA). To collect the data required, the Spanish BEDEC [52] database for environmental and energy consumption estimations is used and completed with the ecoinvent v3.7.1 database [53] in the case where no regional data is available. The economic and social data is based on the BCCA [48]. BEDEC [52] is used in the case where relevant information regarding the building process/element is excluded from BCCA [48]. Although a single quantitative indicator is considered in each dimension for simplification purposes, the method can operate in the same way for multiple quantitative indicators. The CO_2 eq. was selected for LCA because it is the most frequently used indicator for buildings [54]. 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 [48] and BEDEC [52]. The inventory indicator [55] of working hours has previously been used in other S-LCA studies [56,57], and it is also referenced in the UNEP S-LCA guidelines [55] as the most frequently used activity variable. The assessment of the social performance of the building was conducted by linking this indicator to a social midpoint indicator, the so-called working hours of local employment. The step to relate the activity variable of working hours with the potential of local employment creation focused on identifying the types of worker specialization that are systematically classified in the BCCA [48]. It was determined which specializations are potentially more frequent in the community (Seville in this case), and which ones are not. Thus, the resulting indicator can help to identify the potential positive impact (so-called handprint [55]) of the building in a certain community.

Table 2 shows an example of how indicators can be extracted from BCCA [48] and BEDEC [52], and can be employed to complete the SPD and the TBL database. Subsequently, that information can automatically be linked to the BIM model.

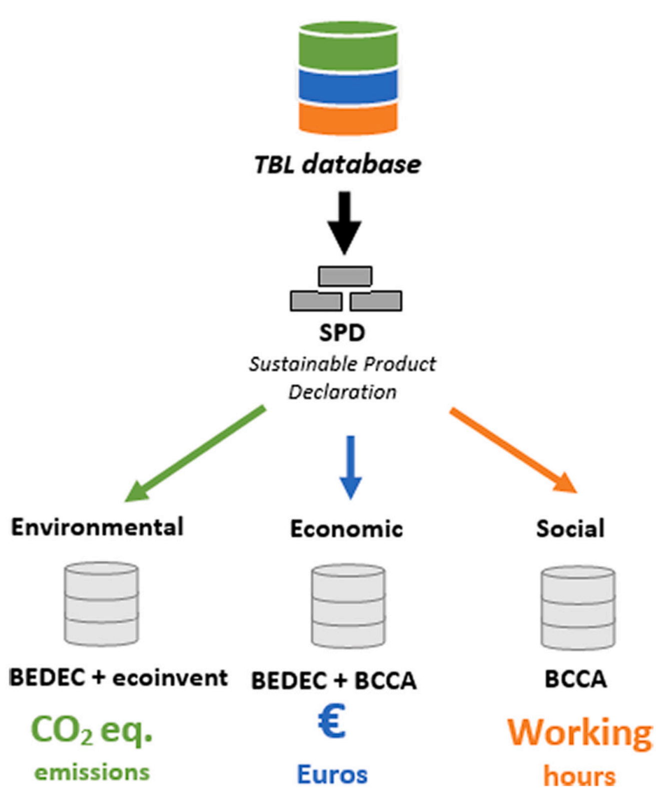


Fig. 3. Schema of the interaction of environmental, economic, and social dimensions and databases to organize the TBL database.

Based on these data sources, the TBL database of building elements is developed to manage the various data sources (environmental, economic, and social data) according to the LCSA modules of information. The TBL database organization and its integration in the IFC schema is developed: i) to improve data acquisition, ii) to reduce possible errors (due to complex equations), and iii) to reduce complexity in the LCSA calculation. The data unification involves a systematic and harmonized data structure for the integration of the three dimensions. It structures the same type of information (e.g., impact categories, indicators, modules, etc.) in all building elements linked to the same reference unit of each building element (e.g., m^3 in the case of concrete in pillars, as shown Table 2). Thus, this organization improves transparency and data reliability thanks to the description of the **building process** and **elements**.

2.3. Step 3: Proposal of LCSA workflow

The existing approach towards combining more than one LCA technique in BIM, as developed in previous research [60], is based on the use of various data sources to separately conduct the LCA and the LCC: for example [53] for environmental data, and CYPE Ingenieros S.A. [61] for economic data. However, the harmonization of the three databases poses a major challenge for the implementation of LCSA in BIM [15]. Therefore, this step aims to combine and unify the information regarding the environmental, economic, and social dimensions of the BIM objects into a single database, as shown in Fig. 4.

The workflow starts by defining a **TBL database** compiled from SPDs of the building elements. The TBL database organizes and harmonizes several data sources according to the modules of information proposed in ISO 21931-2 [50]. The approach also enables a **BIM-object library** to be developed, which contains the enriched objects with the added IFC properties that are needed for the LCSA to be conducted in BIM. The TBL database and the BIM model are connected to a Dynamo script where the information regarding the model (quantity take-off) and the SPD of each building element are linked (see Fig. 4). The Dynamo script also includes the data visualization in real-time. The script enables the obtained graphics to be inserted into a draft sheet in Revit, as an image file.

2.4. Step 4: Proposal of the semantically enriched IFC schema

The proposed approach starts by extracting the existing information from the BIM model. Subsequently, a set of properties is added to the model to enrich the existing information. The official buildingSMART [39] IFC4 includes a list of concepts and definitions of the current IFC schema. These concepts satisfy a number of the LCSA requirements (e.g., *IfcVolumeMeasure*) and partially satisfy others, such as the property set at the element level that considers the Environmental Impacts (e.g., *Pset_EnviromentalImpactIndicator*), but does not permit modular organization of the LCSA information (see Fig. 2).

The LCSA calculation procedure consists of the sum of the LCSA results for each building element and for the aspects of the complete building. This means that to perform the LCSA application in BIM, an element decomposition (described in Section 2.1) of the building parts is needed. It is based on the use of the existing IFC classes associated to the new parameters shown in Fig. 5. The strategy of using dynamically extensible properties (*IfcPropertySet*) is therefore proposed to include the inexistent parameters related to the LCSA modules of information. Consequently, those aspects related to the material and element definition are related to the *IfcElement* class, and those aspects more closely related to the complete building and its performance are related to the *IfcBuilding* class (Fig. 5). Although the *IfcBuildingElement* class fits within the scope of the present approach, the *IfcElement* class covers a wide range of items that can be useful in the detailed stage application of the method.

Hence, additional property sets are added in compliance with the definition of the system boundaries and the modular organization of the

Table 2
Schema of the use of the BCCA [48] and the BEDEC [52] to extract LCSA data on a building element.

Building Element						Impact category, indicator, Data Source		
05HHP00003 m3 Concrete to Pillars HA-25/P/20/IIa						Social	Economic	Environmental
Data Source	**Code**	**Type**	**Item**	**Unit**	**Quantity**	**Labor working hours (h) BCCA / BEDEC**	**Cost Euros (€) BCCA / BEDEC**	**GWP CO_2 eq. emissions (kg) BEDEC**
BCCA	CH02920	Material	Concrete type HA-25/P/20/IIa	m^3	1.03		62.07	376.65
BCCA	TP00100	Labour	Auxiliary	h	0.600	0.600	11.34	-
BEDEC	C1701100	Machinery	Pump concrete	h	0.15	0.15	19.4	11.35
BCCA	MV00100	Machinery	Vibrating	h	0.200*		0.3	2.425
			Indirect costs 15%		-		13.98	-
			Construction waste 4% a)			0.036	0.83	6.59 (b)
			Total			**0.786**	**107.92**	**20.365**
			Data included in the TBL database and organized according to the LCSA module of information			**A5** Working hours of local employment of construction	**A1-A3+A5** Cost of construction, including materials	**A5** GHG emissions produced by energy consumption and waste of construction
						S-LCA data source	**LCC data source**	**LCA data source**

a) Obtained from Llatas (2011) [58], b) Obtained from Bizocho-Tocón and Llatas (2017) [59].
*In BCCA, the working hours related to the use of machinery are included in labor [48].

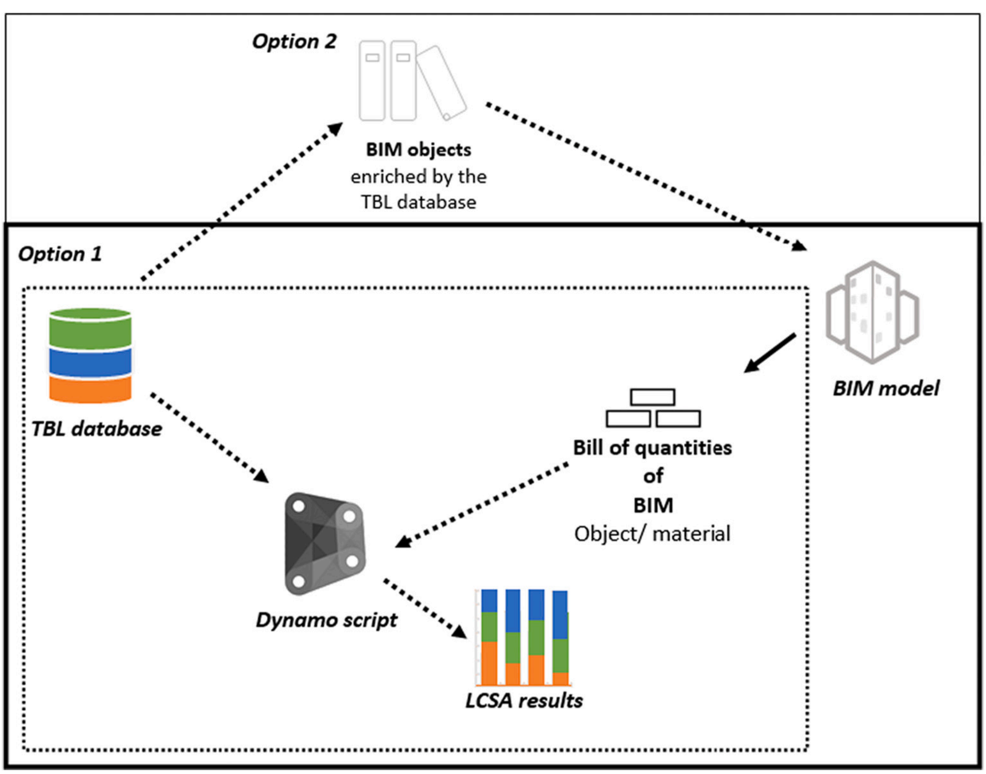


Fig. 4. Proposal of data exchange to deal with the various data sources and the different dimensions of sustainability (environmental, economic, social) (up) and proposed workflow (down).

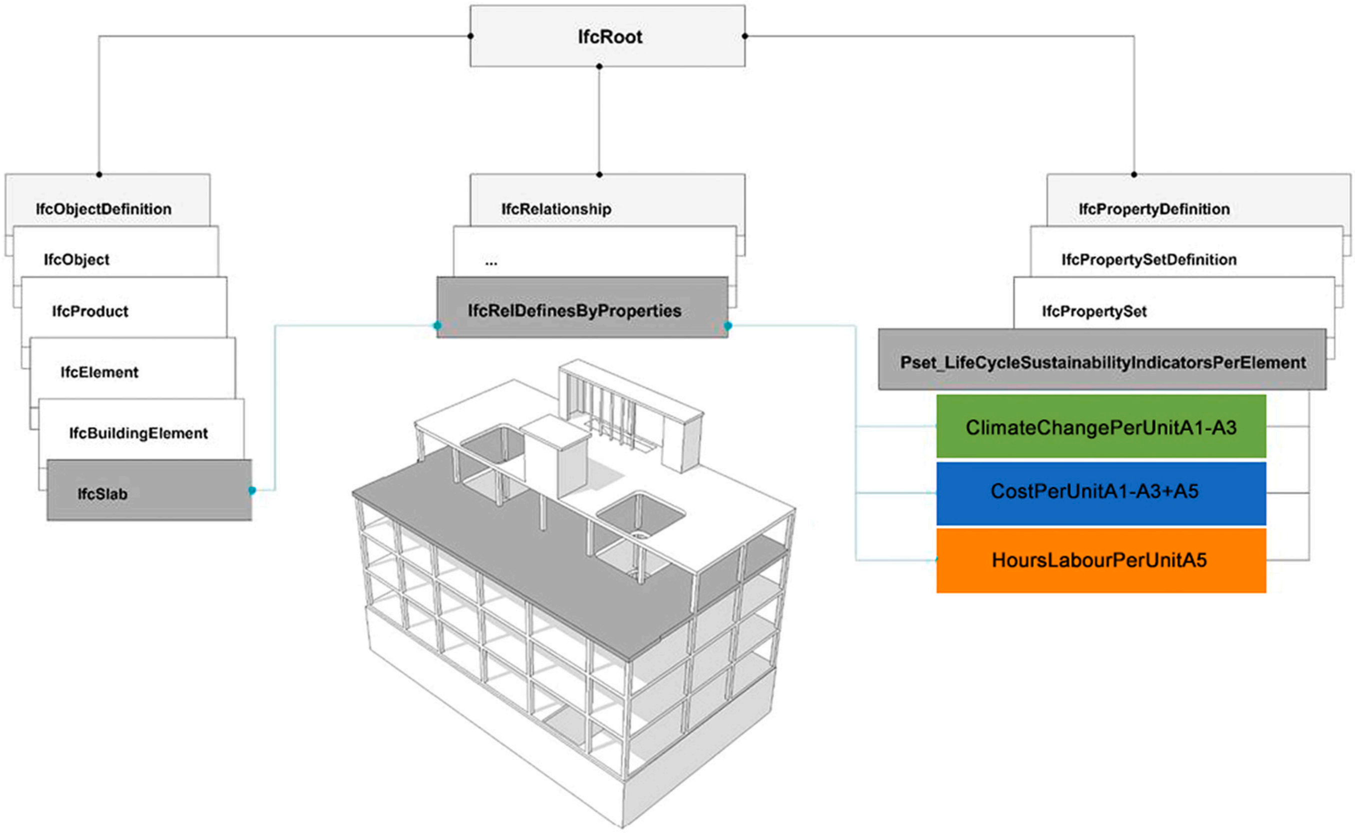
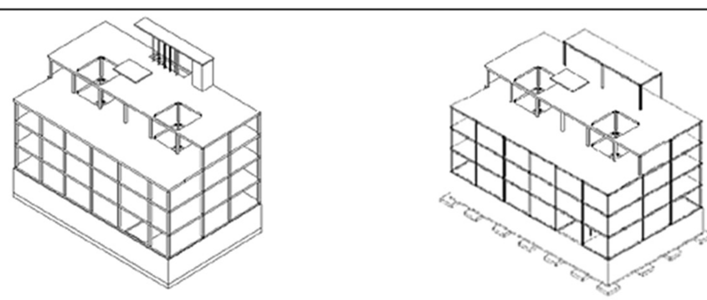


Fig. 5. IFC enrichment proposal schema.

information (Fig. 2). One property is created per life cycle information module, per dimension (environmental, economic, social), and per impact indicator. It enables a transparent and fair comparison between the building elements and dimensions considered. Thus, the present approach includes the following impact categories and indicators: GWP in kg. CO_2 eq. (environmental); costs in Euros (economic); and labor in working hours of local employment (social). These indicators are calculated based on the existing IFC attributes and the new properties



	Option 1- Concrete	Option 2- Steel and concrete
Pillars	Reinforced concrete	Steel
Beams	Reinforced concrete	Steel
Slabs	Reinforced concrete	Concrete and (collaborating) metal sheet
Retaining Walls	Reinforced concrete	Reinforced concrete
Foundations	Reinforced concrete	Reinforced concrete

Fig. 6. Sketches of the 3D model and the main materials for the two options.

created, such as *IfcVolumeMeasure* (existing), *Pset_LifeCycleSustainabilityIndicatorsPerElement* (added Property Set), *ClimateChangePerUnitA1-A3 (*added Property*)*, *CostPerUnitA1-A3 + A5 (*added Property) *or HoursLaborPerUnitA5* (added Property). The complete list of properties and proposed equations are included in the **Supplementary data**. The operational aspects, such as the B6 to B8 modules (including water, energy, and waste in the use stage) can be included through the enrichment of the IFC schema in the *IfcBuilding* class.

2.5. Step 5: Case study validation

2.5.1. Case study

The method is applied to *La María, a* multi-family house located in Seville, Spain, to verify its implementation. The building was promoted by EMVISESA [62], a public enterprise dedicated to the construction of social housing. The gross floor area is 2119 square meters, distributed across five levels (including the ground floor), and 16 apartments. The study compares two optional structural systems: 1) concrete; and 2) steel and concrete; both with the same functional requirements [63], which are modeled in the BP (LOI 1/LOD 200) (see Fig. 6).

2.5.2. LCSA implementation

The validation of the enriched IFC structure and the LCSA calculation is performed in Autodesk Revit 2021 [38] using a Dynamo script. It can provide an integrated and dynamic feedback during the early design stage and a visual representation of the impact produced by the different materials [64]. The developed script includes the use of the BIM model to: i) extract the quantities of the material of the elements, ii) enrich the existing information on the model (by adding new IFC properties and attributes to the current IFC4 (IFC4.1.0.0) schema and by automatically linking TBL database), and iii) calculate and visualize the LCSA results in real-time.

2.5.2.1. Definition of the dynamo script. Fig. 7 shows the structure of the Dynamo script, organized into eight main stages. It includes the definition of the elements comprised in the LCSA, the automatic enrichment of the information covered in the BIM model, the extraction of the information required for the LCSA to be conducted, the development of a set of mathematical operations with the information obtained, and the organization and visualization of the results.

2.5.2.2. Goal and scope definition. The application of the LCSA to the BIM model focuses on the structural system and on the embodied impacts produced throughout its life cycle. The main methodological aspects of the application are based on [15] and focus on the early design stage. Fig. 2 shows the modules included in the case study validation. Furthermore, the following assumptions are included:

- **Design stage (A0):** The estimations of the project are not included since the data sources for the building structure are unknown.
- **Product and construction stages:** A1-A3 and A5 are included, and A4 is excluded due to the lack of accurate data. Regarding the differences in the conceptualization of the building information modules in EN 16627:2015 [18] and ISO 15686-5 [19], and in order to prevent double-counting in the economic assessment of the building performance, the present study includes the acquisition cost of materials and products (A1-A3) in the A5 module (so called A1-A3 + A5). This approach is also performed in [65] to harmonize LCA information modules with the main concepts of LCC. The information related to A1-A3 modules for S-LCA is not included due to difficulties in data acquisition from existing data sources.
- **Use stage:** The use (B1), maintenance (B2), repair (B3), replacement (B4), and refurbishment (B5) modules are considered 0 since it is assumed that no work would be conducted during its life cycle. The reference service life of the structure is considered the same as the building service life (50 years). B6 is excluded given the low incidence of the structural system on the energy demand of the building.
- **End-of-life stage:** The study includes C1 (demolition work), C2 (transport to final disposal considering a generic distance of 25 km and a 16-ton truck), and C4 (final disposal with a landfill scenario).

2.5.2.3. Life cycle inventory (LCI) and life cycle impact assessment (LCIA). The inventory includes the materials, products, components, labor, use, and energy consumption in machinery, and the use of other auxiliary elements that comprise the structural system, in accordance with the classification guidelines of BCCA [48], and previously described in Section 2.2.2. This classification is used for its geographical representativeness. BEDEC [52] is employed to complete several activities that the BCCA [48] had not been included, such as *pumped concrete*. The criteria to include the working hours is based on the BCCA [48]. It includes all the working hours made by workers and the hours of use of machinery driven by workers. However, for those elements in which human work is not accounted in BCCA [48] but only the use of machinery (driven by workers) is included, these hours of machinery are also considered as human working hours.

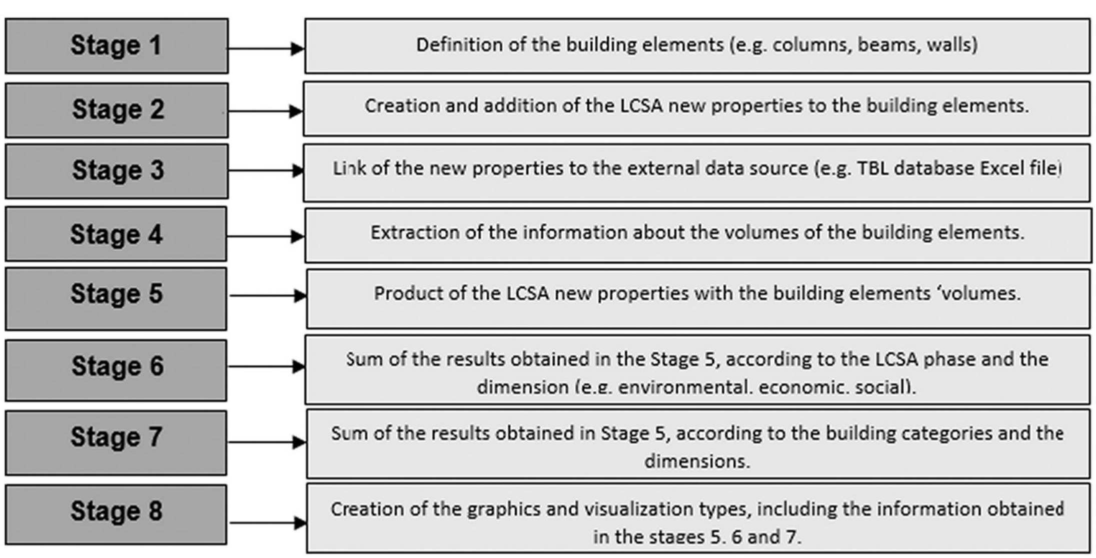


Fig. 7. Stages of the Dynamo script for the case study validation.

3. Results

The results are obtained from running the Dynamo script linked to the BIM Revit model and the TBL database, and subsequently the visualization of the charts including the information in magnitude and comparison of the assessed categories are automatically displayed. Option 2 (steel and concrete) causes less environmental impact and cost than does Option 1 (concrete); however, it produces a lower number of working hours of local employment than Option 1 (see Fig. 8).

Fig. 9 shows the contribution of each module in terms of a color code and dimension for the complete building structure, thereby enabling the highest and the lowest impact phases in each dimension to be identified. Similar trends can be seen in the options analyzed: the A1-A3 modules in the environmental dimension (72% in both cases), the A5 (+A1-A3) in the economic dimension (83% OP1, 87% OP2), and the A5 in the social dimension (81% OP1, 84% OP2).

Fig. 10 shows the differences in the distribution of the impacts depending on the design option. In Option 1, a similar performance for each building element can be seen. In contrast, different trends on the distribution of the results produced by each building element are detected in Option 2. The method allows for identifying the elements with the greatest impact, for example, the slabs in Option 1, and the foundation, slabs, and beams in Option 2.

4. Discussion

4.1. Concerning the case study

The results obtained herein demonstrate the capabilities of the simultaneous implementation of LCA, LCC, and S-LCA to conduct the LCSA in BIM in the early design stage. Furthermore, the method can support the comparison of different design options, the identification of hotspots, and the improvement of the building design before undertaking the detailed design phase. For example, Option 1 (concrete) was identified as the solution that produces the most GWP, at almost 4 times that of Option 2 (steel and concrete) as shown Fig. 8, which is consistent with other LCA studies that compare concrete and steel structures [66]. Other BIM-LCA studies also show that concrete-based materials were responsible for 83% of the total environmental load of the design [67]. Potential errors related to the quantity take-off of the building materials can be reduced because the BIM model is used as a data source of generic quantities (volumes) and the information regarding the building materials is assumed thanks to the frequent scenarios for the product, construction, use, and deconstruction stages in Andalusia, Spain. This strategy enables the complexity in the verification of the quantity take-off to be reduced and allows the same data granularity to be employed in order to compare different types of material alternatives (e.g., reinforced concrete and steel) for a specific element (e.g., slab, column). It also demonstrates that automation in the evaluation is possible by integrating two property sets (*IfcPropertySets*) and 33 new dynamically extensible properties in the current IFC schema (IFC4). Running the script takes only a few seconds. The designer must first verify that the building elements selected to run the script are in fact correct (e.g., columns, beams, and slabs), and that the material codes are correctly assigned to each building element. Thus, the calculation of embodied GWP, costs, and working hours of local employment related to the building elements throughout the life cycle of a building structure can be conducted without much effort. This addresses RQ1, by proposing a strategy and workflow supported by the IFC schema to reduce the effort required to conduct LCSA during the design process. RQ2 is also addressed by defining the IFC properties and calculation processes needed to conduct LCSA in BIM in the early design stages.

The case study also demonstrates the potentiality of the method to be implemented in a Dynamo script, which addresses RQ3, by proposing an automatically LCSA application to a case study and real-time results visualization. This script includes the automatic link to the TBL database, which reduces the effort required for the data acquisition during the inventory phase. However, the existing data sources (BCCA, BEDEC, ecoinvent) that compose the TBL database provide limited data for the implementation of a harmonized LCSA application in the design stages. In the future, data sources should be developed to include, for example, data related to modules A1-A3 in the social dimension (S-LCA). In general, S-LCA for buildings remains underdeveloped. Sustainability building labels and certifications mostly focus the social assessment on the use stage and on the user group of interest. This study focuses on the stakeholder workers and uses the working hours of local employment as a quantitative indicator that concerns other life cycle stages, such as the construction and the end-of-life stages.

The TBL database can be extended to include more social indicators and can later be used with the developed BIM workflow in the same way in the future. The results also provide evidence of the potential of integrating social information throughout the building life cycle in BIM, which remains a scarcely explored field [15]. Among other features, it can support identifying where the highest and lowest number of working hours of local employment are spent, in which LC stage, and on which building element they are spent. This would guide the designer in controlling the job creation at different levels, and in the preparation of the specialization required of the workers. Furthermore, by identifying the

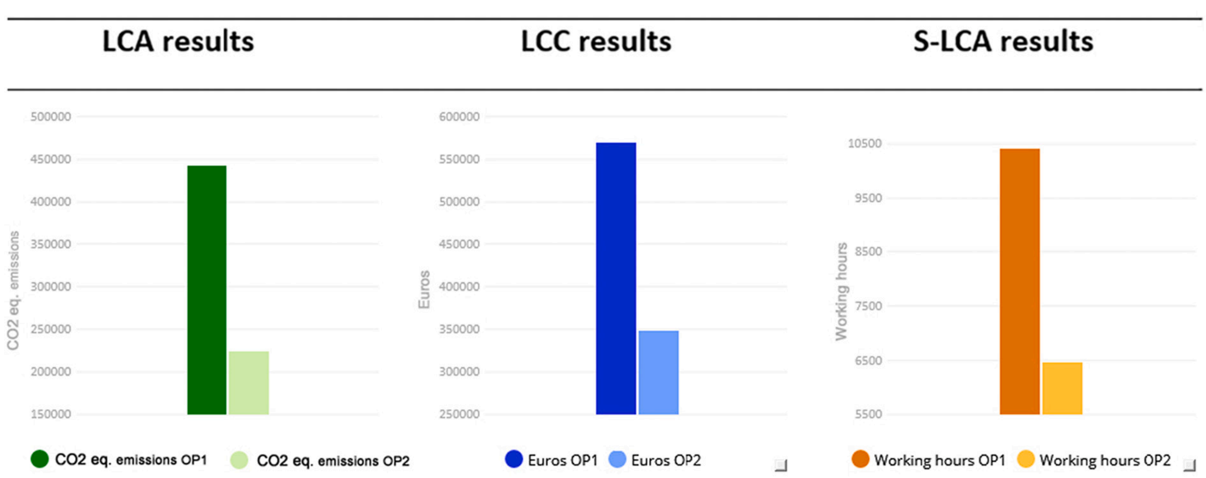


Fig. 8. Overall comparison of the two options for the three indicators.

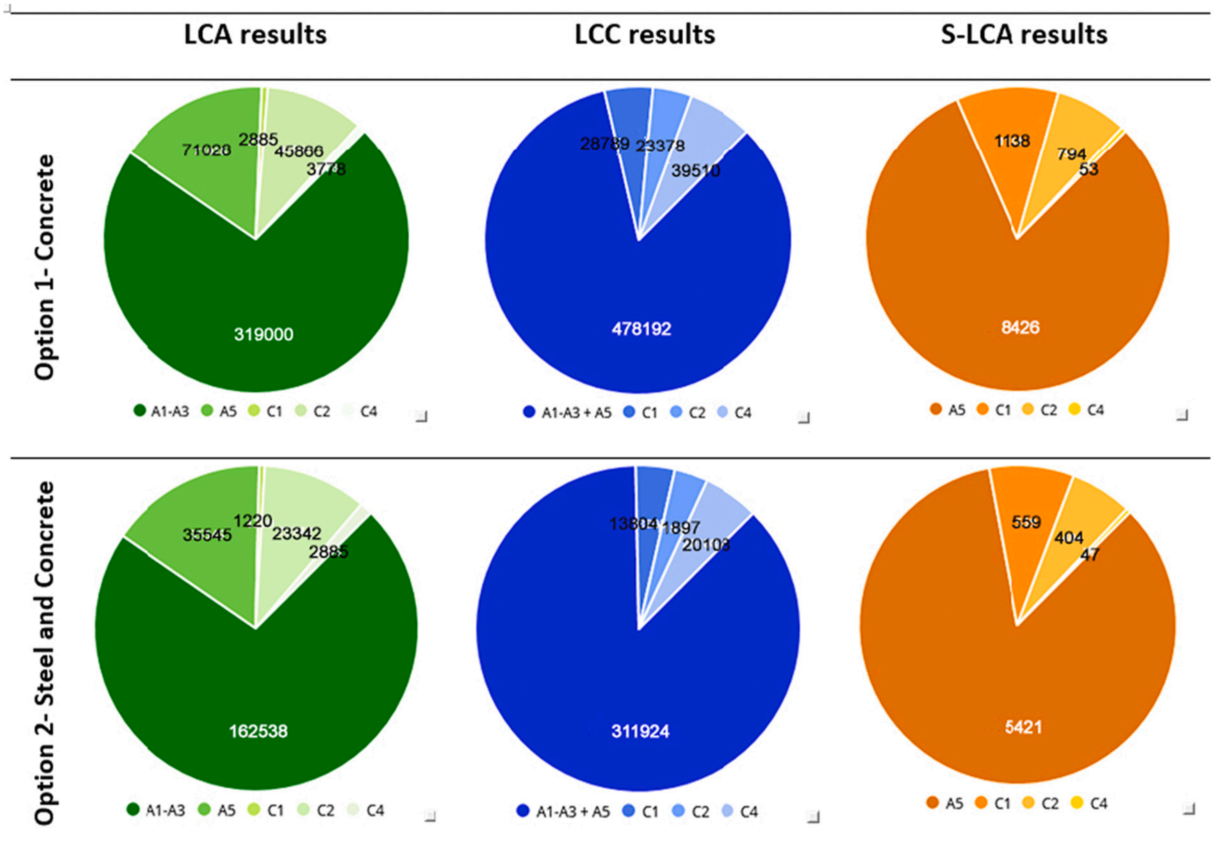


Fig. 9. Comparison of the two options for the three indicators and LC stages included.

potential number of working hours of local employers and the potential for job creation, the potential positive impact (the so-called handprint [55]) of a building in a certain community can be quantified. Other aspects, such as work-related risk factors can also be integrated. The designer can identify which processes are riskier not only on the building site during the execution of the building, but also during the production, use, and end-of-life phases.

This initial trial starts by verifying the potential of its use in the assessment of a building system (e.g., structure). The higher the number of the building elements, the more complex and slower the script can be to run. Other building systems could be evaluated in other contexts, by adapting the data structure to include environmental impacts, costs, and social dimensions from other existing local and regional databases. Furthermore, the impact on cost reduction of design strategies adopted in buildings, such as flexibility and adaptability, or the effects on local job creation due to the use of low-tech processes vs. robotization and automation could be analyzed in further studies. Finally, the current validation failed to perform the calculation of the energy demand. Other studies failed to consider operational energy [e.g., 67], on the condition that operational environmental impacts, which are also influenced by the envelope definition, do not correlate with embodied impacts [68]. Indeed, most of the embodied environmental impacts are a result of the choice of the materials of structural elements [69–71], which is the subject of the present study. The structural systems are significant in achieving a reduction in the embodied impacts [71]. On the other hand, a complete building sustainability assessment is recommended using an enriched IFC schema to calculate the energy demand, such as in [42], in compliance with current Spanish standards [63] and simulation models. Further research should focus on verifying the feasibility of using an IFC-based structure to estimate the operational energy demand within BIM for its subsequent integration into the LCSA implementation and in compliance with the current requirements, project workflow, and national standards in Spain.

4.2. *Concerning the LCSA implementation*

4.2.1. *Challenges in the implementation of the proposed approach in the detailed design stages*

The current approach focuses on the early design stage. The dataset is developed considering that the designer can decide the main material (e.g., concrete, steel) of the building element but cannot change the configuration and definition related to parameters such as quantity of reinforcing steel contained in the reinforced concrete, or the type of concrete. It is assumed that these parameters are defined later when calculating the load-bearing structure in the EP stage, and it is demonstrated that, by using this method, more than 60% of the potential LCSA results obtained in the detailed design stage can be estimated from the early design stage [69]. This approach therefore contributes towards the evaluation of different alternatives of main materials and the combination of materials and forms, thereby allowing non-LCA expert designers to implement LCSA in their projects in a simple and user-friendly way. Another recent study in BIM-LCSA [72], exported the information of each dimension (environmental, economic, social) to external tools for their assessment and weighting, and hence the evaluation and calculation process is not integrated into the BIM software. In current construction practices, digital tools, such as BIM, are mandatory when tendering public works in many countries worldwide [e.g., [73], although it has yet to become widespread. For example, in Europe, only 19% of practitioners used BIM in 2018 [74], although has since trended upwards. In Spain in 2021, more than 50% of public tender integrated the requirements for the use of BIM methodology, but not in all the projects and building stages [75]. Today, the number of digitalization initiatives in the construction sector [76] are increasing the use of digital models throughout the building life cycle. Thus, user-friendly tools,

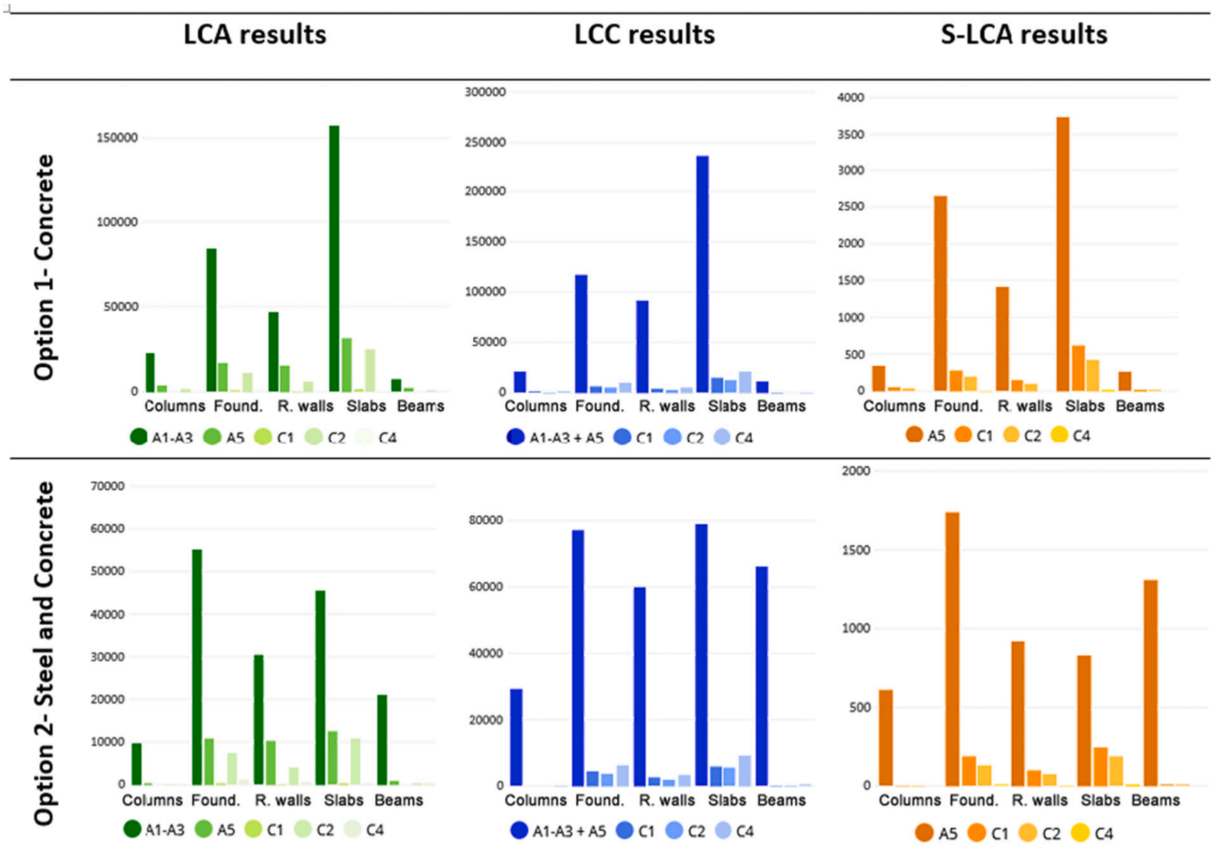


Fig. 10. Visualization of the results of GWP in CO_2 eq., cost, and working hours of local employment spent in alternative structural building elements across the selected LC modules.

integrated in building design tools, will be progressively needed to support sustainable building design. However, it remains necessary to verify the applicability of the current approach based on the enrichment of the IFC schema and its correlation with the databases employed (BCCA, BEDEC, ecoinvent) to implement the LCSA in the detailed design stage. At this stage, the link should be analyzed between the higher data granularity of the materials obtained from BIM models with higher LOD (300) and the TBL data structure. Verification is therefore needed of the consistency of the results obtained in the early design stages, through the comparison with the results in the detailed stages. Further research should verify the variability of the results by means of considering different system boundaries and modules of information across the design stages.

The integration of additional modules, such as A4, C2, C3, and D, in the detailed design stage, should deal with the interactive simulation of distances of transportation and scenarios of waste treatment, reuse, and recycling. Future research should focus on integrating these aspects into the IFC schema and on providing interactive strategies to help designers in their decision-making in the detailed design stages.

Another detected challenge involved the modelling of the C4 module which, in the early stage, included the results for the total landfilling scenario of all the building elements. However, when conducting the LCSA in the detailed stages, these results could be affected if the scenario is changed in terms of the treatment and recycling of a percentage of the produced waste. Thus, the results for C3, C4, and D may vary when considering a different end-of-life scenario, and hence the consistency of the results throughout the design stages should be studied.

4.2.2. Challenges to be addressed by future IFC-based applications

The use of the IFC format enables the information exchange between various software tools and an enriched file based on an interoperable standard to be attained, which can be used in the future for different software versions and commercial software. Furthermore, interoperability specification helps stakeholders develop the virtual collaborative workspace [77]. The Information Delivery Manual (IDM) and Model View Definitions (MVD) are needed when at least two types of software applications are involved in the exchange of information [39]. These are proposed by buildingSMART [39] to provide a common understanding of which information should be presented in the export IFC model for a particular use case [78]. Thus, future research focused on other types of workflows which involve the exchange of information between more than one application based on the IFC schema, will require the definition of the exchange requirements and semantic rules for the implementation of the LCSA.

The current strategy, based on the use of *IfcPropertySet,* allows the IFC format to be enriched by creating user-defined information. However, further efforts should be invested in the improvement of the existing IFC schema (IFC4) to implement the LCSA in BIM. It would entail, for example, the inclusion of new entities and attributes, also highlighted in previous studies focused on the LCA [24], in the operational energy simulation [42], and/or in the quality management during the execution phase of the structural elements [79]. Nevertheless, some of the existing IFC data types that affect the LCSA implementation, such as cost estimation, (e.g., *IfcCostItem-IfcCostValue*), are generic attributes that can no longer be used for a more detailed data desegregation, as required in the present approach.

Moreover, the development of a design-oriented interface to help designers pre-select materials and elements in the very early design stages, before their integration into the BIM model, can become a highly relevant aspect in LCSA implementation. Furthermore, the analysis of improved alternatives can be based on user-friendly visualization types. Hence, further research should address the communication of LCSA results and data visualization, especially in terms of weighting and integrating the multidimensional approach throughout the design stages.

5. Conclusions

Given that the current IFC schema and BIM-object market lack sufficient data to automatically perform the LCSA application in the BIM methodology, the present study demonstrates a possible path towards solving this problem. Its contribution lies in proposing an automatic and real-time LCSA of a building during the early design stage. The case study application provides evidence of the feasibility and potentiality of the present approach as a decision-making aid during the design process of a building structure developed in Spain. It also demonstrates that the proposed approach can fill the information gap between the existing IFC schema (IFC4) and the LCSA data requirements in compliance with the current Sustainability Assessment framework modularity ISO 21931-2 [50]. The development of the Dynamo script enables the visualization of the results linked to the analysis of design alternatives in the BIM model (3D view) and the inclusion of dynamic charts. The TBL database enables the sustainability assessment to be conducted in three dimensions (environmental, economic, and social) of the building elements in the design stages. Despite being based on an existing material, machinery, and labor data structure decomposition of the building elements (BCCA), the innovation of the TBL database lies in the harmonization of data sources in the implementation of the LCSA. This information is matched with the building element volumes extracted from the BIM model to support the decisions made from the early design stage (BP) to the detailed design stage (EP). Future work should address improvements to the approach, through its implementation in various BIM software tools to expand the verification and its potential utility in the design process. Current limitations to the LCSA methodology should be explored in future work, such as the aggregation of the three dimensions, e.g., through weighting of results, and the interpretation of the LCSA results.

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Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.autcon.2022.104259.

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