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To cite this article: C Llatas *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **323** 012107

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Towards a Life Cycle Sustainability Assessment method for the quantification and reduction of impacts of buildings life cycle

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Abstract. The construction and building sectors are one of the highest consumers of resources and energy. Literature evidences the potentialities of the design phase towards the improvement of environmental, economic and social performance of buildings. Thus, the Life Cycle Sustainability Assessment (LCSA). approach is recognized as suitable method. It is based on the “triple bottom line” principle, to calculate environmental, economic, social impacts produced by buildings during its life cycle. The present paper aims to present a methodological framework based on an LCSA, used during design stages of buildings and integrated into a building’s design technology such as Building Information Modeling (BIM). A conceptual approach to conduct the data integration and a possible workflow to integrate the LCSA into BIM is proposed. The value of the present approach is the possibility to conduct quantitative environmental, economic and social assessment of buildings to guide designers to measure and predict the building’s performance.

1. Introduction

The building sector is responsible, from cradle to grave, of significant environmental impacts [1]. In the European context, for example, the use and construction stages of buildings consume half of the extracted materials [2]. Moreover, it is also recognized as one of the most important waste producers, by generating one-third of the total amount [3]. Regarding this situation and given the growing demand for reducing environmental impacts of cities and buildings, the building sector also produces economic benefits [4–6] and positive impacts for the society.

The design stages of the buildings are considered as relevant in order to reduce their impacts among their life cycle [7,8]. Consequently, over the last decades there has been developed several assessment tools for design stages, mainly based on environmental aspects. The Life Cycle Assessment (LCA) is considered one of the most appropriate method to analyzes the impacts produced by buildings, mostly focused on environmental aspects [9]. The utility of LCA-based tools compared to existing Sustainable Building Certification (SBC) or Green Building Rating Systems, such as LEED [12], BREEAM [13], Living Building Challenge [14], is based on the possibility to bring quantitative assessment of building’s



sustainability [15] through the stages of the building's life cycle. Existing SBC are mostly based on the assessment of qualitative environmental aspects of sustainability, generally related to energy [16]. That fact evidences the scarce incidence of other sustainability dimensions, for example socio-economic aspects, such as their contribution to the employment creation in certain region or city. Furthermore, literature [7] recognizes the potentialities of the use of LCA-based methods to be integrated in building design stages. However, the main barriers over the use of LCA methods applied to buildings are related to the time-consuming process and the wide amount of data required [17], especially during the phase of Life Cycle Inventory (LCI). In this sense, several works demonstrate the viability of applying simplification strategies for buildings LCA [17–21]. It is recognized that the feasibility of using environmental assessment tools and methods, lies in the simplicity and effectiveness to verify and calculate the impacts. Malmqvist et al. [17] show the possibilities of simplifying the method without the results being substantially affected. Soust-Verdaguer et al. [22], through the analysis of simplification strategies of LCA case studies (single-family houses), underline that one of the feasible strategy to reduce effort during the LCI phase is the integration of BIM models. The strategy allows to integrate LCA into BIM methodology and helps to visualize impacts during the decision-making process. The potentialities of the integration of LCA into BIM through the development of methods and tools are demonstrated in several works [23–39]. Despite of the great amount of developments that integrate BIM and LCA, they are mainly focused on the use of Life Cycle Assessment method to assess environmental aspects. However, current situation based on “complex systems with extended and durable effects on the society” [40], requires more comprehensive and extensive strategies. Thus, the Life Cycle Sustainability Assessment (LCSA) approach aims to go beyond the limitations of the traditional LCA approach [40], by integrating environmental, economic and social dimensions. Literature review evidences that the application of LCSA into building sector is still scarce, and especially during design stages. To fulfil research gaps on this area, the present paper aims to describe a methodological framework based on an LCSA approach, used during design stages of buildings and integrated into a building's design methodology such as Building Modelling Information (BIM).

2. State of the art

This section presents a definition of the main aspects and a review of studies that integrate the LCSA approach to building products and buildings, and the implementation of LCA-based method into BIM technology.

2.1 Life Cycle Sustainability Assessment (LCSA) approach

The Life Cycle Sustainability framework aims to integrate environmental, social, and economic dimensions of sustainability and to guide the decision-making towards a life cycle perspective [41]. It is based on the formula proposed by Klöpffer (2008) [42] which introduces the application of the three techniques: (Environmental) Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA). Guinée et al. [43] understand the LCSA as a “transdisciplinary framework for integration of models rather than a model in itself” [43]. The UNEP/SETAC Life Cycle Initiative to LCSA [44] recognizes that the three techniques are based on the ISO 14040 [10] and they have similar perspectives and aims (Phases 1, 2, 3 and 4).

Previous literature review [45] evidences that its application into building sector is still scarce. However, several examples have been detected and summarized in Table 1. An example of the application of LCSA to a building product (marble slabs) is performed in Capitano et al. [46]. The study determinates in parallel the environmental, economic and social impacts produced by two existing companies' producers of marble in the Sicilian region. The authors have collected and used primary data for the impact calculation [46]. The LCA includes five impact categories: Human Toxicity Potential; Acidification Potential; Eutrophication Potential; Photochemical Oxidation and Global Warming Potential [46]. The LCC includes: Costs of extraction and production, Fuel costs (diesel and natural gas), Waste disposal costs and Electricity costs [46]. The social impacts analyzed are: total employees, women in administration, immigrants, limited contracts, unlimited contracts, health insurance, annual

health check and monthly salary of employee [46]. The results obtained are reported on a desegregated manner, presenting in parallel environmental, economic and social impacts. This is due to the fact that the authors aim to acquire a transparent procedure to support decision-making into a sustainability perspective [46].

Table 1. List of LCSA studies.

References	Year	Functional unit definition	Scope of the assessment Design /Product	Data sources
Capitano et al. [46]	2011	m ³ of marble	Existing product	Primary data
Dong et al. [47]	2016	building construction project	Existing product	Primary data
Hu et al. [41]	2013	ton of materials from the EOL building	Design stage	Generic data
Onat et al. [48]	2014	national level	Existing product	Primary data
Traverso et al. [49]	2012	1m ² of modules	Existing product	Primary data
Zheng et al. [50]	2019	1-km long pavement with one- lane (3.5mwidth)	Existing product	Primary data – secondary data

Analyzing previous studies in this field [41,46–50], one of the main barriers over the application of LCSA to buildings and building products are related to the data collection, especially for economic and social aspects. Moreover, limitations on the definition of a common functional unit for the three methods is highlighted by Zheng et al. [50]. The study considers that the “social impacts are assessed using management behavior, rather than physical quantities”, due to that social impacts are not linked to the functional unit. Most of case studies [41,46–50] are based on existing products or buildings, extracted from site-specific sources (local companies or suppliers). This means that the application of LCSA requires additional efforts in data acquisition. Thus, Dong et al. [47] underline that in spite of LCSA being a relatively new technique, the S-LCA is especially the most limited part of the method. Specific research on S-LCA [51,52] underlines the difficulties on data availability about social impacts. Moreover, there is no consensus on the specific or consistent S-LCA method [52]. Regarding detected difficulties, Guinée et al. [53] highline the need to develop quantitative and practical indicators for S-LCA.

Another difficulty was found over the communication of results and the effective integration of environmental, economic and social impacts in the assessment process. Difficulties on weighting and calibrating indicators in order to support the decision-making stages have been identified in [46–50]. Moreover, it is concluded that the use of LCSA frameworks is still infrequent in building sector, especially focused on guiding the design stages and assessing scenarios for sustainability. Most case studies [46–50], based the LCSA application on existing products or buildings, excepting Hu et al. [41]. Considering this context, the development of tools and methods focusing on design stages of buildings is becoming an opportunity. However, this type of tools should deal with uncertainty, underlined by Guinée et al. [53] as one of the three most crucial challenges to be addressed by the LCSA, along with variability and the feasibility to obtain reliable results.

2.2 BIM methodology and LCA integration

During the design stages of buildings, it is expected that the BIM methodology can integrate a great amount of information about the building, guide designers on a user-friendly way, and reduce time and effort during design process. Regarding the integration of LCA and BIM, it is expected to be automatic, user-friendly, useful during the design stages, and provide reliable results [38]. Considering previous

research on this field [38], it may be concluded that one of the most relevant challenges of the integration of life cycle perspective into BIM methodology is the interoperability [25]. This means that the ideal workflow should provide the most automatic interaction between the BIM model and the data about environmental, economic and social impacts. Several examples on how it can be conducted are detected. Röck et al. [31], for example, to calculate embodied environmental impacts, solved the link LCA and BIM as a simple product between the total area of building element obtained from the BIM model and the environmental impact values from the LCA database. Soust-Verdaguer et al. [54] proposed a BIM-based LCA method to compare the environmental performance of envelope alternatives during the life cycle. The workflow is based on integrating the automatic bill of quantities (extracted from the BIM model) with various documents of supplementary data, before conducting the environmental impact calculation. Furthermore, Shin et al [24], to conduct simultaneously LCA and LCCA during design stages, required several design documents to conduct the existing two-dimension-based quantity calculations. The authors evidenced that the process requires a large amount of time and errors occasionally result [24]. Case studies analysis conclude that the more complete and complex data structure and information provide, the more difficult to automatize the integration of LCA and BIM.

Table 2. List of LCA-based studies integrated in BIM technology.

References	Year	Design stage	TBL (environmental, economic, social) dimensions of sustainability
Basbagill et al. [34]	2013	Early design stage	Environmental
Peng [55]	2014	Detailed stage	Environmental
Röck et al. [31]	2018	Early design stage	Environmental
Shin et al. [24]	2015	Detailed stage	Environmental and Economic
Santos et al. [56]	2019	Early design stage and Detailed stage	Environmental and Economic
Soust-Verdaguer et al. [54]	2018	Detailed stage	Environmental

Previous research on this field [38] recognized that one of the most important uses of BIM models in the LCA application is to obtain the bill of material quantities. This means that exists a direct relation between the material quantification of the building and the environmental impacts that those materials and process produce. However, regarding the integration of social aspects other difficulties are identified. Specific S-LCA literature [51] recognizes that one of the most relevant difference between LCA and S-LCA is that LCA mainly focuses on collecting physical aspects of a product, and the S-LCA needs to collect additional information about organizations aspects along the chain of production.

Moreover, literature review (see Table 2) evidences the scarce existence of tools or methods, that develop LCA-based studies integrated in BIM technology, nor based on “triple approach” (environmental, social and economic) neither based on the quantification of impacts produced by buildings during their life cycle, that can be used to guide decision-making during the design stages. Considering detected gaps on literature, this paper presents the first steps towards the definition of a conceptual framework based on LCSA of buildings integrated to BIM methodology. The paper proposes methodological considerations to use BIM models to conduct LCSA, by combining LCA, LCC and S-LCA methods.

3. Description of the method

This section aims to provide a general description of the main methodological aspects to be considered to conduct LCSA during design stages of buildings, and a possible workflow. It also aims to identify the main difficulties and challenges towards the interaction of LCSA into BIM methodology.

3.1. Methodological considerations in LCSA

The proposed conceptual method was based on UNEP/SETAC Life Cycle Initiative to LCSA [44], which includes the ISO 14040 phases (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. The approach also complies with the standards on environmental, economic and social assessment of buildings ISO 21931-1 [57] and ISO 21931-2 [58], LCA of buildings EN 15978 [9] and EN 15804 [59], LCC of buildings ISO 15686-5 [60] and UNEP/SETAC Guidelines of S-LCA [51].

Goal and scope definition: Considering previous research on this field [49], the proposed LCSA approach integrated the implementation in parallel of the three methods (LCA, LCC and S-LCA). The use of a “common goal and scope” [44] was proposed. The method considered the UNEP/SETAC recommendation for the definition of a functional unit and the system boundary definition. The functional unit was performed describing the technical utility of the product and the product’s social utility [44]. The system boundary comprised relevant unit processes, at least for one of the methods (LCA, LCC, S-LCA) [44].

Life Cycle Inventory: The inventory analysis phase was supported using the BIM model and the interaction of environmental, economic and social data about the building. Following the recommendations of UNEP/SETAC [44] the LCI “compiles exchanges between unit processes and organizations of the product system and the external environment which lead to environmental, economic and social impacts”. Thus, it was suggested that the “unit process” has a direct correlation between environmental, economic and social aspects, such as shown in Figure 1.

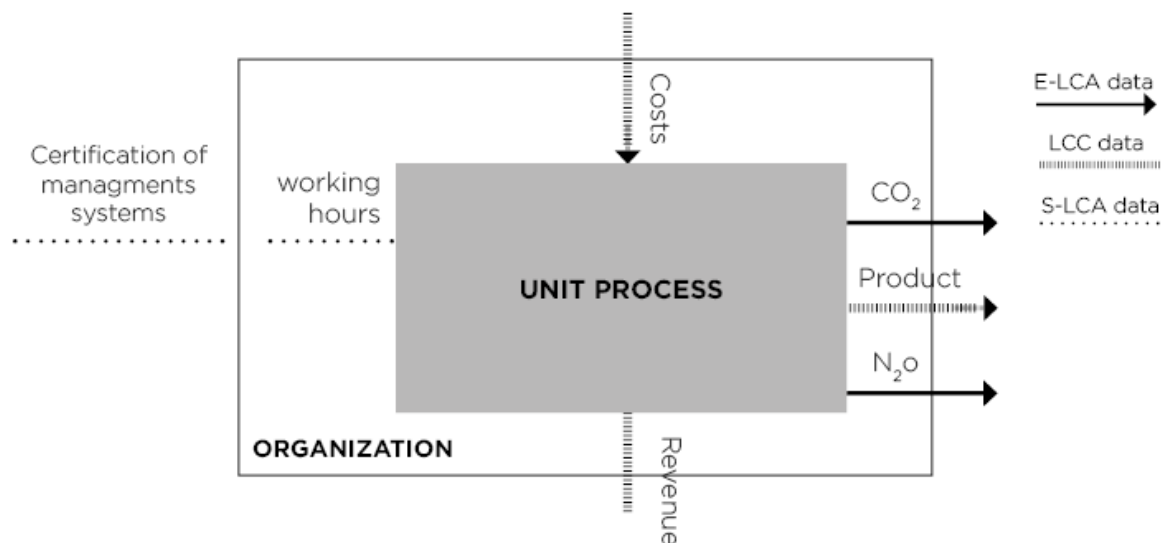


Figure 1 Scheme of the interaction of environmental, economic and social aspects of unit process. (Source: based on [22]).

Life cycle Impact Calculation: The classification and characterization steps were developed following UNEP/SETAC [44] recommendations. Thus, to deal with possible differences in characterization models of impact categories and impacted environments, a combined framework for impact assessment based on the individual S-LCA, LCC and LCA was performed [44].

Interpretation: The method follows the UNEP/SETAC [44] recommendation of combining environmental, economic and social aspects. This strategy can provide designers a sustainable assessment of the building and help decision-making during design stages.

3.2. BIM model to LCSA

The present conceptual framework aims to get the most out of the BIM model (geometry and information) to conduct the LCSA calculation, in order to reduce user manually entering data and reduce effort in data acquisition. Regarding that one of the underlined limitations of BIM to conduct LCA is the limited database [55], the proposed structure integrates a *TBL / sustainability* database about the building with the BIM model. It was founded on previous research [54,61–63] based on the integration of LCA into BIM methodology and the design process of buildings in BIM.

3.2.1 Phases of the method. Following, a possible three steps workflow (see Figure 2) to conduct a LCSA linked to BIM methodology is presented.

Step 1: BIM model. The proposed method started by defining the template, which “helps designers to derive standardized information and outcomes in a consistent work environment” [64]. This step aimed to provide a reliable and normalized structure to build up the BIM model. This step also aimed to provide designers the possibility to integrate different alternatives or scenarios in the model.

Step 2: LCSA calculation. This stage was based on the **interaction** between the **normalized BIM model** with *TBL / sustainability* database, which contains the environmental, economic and social impacts data following the Guidelines of LCSA [44] (Figure 1).

Step 3: Communication of results. This step was focused on the visualization of results, according to a normalized structure which aims to organize results and help designers to optimize the model. To provide an automatic optimization of the BIM model, a simultaneous interaction between the first step and the last one was performed.

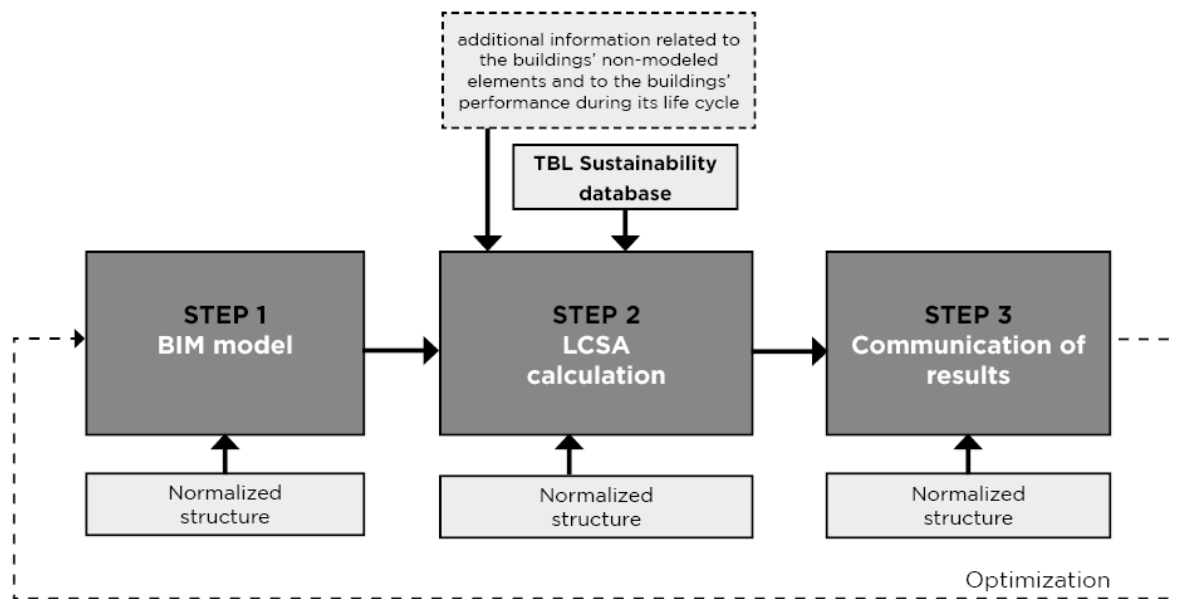


Figure 2. Scheme of the proposed workflow.

4. Discussion

From the literature review and the proposed framework, the following limitations, challenges and resulting research gaps have been detected.

4.1 Limitations on conducting LCI and LCIA

Regarding the integration of the BIM model (bill of quantities) and the implementation of LCI using the structure based on the LCSA unit process approach (Figure 1), it can be problematic in the terms described by Hu et al. [41]. The correlation between environmental, economic and social dimensions of the unit process can neither be linked with the unit process nor with the functional unit [41]. Hu et al. [41] underline that not all the costs (e.g. overhead, profit and loss) can be directly linked with the unit process as well as the qualitative SLCA indicators. The incapability to link the S-LCA assessment to the functional unit is also discussed in the S-LCA specific literature [52]. A possible solution to address the underlined difficulty could be to limit the use of the unit process and the selection of indicators to those that can be integrated in the triple approach (environmental, social and economic), and verified for the case of building design.

4.1.1 Data availability and design-oriented benchmarks. The lack of available S-LCA data is an underlined limitation [47]. Dong et al. [47] propose as a possible solution, to establish a sector-based database of S-LCA, to collect primary data. Moreover, it is also noted that the emerging use of this type of sustainable assessment tools and methods (integrating environmental, economic and social dimensions) can be a powerful tool to improve the performance of buildings, thus the development of benchmarks for guiding designers is recommended. Recent research [116] examines the need of benchmarks and reference values to guide and support decision-making on building design stages. In this sense, the present method also considered the integration of benchmarks and reference values adapted to regional and national scenarios.

4.1.2 Communication of results. The difficulties of integrating environmental, economic, and social aspects in the communication of results were detected. Finkbeiner et al. [65] underline that LCSA requires appropriated multi-criteria evaluation strategies. Life Cycle Sustainability Triangle and the Life Cycle Sustainability Dashboard are proposed as approaches to address this challenge [65]. Thus, it is needed to verify them into building design stages. It is also needed to establish effective strategies focused on helping designer during decision-making.

5. Conclusions

This paper presented the first steps towards the development of a method to automatically perform LCSA calculations during design stages and that uses the potentialities of the BIM methodology to quantify and reduce environmental, economic and social impacts of buildings. In future work, this LCSA framework will be verified in building applications, in order to determine its accuracy and reliability for decisions-making during building design stages.

Acknowledgments

The authors would like to thank the Spanish Ministry of Economy for support the research project (Grant BIA2017-84830-R). The work presented here has a partial financial supporter of the National Research Plan. Thanks to the IEA EBC Annex 72 (<http://annex72.iea-ebc.org>) experts which provided (directly or indirectly) a fruitful input that enriched this study. Also, thank to Prof. Alexander Passer for the rich contributions. The authors acknowledge the reviewers for the constructive suggestions.

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