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Implementing Life Cycle Sustainability Assessment during design stages in Building Information Modelling: From systematic literature review to a methodological approach

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ABSTRACT

The construction sector is a major producer of greenhouse gas and waste. Several studies reveal the close relationship between the design phase and the reduction of environmental impacts caused during the life cycle of buildings, along with better economic and social performance. In order to achieve increasingly eco-efficient buildings, Life Cycle Assessment (LCA) is an objective method to assess and reduce the impact buildings exert on the environment. Nevertheless, current environmental challenges require comprehensive solutions for the integration of the three pillars of sustainability, for which Life Cycle Sustainability Assessment (LCSA) is recognised as an appropriate holistic concept. The present paper conducts a Systematic Literature Review (SLR) which aims to detect opportunities to integrate the LCSA into the building design process and in Building Information Modelling (BIM). The results show that the harmonisation of the three dimensions and the data requirements are main achievements. Based on results obtained, a methodological approach to help on the LCSA implementation in BIM is presented. This proposed LCSA-BIM approach is applied to the Spanish architect's workflow and design stages, to exemplify its purpose.

1. Introduction

The construction sector is one of the major responsible for operational energy consumption and production of GHG emissions [1]. In addition to its prime position as a major consumer of material resources [2], and it also generates one third of the total waste [3]. Given that, cities and buildings have a great potential to reduce environmental emissions, but also produce positive economic [4–6] and social [7] impacts.

In this vein, the building design stages has a potential for the improvement of the sustainability performance of buildings during their life cycle [8–13]. The Life Cycle Assessment (LCA) is a widely recognised method that enables the assessment of building environmental performance [14,15], and this is also demonstrated by reviews in this field [16]. The use of this method compared to existing sustainability assessment methods, such as BREEAM [17], LEED [18], and Living Building Challenge [19], is focused on performing a quantitative assessment of the sustainability of buildings [20]. The LCA application during the design stages is increasingly being recognised by literature [8,21,22]. Nevertheless, there are still barriers that prevent a wider use of it, most of them are related to the complex process of data collection [23]. Therefore, simplifications and assumptions that not affect substantially results are considered by literature [23–27]. Moreover, the integration of BIM (Building Information Modelling) models is underlined as a strategy that can facilitate the calculation and visualisation of the impact during the design stages [11,28]. The contributions of the BIM methodology to the application of LCA go beyond the environmental impact assessment: the literature [29] examines its positive impacts on sustainability, including the triple dimension approach. BIM methodology can contribute through early detection of potential clashes, better engineering decisions and precise ex-ante calculation of costs throughout the whole life cycle of an asset but also towards social sustainability by improving the building process, in terms of waste management, safety at the construction site, among others [29], as well

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as quantification of workers and job creation [30].

Therefore, the Life Cycle Sustainability Assessment (LCSA) overcomes the LCA approach [31,32] by considering a "Triple Bottom Line" (TBL) model of sustainability that integrates the three dimensions and harmonises the three methods (Environmental) Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA).

Although BIM methodology involves all life cycle stages of the building [33], the early stages of design are considered as crucial in the reduction of environmental impacts [12] and also for improvements in the economic and social aspects of the building. Hence, the LCSA gains significance implementation in the design stages.

The literature provides evidence that the use of LCA-based tools in the first stages of design remains infrequent in the current practice of architects [12], and the application of LCSA is even more unusual. In order to fill research gaps in this area, this study conducts a Systematic Literature Review (SLR) to detect the main issues and challenges regarding the integration of LCSA and BIM. Supported by obtained results, a methodological approach for the LCSA implementation into building design stages and into design-oriented tools, such as BIM, is carried out. With all this, this study aims to contribute to the development of tools based on LCSA and integrated in design tools, that can help designers, architects, engineers, sustainable building advisors, LCA and BIM specialists to encourage the implementation of the LCSA in the building sector.

2. Materials and methods

2.1. Systematic Literature Review (SLR)

The research began with a SLR (Section 3) to answer two research questions (RQ) by analysing previous studies on the application of LCSA in the building sector and the BIM-based LCA techniques. Secondly, a method combining different aspects was proposed based on the SLR results.

- **Research Question 1 (RQ1):** What are the main methodological aspects for the application of LCSA to buildings?
- **Research Question 2 (RQ2):** How can LCA techniques be integrated into building design tools?

To answer the RQ1, the SLR focused on identifying case studies that applied LCSA in buildings. The review performed in Scopus, integrated the key words "Life Cycle Sustainability Assessment" in the title, abstract, or keywords. Finally, a selection of LCSA case studies was made, excluding those that failed to effectively integrate all three dimensions in the LCSA application, such as [34], which proposed the integration of the social aspects for future research.

To answer the RQ2 the SLR focused on detecting case studies in Scopus that used LCA techniques (LCA, LCC, and S-LCA), based on BIM methodology. The research criteria first consisted of integrating the key words "BIM-based LCA" or, "BIM" and "Life Cycle Assessment" in the title, abstract, or keywords, due to the fact that LCA is recognised in the literature [35] as the methodological basis of all three techniques. Secondly, the SLR focused on identifying those cases that integrated BIM methodology and any combination of 2 techniques ("LCA and LCC" or "LCC and S-LCA" or "LCA and S-LCA"). Finally, the focus was placed on those cases that integrated BIM and all three techniques. Moreover, the selection of S-LCA case studies was focused on the integration of LCA-based techniques, excluding those case studies which performed the social assessment of the building only focusing on the user stakeholder. According to Ref. [36] results from building S-LCA can be expressed regarding two subsystems: the first one of these conceives the building as a product, and the second perceives it as the support for different activities and processes. The present approach was focused on the first subsystem.

2.2. Methodological approach BIM-based LCSA

The methodological approach (Section 4) was carried out from SLR, taking into account two key issues, as shown in Fig. 1: 1) considerations in the application of LCSA in buildings during design stages; and 2) considerations in the integration of LCSA into building design tools, such as BIM methodology.

The analysis was conducted integrating two perspectives: 1) the methodological perspective, considering the ISO 14040 [37] standard phases as the regulatory framework for carrying out LCSA [35], and how these can be performed; and 2) the simplification strategies that could be considered, based on an example of the design stages of buildings (in the Spanish context). The particularities for the execution of each LCA technique and their adaptation for the building sector were also considered. For example, in the assessment of the sustainability of buildings, this approach was based on EN 15643 [38–41].

The environmental performance considered the ISO 21931–1 [42], EN 15978 [14], EN 15804 [15] and ISO 21930 [43] standards. The economic assessment was performed following the LCC approach based on ISO 15686–5 [44]. The social assessment was performed taking the S-LCA Guidelines into consideration [45]. Moreover, the ISO 21931–2 [46], was used as a reference for the development of the present approach since although this ISO focuses on civil engineering works and not on buildings; it is currently the only ISO standard that considers the triple LCA.

Finally, a proposal for the integration of LCSA into design tools (BIM) was developed regarding the workflow in design-oriented tools (such as BIM), and includes considerations related to data input, calculation, and data output.

3. Review results

3.1. Life Cycle Sustainability Assessment (LCSA)

The LCSA was conceived as a life cycle thinking method that integrates the triple dimension of sustainability [47], and it is considered as the sum of (E)LCA + LCC + S-LCA [48]. These three techniques have the same methodological base on the ISO 14040 [37].

Despite the fact that LCSA is a combination of three techniques which have similarities, several peculiarities in each technique have been detected. LCA is the most widely applied life cycle-based technique and is used to assess the environmental aspects related to a product over its life cycle [37]. LCC is based on an aggregation of costs that are directly related to a product over its entire life cycle [44]. S-LCA aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts during their life cycle [45].

3.1.1. LCSA case studies

The SLR identified in Scopus (based on title, abstract, or keywords of papers published until the end of 2019) a total of 250 papers about the LCSA application to buildings or building materials. It also provides evidence that its application in the construction sector remains insufficient, since only 17 papers were linked to the building sector, previously detected by Ref. [49]. The selection included 9 case study articles shown in Table 1, that were published in indexed journals in SJR and JCR, and conference proceedings.

3.1.2. LCSA case study analysis

In order to answer **RQ1**, a case study analysis was performed. Regarding the definitions of the **goal and scope**, the scope of the assessment was mostly focused on construction products [52,55–57]. However, Onat et al. [32] analysed existing US residential and commercial buildings by using a "Triple-Bottom Line" (TBL) economic input/output-based hybrid LCA model and Albertí et al. [50] focused on the application of LCSA in cities.

In order to develop **LCI** independently of the dimension assessed

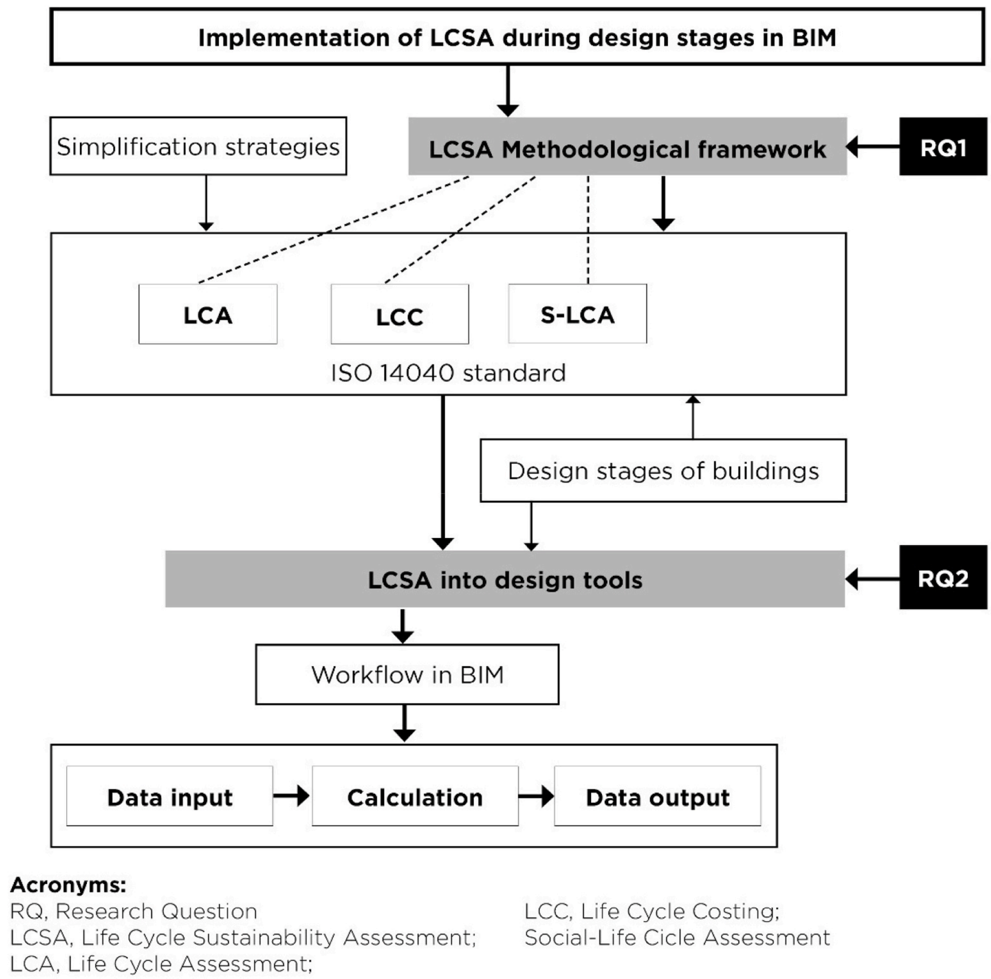

Fig. 1. Structure of the analysis and methodological approach.

(environmental, economic, social), various data sources were considered. Traverso et al. [56] for example, collected most of the LCC data directly through interviews and questionnaires from the production facilities. For the development of the LCA, the data were obtained from the Ecoinvent database [58] and the social-LCA data was largely primary data collected from the companies. Dong and Ng [53] developed the three models by collecting data mainly based on questionnaires given to project managers and on a local study regarding building materials and components. However, most case studies used primary data to integrate social data.

In order to perform **LCIA,** diverse impact categories, sub-categories, and indicators were considered. Most coincidences were related to environmental impact assessment, where GWP, GHG emissions, or climate change categories were assessed by the total number of case studies [32,51–57]. Diverse criteria were detected for economic and social indicator selection. Several case studies included costs related to production, operational, and end-of-life stages [51,52]. Social indicator selection was mostly related to employment [51–53,55–57]. One of the obstacles in applying the LCSA to buildings, building materials and cities, lies in the difficulty of obtaining economic and social data underlined by previous studies [32,50–57,59]. Another detected gap is the lack of evaluation during the design stage, since most of the case studies [32,52,53,55–57] focused on existing products or buildings and products. Moreover, the S-LCA is the least developed technique [53,59], mostly due to the data availability in the context of social impacts [45,60]. There is even a lack of consensus on a specific, consistent [60] and standardised S-LCA method. That fact reinforces the statement that quantitative social indicators are needed [61].

Other hindrances, already detected by Ref. [59], are the communication of results and the triple bottom line assessment. This statement was reported by Ref. [32,52,53,56,57], which proposed various alternatives. For example, Zheng et al. [57] applied a multi-criteria decision-making model to unify the three sustainability dimensions and to select the appropriate alternative sustainable pavement. Onat et al. [32] used a spider diagram of TBL impacts to visualise the interaction of the triple dimension assessment of the two building typologies. This strategy allows a "holistic perspective" to be obtained of the sustainability impacts produced by the residential and commercial buildings [32]. In contrast, Capitano et al. [52] reported results in an integrated way, and presented the triple impacts in parallel.

In conclusion, the present study reinforce the statement that previous studies detected [59], which confirms that the use of LCSA remains scarce in the building sector, especially on assessing scenarios for sustainability, since the case studies scarcely [50,55] used the method to guide decision making. This fact also affected the data involved in the LCSA application because case studies mostly used primary data. Therefore, the development of integrated LCSA-based methods in the design stages of buildings and the implementation of simplifications strategies without altering reliability of results are research challenges. Moreover, uncertainty in LCA [62–67], together with variability and obtaining reliable results are key challenges to be addressed by LCSA, as it has been already highlighted by Guinée [68].

The harmonisation of the three techniques is also concluded in other reviews, being a challenge for LCSA [69–71]. However, with the analysis of case studies and based on previous research in this field [72], there are two possible options for the consideration of the three techniques: 1)

Table 1
List of LCSA related to building sector.

Nº	Reference	Scope	Indicators			Data sources	Application during the design stage	Based on building LCA/ LCC or TBL sustainability standards
			Environmental	Economic	Social			
1	Albertí et al. (2019) [50]	Proposal for city	GWP	City Prosperity Index	City Prosperity Index	Secondary	**YES**	**NO**
2	Balasbaneh et al. (2018) [51]	A timber structure for low medium cost single-story residential building	5, including GWP	Life cycle cost Present Value	Wage of foreman, Number based on Job creation	Primary (social) and Secondary (environmental and economic)	**NO**	**NO**
3	Capitano et al. (2011) [52]	Marble slabs	5, including GWP	Costs of Extraction and Production, Fuel Costs (Diesel And Natural Gas), Waste Disposal Costs And Electricity Costs	Total Employees, Women in Administration, Immigrants, Limited Contracts, Unlimited Contracts, Health Insurance, Annual Health Check, Monthly Salary of Employee	Primary	**NO**	**NO**
4	Dong and Ng, (2016) [53]	An existing building in Hong Kong	18, including GWP	Costs of Foundation, Carcase, Finishing Service, Other material, Carbon, Acidification, Particulate matter, Plant rental	Freedom of association and collective bargaining, Child labour, Fair salary, Working hours, Forced labour, Equal opportunities/ discrimination Cultural heritage, safe/healthy living, conditions, Access to material resources Public commitments to sustainability issues, Local employment, Health and safety, Community engagement	Primary	**NO**	**NO**
5	Gencturk et al. (2016) [54]	A building structure	10, including GWP	Costs of Material Production, Construction, Repair/Replacement End-of-Life Downtime (indirect)	Deaths	Secondary	**NO**	**NO**
6	Hu et al. (2013) [55]	Concrete recycling	(Resource & Emission)	Costs, Revenues	Person-hour employed	Primary and Secondary	**YES**	**NO**
7	Onat et al. (2014) [32]	US existing building (residential and commercial)	4, including GHG	Foreign Purchase (Imports), Business Profit, Gross Domestic Product (GDP)	Income, Government Tax, Injury	Secondary	**NO**	**NO**
8	Traverso et al. (2012) [56]	Photovoltaic modules	11, including GWP	Revenues, Costs of PV cells, Raw materials, Labour, Electricity and Machinery.	Discrimination, Child Labour, Wages, Working Hours, Social Benefits and Health Conditions	Primary (social) and Secondary (environmental)	**NO**	**NO**
9	Zheng et al. (2019) [57]	Pavement maintenance alternatives	5, including GWP	Costs of Material, and Energy.	Working hours, Health and safety, Professional growth, Access to material resource, Safe/healthy living conditions, Public commitments to sustainability issues, Technology development, Health and safety	Primary	**NO**	**NO**

the three independent LCA techniques can be performed without weighting the dimensions, which ensures greater transparency and clearer information in the results; 2) the impact categories of LCC and S-LCA can be added to the typical impact categories of LCA, based on the same LCI model. Furthermore, a detected common gap of the case studies based on building LCSA and building product LCSA application has been the lack of standardisation in the integration and harmonisation of the three techniques. For example, none of the case studies have based the environmental assessment of the buildings nor of the building products on the existing LCA-based standards provided for that purpose (EN 15978 [14], ISO 21930 [43], and EN 15804 [15]). Moreover, the LCC has not been based on ISO 15686–5 [44], nor have any of the case studies considered the integration or harmonisation of both techniques, or how they could be integrated into the S-LCA guidelines [45].

3.2. BIM methodology to improve sustainable building performance

The use of BIM methodology in AEC (Architecture, Engineering and Construction) has optimised the design process and data management.

This building design tool has grown significantly in recent decades and is also supported by the recent European Directives, which, since 2018, have been promoting the use of BIM methodology for new public building development [73]. Volk et al. [74] recognise that certain trends, such as sustainability requirements, will stimulate and extend BIM implementation.

The use of BIM methodology during the building design stages enables to manage the complexity of the building's data and supports designers for the decision-making to reduce both time and effort. Thus, by coupling LCA based techniques in BIM, it can be provided an automatic and user-friendly support to improve the building sustainability performance during the design stages.

3.2.1. BIM-based LCA technique case studies

The SLR identified 123 papers published in Scopus and selected 36 papers published in indexed Journals SJR and JCR, in which a case study application was performed based on the integration of the BIM and LCA methods. The review also shows the increasing number of publications and works related to the integration of BIM and LCA-based techniques (see Fig. 2), as evidenced in Ref. [75]. It is expected that their number will increase in the next few years.

3.2.2. Integration of the triple LCA approach in BIM case studies

In order to answer **RQ2,** selected case studies were analysed (see Table 2). The SLR aimed to identify the dimension of the sustainability assessed. The results show that most case studies are based on BIM methodology for the purpose of assessing environmental impacts produced by buildings. The simultaneous assessment of environmental and economic aspects is detected in six studies [76–81]. None of the case studies includes the S-LCA technique in BIM, therefore, there are no studies with a triple LCA approach integrated in BIM methodology; an opportunity to be addressed can thus be seen here.

The interoperability was underlined by previous studies in this field [27,59,83,85,111] as one of the greatest challenges towards the integration of the LCA based method into BIM methodology. Hollberg et al. [90], for example, proposed the link between LCA and BIM as a multiplication between the quantities of each material with the LCA factors (embodied impacts) from the KBOB database. Soust-Verdaguer et al. [109] proposed to enrich the bill of quantities, automatically extracted from the BIM model, with supplementary data (such as auxiliary materials, transports). Other studies, such as Shin and Cho [80], based the LCA and LCC application in BIM, on various design documents and equations to develop the calculations, which required time to avoid errors in result. Therefore, the more detailed structure and information is needed in the LCA application, the more difficult to conduct free-error and automatic LCA techniques in BIM, as already indicated in Ref. [59]. Moreover, the analysis of case studies reveals the need for data sources (such as background data or specific data) adapted to the specific requirements (e.g., tags, families of elements, proprieties) to conduct LCA techniques in BIM.

On the other hand, the bill of material quantities is considered one of the most relevant purposes of coupling BIM and LCA based techniques [111], which together with the finding of datasets of the building material LCA database, represents the most time-consuming effort process [90]. Other difficulty also detected in Ref. [59] is the integration of S-LCA in BIM. That can be due to the complexity in collecting information about organisational aspects along the chain of production, as it is recognised by Ref. [45], and to its scant application in the building sector, as evidenced by Ref. [112].

3.3. RQ answers and new challenges

Results reveal that in spite of the growing use of the technique, the LCSA is still considered a new research area, as it has already highlighted by other study [113]. Furthermore, the SLR showed that neither the LCSA application case studies are integrated into building design tools, nor did the BIM-based LCA application case studies integrated the TBL assessment of sustainability. The answers to the RQ also reveal that:

- RQ1 answer. The harmonisation of the three techniques is the main methodological challenge to conduct LCSA of buildings; and other relevant aspects are the use of reliable simplification strategies related to data acquisition, scope and boundary definition, indicators selection, and communication of results along with the TBL assessment.
- RQ2 answer. The interoperability in the data sources between the three LCA techniques and BIM, the implementation of the harmonised three LCA techniques in BIM, and obtaining effective, automatic, and reliable results are the main challenges for the integration of TBL approach in BIM.

The following section proposes a method to integrate the LCSA

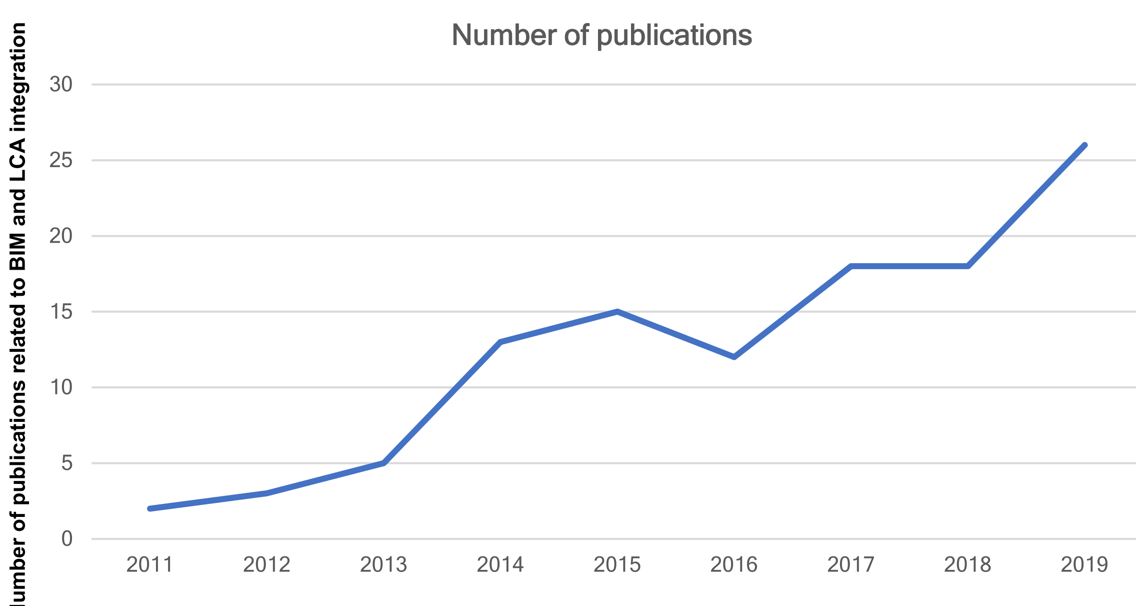

Fig. 2. Number of publications related to BIM-LCA integration per year.

Table 2
List of BIM-based LCA case studies.

	Reference	Assessed dimension of sustainability			TBL approach
		Environmental	Economic	Social	
1	Abanda et al. (2017) [76]	X	X		NO
2	Ajayi et al. (2015) [82]	X			NO
3	Basbagill et al. (2013) [83]	X			NO
4	Bertin et al. (2020) [84]	X			NO
5	Bueno and Fabricio, (2018) [85]	X			NO
6	Cavalliere et al. (2019) [86]	X			NO
7	Eleftheriadis et al. (2018) [87]	X			NO
8	Feng et al. (2020) [88]	X			NO
9	Georges et al. (2014) [89]	X			NO
10	Hollberg et al. (2020) [90]	X			NO
11	Houlihan Wiberg et al. (2014) [91]	X			NO
12	Iddon and Firth, (2013) [92]	X			NO
13	Jalaei and Jrade, (2014) [93]	X			NO
14	Jrade and Jalaei, (2013) [94]	X			NO
15	Lee et al. (2015) [95]	X			NO
16	Lu et al. (2020) [96]	X			NO
17	Marzouk et al. (2017) [97]	X			NO
18	Najjar et al. (2017) [98]	X			NO
19	Naneva et al. (2020) [99]	X			NO
20	Nizam et al. (2018) [100]	X			NO
21	Panteli et al. (2018) [101]	X			NO
22	Peng, (2014) [102]	X			NO
23	Raposo et al. (2019) [81]	X	X		NO
24	Rezaei et al. (2019) [103]	X			NO
25	Röck et al. (2018) [11]	X			NO
26	Santos et al. (2019) [79]	X	X		NO
27	Santos et al. (2020b) [78]	X	X		NO
28	Santos et al. (2020a) [77]	X	X		NO
29	Schneider-Marin et al. (2020) [104]	X			NO
30	Shadram et al. (2016) [105]	X			NO
31	Shadram and Mukkavaara, (2018) [106]	X			NO
32	Shafiq et al. (2015) [107]	X			NO
33	Shin and Cho, (2015) [80]	X	X		NO
34	Soust-Verdaguer et al. (2018) [108]	X			NO
35	Soust-Verdaguer et al. (2020) [109]	X			NO
36	Yang et al. (2018) [110]	X			NO

approach into the BIM building design tool.

4. Proposal for LCSA application to building design stages

Recent studies [68,114] confirm that one of the most important difficulties to be solved in the LCA and LCSA techniques application, involves the development of the life cycle-based approaches for the evaluation of scenarios for sustainable futures and for the integration of this technique into product design stages. Thus, an example of design stages of buildings illustrates the present approach. Based on the Spanish context, and following a representative architects' work method, there are four consecutive stages in compliance with national regulations for architects [115], described in Table 3.

The present methodological considerations were developed to be applied during Basic Project (BP) and Execution Project (EP) stages. The reason is that during these stages there is more specific information on the characteristics of the future building that allows the most out of the BIM technology by performing the TBL assessment and therefore, by performing design strategies to reduce impacts. Furthermore, the greatest number of decisions related to the physical characteristics of the buildings are taken into account during BP and EP. At BP and EP, feasible modifications such as changing the type of construction and its materialisation, choosing a product from a specific producer [116], changing the thickness of materials, and modifying the room dimensions, can all be performed to improve the sustainable performance of the building. Thus, the level of development (LOD) provided for the following methodological considerations was adapted to the example. However, the BIM forum [117] shows that the LOD is not directly defined by design stages: different LODs of different elements can be part of the building model, for example in the Schematic Design phase. The LOD establishes the requirements that must be achieved so that the geometry and the information can be considered reliable [118]. Therefore, the methodological approach set the estimate of the LOD as the minimum degree to which most of the geometry and attached information of the building element has been thoroughly thought through [117]. Following the Spanish guide for BIM users [118], the resulting LOD for the Spanish design stages of buildings are shown in Table 3.

Table 3
Spanish design stages of buildings and LOD (Based on [115]).

	Design stages of building for architects (Spanish context)			
	"Concept stage" (CS)	"Preliminary stage" (PS)	"Basic project" (BP)[a]	"Execution project" (EP)[a]
Aims	Estimate the allowed building area/ volume according to the urban regulations. Estimate of the overall cost of the building.	Estimate the building area/ volume and the main building characteristics.	Define the main characteristics of the building to obtain the building permit application. This includes the internal distribution, main materials, structure, and main technical characteristics. The documents and drawings are needed	Define the technical characteristics of the building, relating to the construction stage. Include all the technical characteristics and drawings of the building as well as the demonstration of compliance with national [119] and regional regulations.
Estimated LOD	–	(at least) 100	(at least) 200	(at least) 400

[a] design stages in which the proposed BIM-based LCSA method is focused.

4.1. LCSA methodological aspects applied to buildings

This approach aims to identify the main methodological aspects for the integration of LCSA into building design stages and for the proposal of feasible simplification strategies. The present framework also identifies difficulties and suggests alternatives for their solutions.

SLR results show that the EeB Guide Project [120] is a suitable reference to define the system boundaries considering the different design stages in BIM. This Guide recognises three types of LCA applications in terms of the level of detail: *Screening, Simplified,* and *Complete*. Fig. 3 shows the relation between Spanish design stages (Table 3), the Eeb Guide [120], LCA-type studies, and the resulting most frequent LOD of the BIM model that is defined by the Spanish BIM guide for users [118]. Regarding Fig. 3, the study applied to the present work was based on the *Simplified* LCA type.

4.1.1. Goal and scope definition

Although, the implementation of LCSA implies the simultaneous application of three methods: LCA, LCC, and S-LCA [56], it also involves the combination and harmonisation of system boundaries and functional unit. Thus regarding the system boundary and the same functional unit definition, and reference in the field [35] a "common goal and scope" should be considered. However, the SLR results show that the same system boundary cannot always be assumed for all three dimensions. Zheng et al. [57] for example, considered slightly different system boundary for each technique. This type of decision is in accordance with previous research in this field [121–123].

4.1.1.1. LCSA information modules. Regarding the scope of the study in terms of the LCA information modules (described in EN 15804 [15] standard) and the EeBguide [120] recommendations, the present methodological approach intended to integrate the mandatory information modules (at least for the simplified LCA study): A1-A3, B4, B6, B7, C3, C and D information modules, described in Table 4. The information modules are conceived as a data compilation for the development of Environmental Product Declarations (EPDs) Type III, that include a unit process or a combination of unit processes of the product life cycle [15]. The integration of the rest of the LCA information modules was conditioned by data availability and the relevance for the assessment during the design stage.

Various approaches towards conducting the LCC were detected and classified by the literature [124,125] as conventional, environmental, and societal life cycle costing in dependence on the cost category and scope of assessment. References based on the BIM-based LCA and LCC, such as [77–79] considered the conventional approach, whose application to buildings is described in the ISO 15686–5 [44] standard. Thus, the present approach focused on that type. The inconvenience of considering that approach is that the costs related to product stage (e.g., raw material supply, transport and manufacturing) are not included in the system boundaries. Therefore, the scope of costs in this work included those of construction, operation, maintenance, and end of life. Since this methodological proposal aims to cover those processes that can be linked to any quantitative unit, the stakeholders analysed in S-LCA included workers (contractors, subcontractors, etc.).

Regarding the aforementioned aspects, a proposal for modular consideration of the life cycle stages of buildings in the Spanish context is shown in Table 4. The proposal was developed considering the two main milestones during the design stages, the deliverables of the project: BP and EP. One major advantage is that through these stages the BIM model is checked by specialists (such as BIM manager) and therefore the information related to processes such as the material quantities take off (relevant for the LCSA calculation), underlined by Ref. [90] as problematic in the BIM-based LCA process, can contain less errors. The proposal intends to integrate and harmonise: the modular consideration of sustainability assessment for construction works included in the ISO 21931–2 [46] standard; the scope definition proposed in ISO 15686 [44]; the EeBguide [120] recommendations for the LCA type of application to buildings; the guidelines for S-LCA [45] application; the requirements [118] and data availability during the design stages in BIM for the Spanish context; and the SLR results (see Table 1). The proposal considers including slight differences in the system boundaries definition (modules of information) depending on each technique (LCA, LCC, and S-LCA), and design stage (BP or EP). It takes into account the relevance and feasibility of data collection for each information module during each design stage and LCA technique, being supported by previous research in this field [57]. For example, Module A0, was included in LCC and S-LCA due to the relevance of the costs of the preparatory work and administrative processes during the pre-construction stages. However, module A0 was not included in LCA, since it is an irrelevant phase in generating environmental impacts with respect to the others. The main utility of the present sustainability assessment is to help users to model and predict the environmental, economic, and social impacts

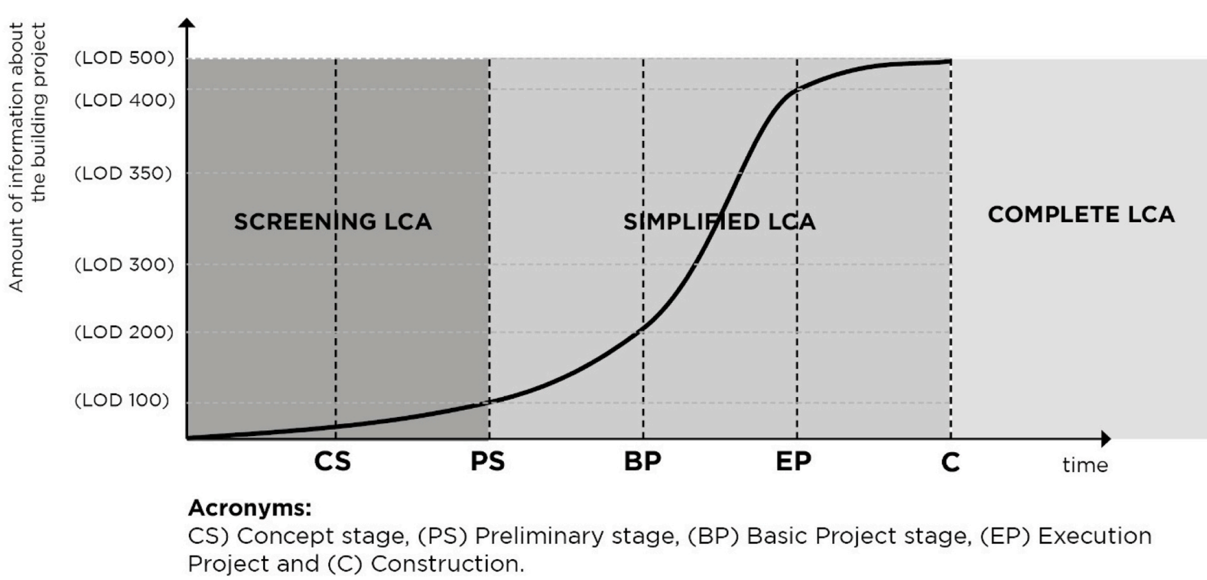

Fig. 3. Relation between Spanish design stages of buildings, the types of LCA studies, and the LOD of the BIM model (Source prepared by authors and adapted from Ref. [12]).

Table 4
Proposal of modules of information included in the LCA, LCC, and S-LCA of buildings for being considered in the design stages.

		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	BP		X		X				X		X	X		X		X	X		X
	EP		X	X	X		X	X	X		X	X	X	X	X	X	X		X
Economic LCC	BP	X			X				X		X	X		X		X	X		X
	EP	X		X	X		X	X	X		X	X	X	X	X	X	X		X
Social S-LCA	BP	X			X				X		X	X		X		X	X		X
	EP	X		X	X		X	X	X		X	X	X	X	X	X	X		X

BP: Basic Project; EP: Execution Project.
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 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 [46].

during the life cycle stages of the building in order to help decision-making. Thus, during the EP stage, most of the pre-construction work has been completed, being outside the system boundaries. Modules A1-A3 were included in the LCA and excluded from the LCC and S-LCA applications, since existing databases and data availability of the economic and social costs of these processes (e.g., related studies) are limited or inexistent in Spain. Modules A4 and C2, related to transport, were included in the three-technique application and for EP design stage, due to their relevance in material selection. Modules A5, B4, B6, B7, C1, and C4 were included in the three-technique application and for BP and EP: the information obtained could be based on estimations and could differ (from BP to EP) depending on the level of accuracy of the BIM model. Finally, the inclusion of C3 and D modules is recommended due to their potential contributions towards the circular economy in construction [126], although its integration depends on data availability.

4.1.2. Life cycle inventory (LCI) and life cycle impact calculation (LCIA)

The LCI is considered one of the most time-consuming phases according to the ISO 14040 [37] standard application. Therefore, from the perspective of LCSA application in building design stages, two issues were considered: how the LCI can be simplified; and how the LCIA can be easily conducted during design stages.

According to the recommendations of UNEP/SETAC [45], it is proposed that the building “unit process” is linked with environmental, economic and social dimensions, as illustrates Fig. 4. Moreover, specific regulations [14,15,43] on building LCA, considers the EPD a major data source for LCA application [120,127,128].

4.1.2.1. Sustainability Product Declaration (SPD). The SLR results (see Table 1) show that most of case studies are based on primary data to conduct the LCSA. However, during the building design stages in BIM the availability of primary data can be inexistent or limited, due to the uncertainties and variability of the processes. To overcome this limitation, the use of background data and secondary data became a possible solution. In this vein, the analysis of case studies included in Table 2 confirm that the data sources to conduct BIM-based LCA and LCC are in all cases databases (e.g., Ecoinvent), and EPDs. Regarding the possibility of adapting existing sources (e.g., environmental and construction cost databases) to support the application of LCSA to buildings and to take advantage of the potential for the EPD (generic or specific), a TBL data source, named the Sustainability Product Declaration (SPD) was proposed and defined.

The SPD integrates the correlation between environmental, economic and social aspects (see Fig. 4) and helps to organise the information of the building during its life cycle. Furthermore, the SPD can reduce the efforts required for data acquisition by the integration of specific information of building products and materials. The present methodological approach considers the use of a TBL/Sustainability database that integrates specific and generic SPD of the main building materials and products. This strategy can also provide a potential solution to the limitations in S-LCA data availability, as underlined Dong and Ng [129], who proposed the development of the S-LCA database based on primary data.

Nevertheless, a direct link between the three dimensions of the unit process cannot always be assured [59]. Hu et al. [55] for example, emphasised the limitations of this approach on integrating the cost, where costs such as (e.g., overheads, profit and losses) cannot be directly associated to the unit process. Moreover, several limitations are also discussed by S-LCA specific literature [60] when considering this approach. Hence, to solve this problem Llatas el al [59]. Suggest to limit the use of the proposed data sources (SPD generic or specific, whenever

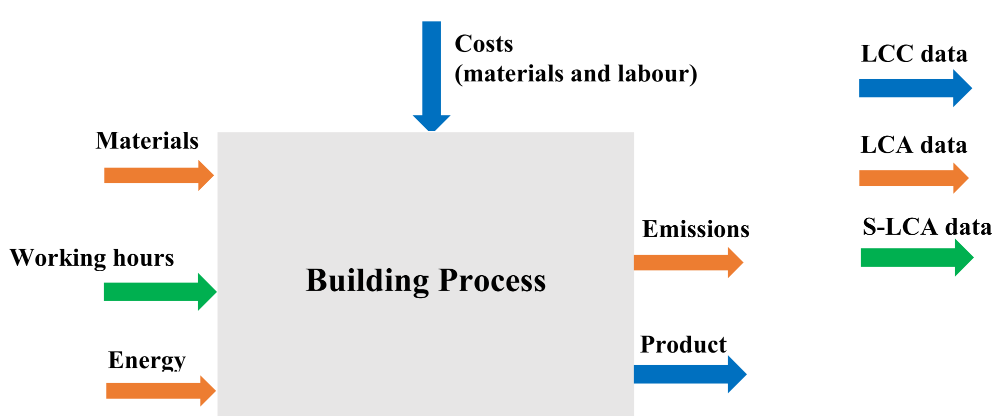

Fig. 4. Integration of environmental, economic and social dimensions into building unit process (Proposal based on UNEP/SETAC Life Cycle Initiative [45,59]).

possible) and the selection of indicators (environmental, economic and social) to those that can be effectively integrated.

The SPD is conceived as a tool to deal with the main methodological aspects of LCSA implementation. It is an enriched version of the EPD by integrating environmental, economic, and social information about a building process/material or product, and it is developed in accordance with the existing standards of building LCA (EN 15978 [14] and EN 15804 [15]), as a basis of the method. One of its main utilities is the reduction of efforts in calculating the total impacts of the building. Resulting impacts are calculated as the sum of the bill of quantities (extracted from the BIM model) multiplied by the impact quantification factors obtained from the SPD (e.g., CO2 emissions, costs, and working hours) of each element/material/product depending on the design stage. Thus, the most relevant methodological issues of the LCSA application can be transferred to the SPD and the TBL database definition. For example, to deal with allocation issues it is proposed to establish a harmonised and common criterion (considering the allocation strategies exposed in Ref. [130]), that can be included in the Product Category Rules (PCRs) of each SPD. That fact can considerably reduce possible differences in the choice of allocation procedures. Other issues, such as the discount rate, direct and indirect costs, frequency and time period of use, and land-use accounting can also be included in the PCRs and assumptions. The energy consumption for the construction/deconstruction process can also be taken into account in the SPD, from construction work regional database (BCCA) [131], for example. The strategy is based on an elemental/material/product decomposition of the building to calculate individual impact quantification factors (similar to cost estimations in BIM [132]) in such a way that the resulting total impacts can be obtained following the indicated procedure proposed by the EN 15978 [14] for the building LCA.

4.1.2.2. Harmonisation of the LCA techniques. In the LCSA application to buildings, the correlation between the aspects of unit processes can also be verified at two levels: 1) the building material/product/component; and 2) the building. To deal with the first level, the present approach recommends organising the aforementioned SPD database and harmonising (whenever possible) the scope and system boundary of the three techniques. At building level, specific information regarding the building processes should also be considered for harmonisation in terms of the scope of the study, system boundaries, and indicators. Following these criteria, Fig. 5 shows a Spanish example, for the midpoint categories, subcategories of stakeholders, and cost category selection. The example illustrates how the three dimensions of sustainability, can be integrated from the data input to the results. The aim is to combine and harmonise the three techniques, a gap found in literature (see Table 2). A qualitative correlation between the unit processes was established to select environmental, economic, and social impact categories. The example considered a square metre of the building's roofing (code 07HTF00001 of the BCCA [131]) as a functional unit. It followed an elemental decomposition of the building based on the data structure used by this regional database for cost estimations in the building sector in Andalusia. This strategy was suggested by previous research [132], and adopted for other related purpose [133], since it can reduce efforts and simplify LCSA implementation in BIM. Moreover, this approach is also considered in the S-LCA application to buildings [36]. Based on existing data sources regarding the building project, (described in Table 3), the bill of material quantities (taken off from the BIM model) and the generic or specific data (contained in the SPD database), then the quantification of CO2 emissions, costs (materials and labour), and working hours related to the material flows, transport, and energy consumption involved can be obtained.

The example included the most frequent LCC categories results obtained in the SLR (see Table 1), the *labour cost* and *material cost* categories. Regarding the social dimension, and based on the results obtained in the SLR (see Table 1), the example also included the most frequent stakeholder *workers* and integrated the *working hours* as a subcategory of stakeholders. Thus, the selection of a balanced number of quantitative indicators (one in this case) per dimension could facilitate the weighting and combination of the three dimensions.

4.2. Integration of LCSA in design tools

The following section aims to propose an operative framework to conduct LCSA in design-oriented tools, such as BIM methodology. It was defined supported by the SLR results (see Section 3), previous applications of LCSA in buildings, the integration of LCA into BIM, the integration of LCA and LCC into BIM (see Fig. 6), and previous studies in the field [59]. The conceptual framework focuses on a three-step method. Step 1:data input, Step 2: calculation, and Step 3: data output. Moreover, the proposed framework is organised following the modular classification to implement LCA application into design practice proposed by Ref. [134]. The general module structure that was followed to categorise the origin and to propose the elements that compose the proposed integration includes: background data, modelling, calculation, and post processing as shown Fig. 6.

The proposal was based on the Level 2 of BIM maturity, regarding the state of BIM implementation in Spain [135]. This means that, considering the four levels (Level 0 to Level 3) defined by the BIM Industry

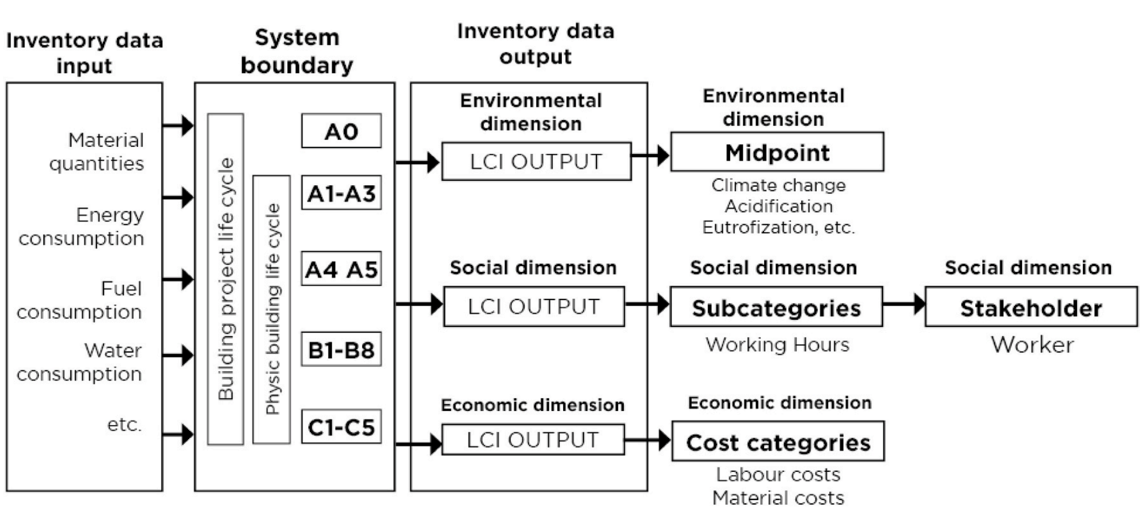

Fig. 5. Proposal of Inventory data input, System boundary (modules defined in Table 4); Inventory data output, midpoint categories, subcategories of stakeholders, and cost categories for LCI to be conducted in buildings. (Proposal elaborated considering [35,46]).

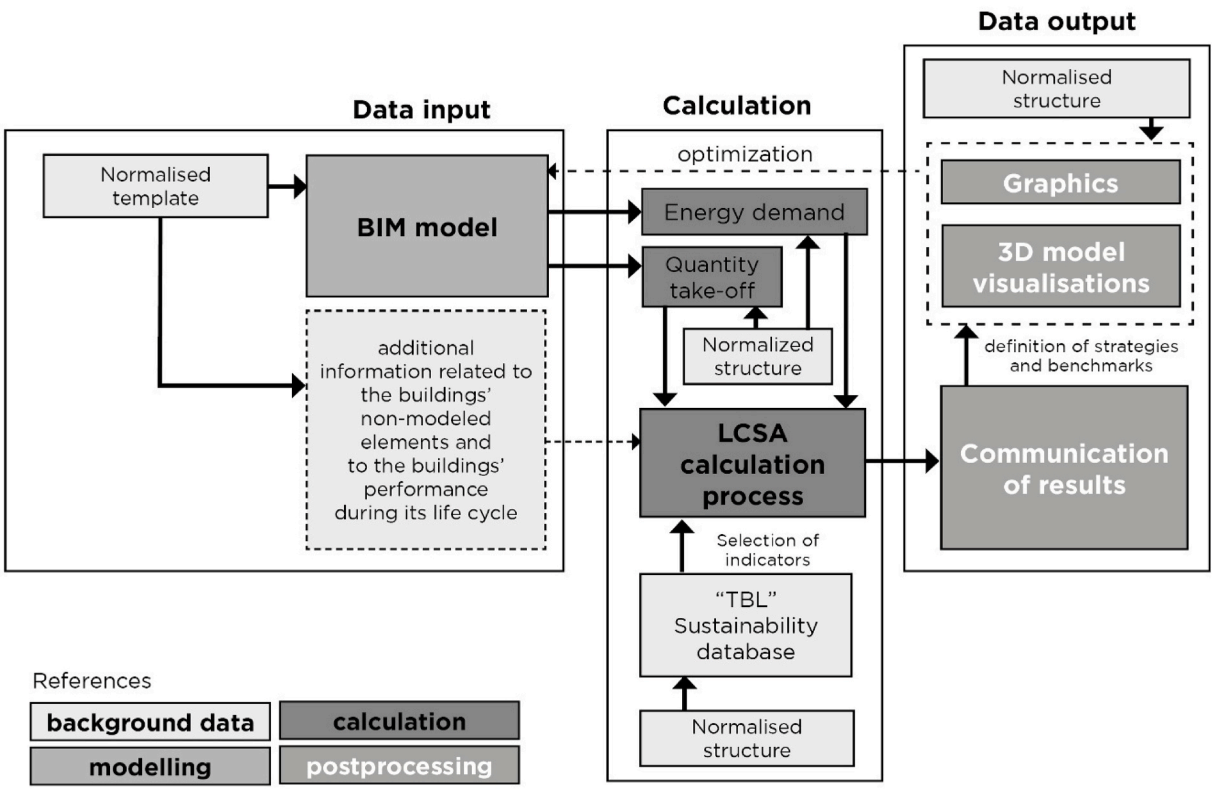

Fig. 6. Scheme of the proposed integration.

Working Group [136], it is possible to manage the 3D environment held in separate discipline "BIM" tools with attached data. At this level, model-based collaboration, file-based integration, and library management are feasible. Special file exchange formats and input/output standards are also needed to manage the information across various disciplines [137].

4.2.1. Step 1: data input

The first step aimed to provide a template with a normalised and reliable structure to compose the BIM model [59]. The use of a normalised structure, both in this step and in the following ones, is a useful resource that considers a set of standardised parameters. Therefore the normalised template (see Fig. 6) provides a structure to organise information about the building, its classification, and its hierarchical decomposition, in compliance with the ISO 12006 [138] standard. The step is focused on offering designers different alternatives or scenarios during the modelling process [59], but also aimed to take full advantage of the BIM model (geometry and data) and to reduce (to a minimum) manually data entering. The normalised template can also contribute towards verifying the completeness of the LCI, by helping to identify which information can be automatically extracted from the model and which information should be inserted by the designer.

It is assumed that the building project is an evolutionary process with several milestones that are mainly related to the establishment of national regulations. The decision-making process, however, is also linked to the verification and testing of various design options at different levels of detail. In order to attain the maximum benefit from the BIM model (geometry and data), and supported by Refs. [12], the method proposed the use of default values and settings (generic data about materials and scenarios) for those stages in which the granularity of the model is insufficient to ensure reliable results. For example, in the event that information, such as that on installations, was not included in the BIM model (e.g., in the BP stage, LOD 200), a set of default values regarding materials and life cycle performance of the building could be provided.

4.2.2. Step 2: calculation

This step proposed the link between the Step 1 (normalised BIM model) with the TBL database (generic or specific data, containing information about the three dimensions) [59]. The calculation process consists of the phase in which specific information about the building, the energy demand and the TBL/Sustainability database are matched. To this end, the use of a normalised structure again, to organise this phase is recommended in order to enhance information exchange, especially between the LCI (information regarding the building) and the databases. The modelled elements of the building are related to (generic or specific) data regarding the environmental, economic, and social performance of materials and products contained in the TBL/Sustainability database. In order to perform the calculation of impacts on BIM methodology, there is a variety of methods classified by Refs. [132] such as: the Bill of quantities (BOQ) export [108], the IFC import of surfaces, the BIM viewer for linking LCA profiles, LCA plugin for BIM-software or the use of enriched BIM models (e.g., IFC format) [77–79]. The present methodology proposed that the most suitable method in each case should be selected based on three key issues: the data interoperability, the data actualisation capability and the compatibility with the work method of the architects.

4.2.3. Step 3: data output

Supported by a standardised classification system for the decomposition of building elements, the communication of results should provide a transparent structure to help the designer visualise the impacts. For an automatic optimisation of the BIM model, a real time connection between the first and last steps should be adopted [59]. Relevant information during the considered design stages should be shown, such as: impact of the materials used, impact of the building elements (structure, walls, floors, etc.), impact per life cycle stage, and impact per room.

Another relevant aspect to be addressed in the LCSA implementation in BIM is the communication of results, which involves the integration and weighting of environmental, economic and social aspects [59]. References in the field [139] emphasised the requirements of appropriate multi-criteria evaluation in the LCSA application, thus, Life Cycle Sustainability Triangle and the Life Cycle Sustainability Dashboard [56] can be considered possible solutions to deal with it [59]. Since the proposed approach also should deal with different system boundaries, if applicable, the modularity principle should be considered in the communication of results. In the proposal, not only the appropriate integration of environmental, economic and social aspects is relevant, but also the use of design-oriented values to guide architects during building design stages. Moreover, the present methodological approach, though extending previous studies in the field [59], recommends defining, obtaining and integrating benchmarks and reference values adapted to regional and national scenarios, as it has already been examined to guide and support decision-making during building design stages by previous study [140].

5. Conclusions and further research

This paper provides evidence of the non-existence of an integrated "Triple Bottom Line" approach based on the LCSA of building design stages in BIM. The SLR identified the most relevant problems and challenges in this field, mainly: the harmonisation of the three techniques (LCA, LCC and S-LCA) and the data sources. Subsequently, supported by previous literature on the subject, the paper provided solutions to deal with the detected problems and presented a methodological framework for the implementation of LCSA during design stages through the use of the potential for BIM methodology to quantify and visualise the TBL/Sustainability assessment of buildings. The results of the SLR also reveal the lack of specific standardisation to implement the LCSA based on the integration of the triple approach and the LCA-techniques. Recent developments, such as the standards ISO 21931–2 [46], can be used as a general support to implement the sustainability assessment of construction works based on the Triple Bottom Line approach, and LCA-techniques in BIM. Moreover, further specific standardisation is required when conducting LCSA in buildings. In this vein, the harmonisation of SPDs and their PCRs could be analysed, as this exists in EPDs.

The present study proposed to address one of the most complex and time-consuming stages of the LCSA application in building design stages (LCI), through the development of a TBL/Sustainability database that organises the SPD (generic or specific) of the most significant products used in the construction sector. This represents the starting point for the definition of a structure of BIM attributes and properties, as well as the data interoperability, and the operative integration of LCSA in BIM which reminds an opportunity for future research. Thus, the main contributions of the present paper corresponded to the definition of the SPD organised into a TBL database (firstly presented in Ref. [59] and better described here), the definition of system boundaries of each dimension (environmental, economic and social) considering the building design stages (Table 4), the proposal for harmonisation of LCI and LCIA integrated to the workflow in BIM, and the framework for LCSA implementation in BIM. The methodological challenge of integrating the three LCA techniques also requires further development towards the definition of data sources (generic or specific) that consider the same system boundaries for the three techniques. Furthermore, the implications of considering different system boundaries, as a consequence of the data availability during the building design process (for example for BP and EP), should be addressed in the future.

Although an example based on the Spanish context illustrated purposes, this methodological approach could be tested in other case studies, in order to determine its feasibility. The objective of the case study application involves the determination of the most suir communication strategy of the results, regarding data availability, interoperability of software and data, and the architect's work method (e.g., design protocol). Finally, future implementations should also consider the definition of benchmarks and design-oriented visualisation strategies, especially focused on considering the weighting and the ponderation of the multicriteria assessment.

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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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