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Application of building information modelling (BIM) to perform life cycle assessment of buildings

Abstract

The environmental impacts from construction materials are often considered only as resources depletion in the buildings environmental assessment and certification applications. Building materials life cycle is rarely taken into account in such methodologies. That remark can be explained by the limitations of the Environmental Product Declarations (EPDs), which provide environmental information that does not allow direct comparison and choice of construction products. The insertion of Life Cycle Assessment (LCA) data in models developed in the Building Information Modelling (BIM) platform would facilitate the implementation of such environmental assessment quantitative methodology in the construction field. Therefore the aim of this research is a literature review on the integration of environmental assessment studies in BIM platform, so that it becomes possible to predict and assess the potential environmental impacts of construction and technological choices made in the building design phase. An investigative approach on existing applications that enable such integration is developed, especially addressing the inclusion of LCA data in BIM platform. An action research is performed by BIM users, towards the evaluation of the selected applications. The final outcome of this paper is an overview of existing BIM-LCA applications and, moreover, the presentation of the main potentialities and limitations of such applications in order to understand the next steps in the development of new evaluation tools and methodologies.

Keywords

Life cycle assessment. Building information modeling (BIM). Building environmental assessment. Construction materials.

doi: http://dx.doi.org/10.11606/issn.2317-2762.v23i40p96-121

APLICACIÓN DE MODELADO DE INFORMACIÓN DE CONSTRUCCIÓN (BIM) PARA LA REALIZACIÓN DE ESTUDIOS DE EVALUACIÓN DEL CICLO DE VIDA DE LOS EDIFICIOS

Resumen

Los impactos ambientales de los materiales de construcción a menudo se consideran sólo como consumo de recursos en aplicaciones de evaluación y certificación ambiental de los edificios. Su ciclo de vida rara vez se toma en cuenta en tales metodologías. Esta observación puede explicarse por las limitaciones presentadas por las Declaraciones Ambientales de Producto (*Evironmental Product Declarations* - EPDs), que proporcionan información ambiental que no permite la comparación directa y la selección de los productos de construcción. La inserción de los datos resultantes de estudios de Evaluación del Ciclo de Vida (ACV) de los elementos de construcción en modelos desarrollados en la plataforma *Building Information Modelling* (BIM) facilitaría la inclusión de dicha metodología cuantitativa de la evaluación ambiental en el campo de la construcción. Así que el objetivo de esta investigación es examinar el estado de la técnica de la integración de los estudios de evaluación ambiental en la plataforma BIM, por lo que se hace posible predecir y evaluar los potenciales impactos ambientales de la construcción y las elecciones tecnológicas realizadas en la fase de diseño del edificio. Se desarrolla un enfoque de investigación sobre las aplicaciones existentes que permiten a dicha integración, especialmente dirigida a abordar la inclusión de datos de ACV en la plataforma BIM, con la realización de una investigación-acción para la evaluación, por los usuarios de la plataforma BIM, de las aplicaciones seleccionadas. El resultado final del artículo es, además de presentarse una visión general de las aplicaciones existentes, la presentación de las principales ventajas y limitaciones de la aplicación de estudio con el fin de comprender los caminos a seguir en el desarrollo y mejora de nuevas herramientas y metodologías de evaluación.

Palabras clave

Evaluación del ciclo de vida. Modelado de información de construcción (BIM). Evaluación ambiental de edificios. Elementos constructivos.

APLICAÇÃO DA MODELAGEM DE INFORMAÇÃO DA CONSTRUÇÃO (BIM) PARA A REALIZAÇÃO DE ESTUDOS DE AVALIAÇÃO DE CICLO DE VIDA DE EDIFÍCIOS

Resumo

Os impactos ambientais provenientes dos materiais de construção são muitas vezes considerados apenas como consumo de recursos nos aplicativos de avaliação e certificação ambiental de edifícios. Seu ciclo de vida raramente é levado em consideração em tais metodologias. Essa observação pode ser explicada pelas limitações apresentadas pelas Declarações Ambientais de Produtos *Evironmental Product Declarations* (EPDs), as quais fornecem informações ambientais que não permitem a comparação direta e escolha de produtos de construção. A inserção de dados resultantes de estudos de Avaliação de Ciclo de Vida (ACV) de componentes construtivos em modelos desenvolvidos na plataforma *Building Information Modelling* (BIM) facilitaria a inserção de tal metodologia quantitativa de avaliação ambiental no campo da construção civil. Assim o objetivo desta pesquisa é o levantamento do estado da arte da integração de estudos de avaliação ambiental na plataforma BIM, de modo que se torne possível prever e avaliar os potenciais impactos ambientais de escolhas construtivas e tecnológicas realizadas na fase de projeto do edifício. Uma abordagem investigativa sobre os aplicativos existentes que possibilitem tal integração é desenvolvida, especialmente direcionada aos que abordem a inserção de dados de ACV na plataforma BIM, com a realização de uma pesquisa-ação para avaliação de um dos aplicativos selecionados por usuários da plataforma BIM.O resultado final do artigo é, além da apresentação de um quadro geral dos aplicativos existentes, a apresentação das principais potencialidades e limitações do aplicativo estudado, de forma a entender os caminhos a serem percorridos no desenvolvimento e aprimoramento de novas ferramentas e metodologias de avaliação.

Palavras-chave

Avaliação de ciclo de vida. *Building information modelling* (BIM). Avaliação ambiental de edifícios. Componentes construtivos.

1. Introduction

In the last decades, the expansion of environmental concerns led to the consideration of waste emissions and use and depletion of natural resources, which should be incorporated into a more comprehensive environmental assessment framework. In order to evaluate the overall impact of resource consumption reduction measures during the buildings lifetime, the realization of Life Cycle Assessment (LCA) can be a useful tool (VERBEECK; HENS, 2010b). Its principle is to analyze the environmental impact of products or activities, from an inventory of inputs and outputs (raw materials, energy, products, by-products and waste) of a given system (SOARES *et al.*, 2006). At the same time, the complexity of construction products – including materials, systems, subsystems, and the many possibilities of combining them in a building – has created products more complex than consumption goods that were being assessed by the LCA methodology so far (JOHN *et al.*, 2006).

Environmental considerations should be integrated into decisions related to goods and services, and therefore, information related to such activities should be available. When considering the environmental impacts from goods and services it is important to use a life cycle perspective, in order to avoid the transference of issues from one stage of the life cycle to another (FINNVEDEN *et al.*, 2009).

2. Goal

The aim of this study is to develop a theoretical review of the integration of LCA databases within Building Information Modelling (BIM) platform, present some applications currently available for such purpose, and analyze their applicability from the BIM user's perspective, so that it becomes possible predict and assess the potential environmental impacts of technological and constructive choices in the building design phase.

3. Methods

This paper is based on a conceptual theoretical method, once it discusses the theoretical background for the maturity of implementation of LCA and BIM framework, and its main integration applications. A theory is an interrelated set of constructions made up of propositions or hypotheses that specify the relationship among variables. The systematic view may be an argument, a discussion or a justification, which helps to predict phenomena occurring in the world (CRESWELL, 2009).

Moreover such conceptual background is taken as a basis for the development of a new theoretical approach towards the implementation of reproducible LCA data into BIM platform, throughout qualitative discussion and some examples on BIM software tools.

The methodological procedures are mainly aggregated into five main research phases, which are described below:

- Setting the state of the art of LCA data integration within BIM platform through a literature review and discussion of the development and maturity of both methodologies individually, and their integration possibilities;
- Review and discussion of the main applications of both methodologies, and the main stakeholders involved in their development, maturation and use;
- Investigation of the practical possibilities of development of reproducible LCA data and its implementation within BIM platform, using a hypothetical example based on the Autodesk Revit® software interface
- Review of the main existing BIM-LCA integration applications, pointing their key features;
- Action research for evaluation, by BIM users, of a selected application, in order to understand the main contributions and challenges in the implementation of such kind of assessment tool.

3.1. Action research: application assessment by BIM users

Tally™ software was chosen for evaluation, among all presented BIM-based LCA applications due to two main reasons: a) it is one of the few tools that works as a plug-in directly into a BIM software (Revit®) interface without the need to export an IFC file to a LCA dedicated program, b) this plug-in was developed by two of the most important institutions in the addressed knowledge fields – Autodesk® and PE International, providing the software a high visibility and reliability, increasing their chances of spreading.

The software evaluation action research was performed in partnership with an architectural design company, in São Paulo, Brazil, which works mainly in the BIM platform and has a strong interest in applying LCA in the early stages of building design. A workshop was organized along with building designers and architects, comprising 20 BIM users. The plug-in and its features were presented by the researchers and the users were invited to apply the software in a simplified design case study, in order to assess its features, and then answer a questionnaire regarding such experience. The evaluation questionnaire is shown in Table 1.

For each of the questions, it was established the choice among the gradations: bad, poor, fair, good or excellent, always with the possibility of justification whenever the user considered necessary.

The survey responses have been grouped together and analyzed in order to obtain an overview of the users' inborn abilities and limitations observed in the use of software.

This research step provides a deeper analysis of the software usability, as well as the evaluation of the user needs, limitations and preferences in the design process.

Part I: Interface friendliness and Use potentialities	Part II: Interpretation of Results
1. How intuitive is the software operation?	1. What is your previous knowledge about Life Cycle Assessment?
2. The workshop length of time was enough for understanding and using the software?	2. What is your previous knowledge about Life Cycle Impact Assessment methods?
3. How easy is the process of defining the materials in Tally?	3. What is your previous knowledge about the environmental impact indicators?
4. How wide is the availability of environmental data of building materials in Tally?	4. What is your previous knowledge about the actual environmental impact related to the potential impacts addressed by the indicators?
5. What is the requirement of specific knowledge to define materials in Tally?	5. What is the possibility of interpreting the results without specific knowledge in LCA?
6. How agile is the process of defining materials in Tally?	6. What is the potential use of the results for the materials and design definitions?
7. What is the need for use of estimates and approximations in the definition of materials in the software?	

Table 1: Plug-in evaluation questionnaire.
Source: Authors´ elaboration

4. Bim-lca integration

4.1. State of the Art and Maturity

LCA is still a young field mainly developed from the mid-1980s (FINNVEDEN *et al.*, 2009). Regarding its development and maturity, Klöpffer (2006) stated that the LCA has become a widely used methodology due to its integrated way of dealing with issues such as scope, impact assessment and data quality. LCA is applicable to all levels of the system in the construction sector, with two main approaches: a "bottom-up" approach, focused on the selection of building materials, and a "top to bottom" one, which considers the whole building as a starting point for further improvements (ERLANDSSON; BORG, 2003).

LCA has proven to be a very useful tool to assess the overall impact over the life of a building (VERBEECK; HENS, 2010b). From an environmental point of view, such methodology provides inventories of material and energy flows for each system, and allows the comparison of these balances as environmental impacts (SOARES *et al.*, 2006). This allows a scientific assessment, facilitating the identification of potential improvements associated with changes in the different stages of the cycle, which results in an overall improvement in the environmental profile. The life cycle of a building includes the production of materials, construction, operation, maintenance, dismantling and waste management (GUSTAVSSON; JOELSSON, 2010), thus, the LCA methodology can be an important part of environmental assessment methods for buildings.

Ortiz *et al.* (2009) systematically assessed the different uses of LCA for building materials, combinations of components and the entire construction process, and classified the environmental assessment tools on three levels: level 3, compound by methods such as environmental certification of buildings; level 2, which consists of design decisions for the entire building or decision support tools; and the level 1, consisting of product comparison tools, including LCA programs.

The development of LCA studies in buildings requires some adjustments, since engineering projects unlike products with life span of weeks or months, are generally characterized by a lifetime which extends for years, decades or even centuries (SOARES *et al.*, 2006). Due to the relatively long life of the construction products, the assumption of stability over time may also provide highly uncertain results (VERBEECK; HENS, 2010a).

According to Kaebemick *et al.* (2003), the simplified LCA methodologies are very useful tools, in the early design stages, to estimate the environmental impacts of alternative products and to predict the environmental costs or burdens for manufacturers. The author presents a simplification method based on the analysis of complete LCA case studies, and has proposed an environmental performance indicator, using two sets of guidelines based on impacts from energy and materials consumption.

Thereafter Kellenberger and Althaus (2009) performed a detailed analysis of LCA results for building components in different levels of simplification, and noticed that transport and auxiliary materials are relevant for the final results while, in some cases, the construction process and waste from loss can be neglected. It is important to stress that, for some building systems traditionally used in Brazil, such as masonry, the impacts related to losses in the construction process can be quite significant and may not be neglected.

A survey on the implementation of LCA in the assessment of building materials in some of the most traditional environmental certification systems of buildings showed that most of them use the product attributes recognition approach, such as cost, durability, renewability, recycled content, etc. (BUENO *et al.*, 2013a). However, by analyzing the evolution of the LCA application in newer versions of some of these certification systems, it is possible to observe the emergence of the life cycle concept in several evaluative credits (BUENO *et al.*, 2013b; BUENO *et al.*, 2013c).

Among the national studies related to building systems environmental performance it is important to highlight the one presented by Kulay *et al.* (2010), which deals with the life cycle inventory of enamelled porcelain. Another important research regards the production processes of ceramic flooring and bricks, by Soares and Pereira (2004). The aspects considered in the study of Soares and Pereira (2004) emphasizes the environmental quality (externalities) of the production process (the plant), not taking into account the human health and safety, nor product quality aspects (SOARES *et al.*, 2006).

Therefore, LCA is increasingly present in the demands of the construction sector, leading professionals to seek new ways to incorporate such methodology into design and construction processes, the most transparent and simple as possible. A promising possibility currently highlighted is the incorporation of LCA data of construction systems, by functional unit, within BIM platform.

There was a considerable time lag between the emergence of visionary expectations of the transforming potential of BIM platform in the architecture, engineering and construction industries, and implementation of such technology in the daily practice, however, the possibility of the incremental implementation of BIM applications is well aligned with the industrial context (LINDEROTH, 2010). Wong *et al.* (2005) stated that the previous research efforts have mainly dealt with three aspects, including advanced and innovative research technologies, performance evaluation methodologies and investment valuation analysis. The LCA implementation in BIM structure is a mixed field, composed of all three mentioned aspects. Thus, the inclusion of LCA datasets in BIM models can support the dissemination of quantitative environmental assessment for the conscious choice of construction materials and systems during the building design phase.

BIMs are gaining market share and in the near future, they will be used as unique features to enable the full interoperability of data, facilitating the processes in the building life cycle (IBRAHIM; KRAWCZYK, 2003).

Wu and Issa (2012) point to the BIM platform as an enabler for a more viable approach to building management, since the current design practice is laborious and deliveries are based on 2D documents, which are inefficient for use in the building operation and maintenance. The authors show that, as a life cycle information management tool, the following BIM features come to legitimize its application in the commissioning of buildings: a) BIM models are comprehensive and rich in information as they cover all physical and functional characteristics of a building; b) they are able to store, share and exchange data with other applications; c) they are able to perform several complex building analysis and profitability simulations, producing relevant results in standardized documentation format; d) they cover all stages of the life cycle; e) they facilitate collaboration and communication among the design team, working as a central source of information.

Love *et al.* (2014) shows that, for an owner of assets, the implementation of BIM platform should not be seen as a discrete information technology project, but a business change program that can potentially affect the value of the final product. The author acknowledges that such technology alone cannot directly generate business results, but its implementation process, proactively, can ensure that a given organization achieves expected results, with minor variations from the traditional design practices.

Eadie *et al.* (2013) presents a survey of a significant sampling of BIM users in the United Kingdom, from which several conclusions could be drawn such as: a) BIM models are more often used in the early stages of the design process, being progressively less employed in the final stages of completion and construction; b) the most positive impact, according to users, are the expansion of collaborative capacity of the project team, and among the different teams of designers and builders; c) the aspects related to improvements in the design process and the BIM implementation were considered more important than the technology used in the software, so that investment in training and new developments in software were still considered necessary to achieve best practices; d) Finally, users argue that the most benefited by BIM platform are the final customers and the building managers and operators.

According to Leite *et al.* (2011) although the potential benefits of using BIM models are outstanding, there are not many studies that investigate the modelling effort associated with the generation of such models at different levels of detail. This author showed that more detailed models do not necessarily mean more modelling work, whereas such extra effort can lead to higher accuracy, improving decision support during the process of design and construction. The research also showed that the increase in the time demand for modelling may range from doubling the effort up to eleven times, depending on the level of detailing.

Rezgui *et al.* (2013) presents a governance approach for multidisciplinary management of total life cycle data, identifying the main issues of working with BIM, in order to facilitate collaboration on integrated design, for instance, those relating the legal and contractual concerns, such as data security, intellectual property, interoperability, risk allocation, professionals' reliability, confidentiality, etc. The research was conducted at the context of design practices used in the United Kingdom.

Hjelseth (2010) raises the main issues of information exchange between different software based on BIM platform, and how quality improvements of such exchanges could help in the development of integrated design solutions. Among the main conclusions is the need for standardization of information to be inserted in BIM objects, which should be classified as mandatory or optional, according to the determination of the construction industry professionals. In addition, the research also provides guidance for the development of such information, which could still be developed by computer professionals, as long as following the suggested standardization.

In the Brazilian scenario, several researchers have been devoted to the study of BIM platform and its implementation and development possibilities.

Scheer *et al.* (2007) have worked on the investigation of the understanding and use of Information Technology (IT) tools in the Brazilian construction industry, and concluded that a more intensive application of information systems in construction management projects still depends on the solution of quite complex issues. At the design stage, it can be seen the use of IT tools, however, such usage becomes more restricted in the project management stage when personnel technical skills are quite limited and such tools have shown to be inadequate to the technical culture. The author argues that, to overcome such obstacles, a further integration of research groups and companies involved in the projects development and commercialization is needed.

Amorim (2007), through a discussion of international research on the subject, provides an approach of the advantages and difficulties of deploying BIM platform applications in the design process, showing their main benefits and use potential. The author highlights as the main benefits of implementing BIM the early detection of conflicts among projects of different specialties, incorporation of temporal dimension and information on the execution, use and maintenance, integration with suppliers, simulation possibilities and automation of processes in the project, such as quantification, burdens, schedule, cost estimates, etc. As primary challenges are the fact that BIM implementation is a process of innovation that requires cultural changes, personnel qualifications, adequacy and acquisition of equipment and software, and mainly, the reorganization of the design process.

Andrade and Ruschel (2009) developed a preliminary analysis of BIM research production in the Brazilian scenario, in order to summarize the current frame of publications on the subject. It was concluded that the publications on BIM case studies in Brazil are few and still initial, mostly addressing the design process. Regarding the practice at architectural firms, it was found that the BIM design process in Brazil is still an isolated design activity, with a project documents coordination capacity limited to the internal office environment.

Barison and Santos (2010) conducted a survey of the main skills required in various areas of responsibility of BIM experts, such as modeller, simulator, application developer, modelling expert, consultants and researchers, and, finally, the project manager, considered central in the BIM implementation process. The authors outlined that BIM consultants and managers have an important role in the transition from current practice to the use of BIM platform, being the main responsible for its implementation in organizations. The CAD operators should become BIM modellers, thus acquiring new skills and knowledge, however, in most cases, they still tend to resist change and implementation of new modelling practices in the design process.

Biotto *et al.* (2012) reported the main results of a research which investigated the use of 3D and 4D modelling to support decision-making in the management of production systems, by means of case studies in construction companies involved in the residential buildings design development and construction in the city of Porto Alegre, Brazil. The use of 3D modelling facilitated the extraction of materials quantification in order to scale transport capacity required to equipment at the construction site, and the other information in BIM models have proven to be able to help in many other decisions on project management and production process. The main conclusions of the study refer to the benefits of using BIM 4D models in regard to physical arrangement and site logistics decisions, definition of the activities organization in the unit and the definition of enterprise development strategy, which is reflected in the workflows conformation on site. Through the BIM 4D models, the problems in the construction site can be figured out before and during the execution of the project, allowing the consideration of such information for decision making.

According to Succar (2009) the BIM implementation will, undoubtedly, change the components and the relationship among the life cycle stages.

4.2. Integration possibilities and limitations

Regarding the LCA methodology, according to ISO 14044 (ISO, 2006) a full LCA study includes four phases: a) Goal and Scope Definition; b) Life Cycle Inventory Analysis (LCI), c) Life Cycle Impact Assessment (LCIA), and d) Interpretation.

The scope of the LCA study is defined according to its goal and intended application of the results, and it determines, in detail, how the product system should be bordered and which are the core requirements considering the reasons for the study, decision context, intended applications and target audience (EC-JRC, 2010). It is in the scope phase of a LCA study that are determined the different fields in relation to the defined goal as: functional unit, reference flow, system boundaries, impact assessment categories, data quality requirements, special requirements for systems comparison and the need for critical review (EC-JRC, 2010).

Among the challenges of implementing environmental assessment methods based on LCA in the field of construction are the subjectivity and uncertainty inherent to the inventory data collection, the complexity of the functional unit and how those influence the viability of methodology application.

The first challenge is the definition of functional unit that is often hard to be handled in isolation from other building functions in order to evaluate building materials individually. In addition, there are also regional and temporal specificities that make the data collection complex and full of uncertainties (BUENO; FABRICIO, 2015).

LCA studies are often used to support comparisons between different products with similar functions or between different systems that provide the same service. In order to ensure a fair comparison, it is essential that the systems to be compared provide the same function for the user, since it is the main basis of comparison in LCA studies. There is no LCA comparing objects or products, but each LCA should be based on a functional unit, so that different products or services which provide the same function can be compared (EC-JRC, 2010).

Building materials do not usually have the same functions and applications on a building (LEMAIRE *et al.*, 2007). Often there is no clear division of functions and performance among individual technical requirements of a construction product: once the product is part of the building's life as a component, one has to choose to allocate certain flows to the product or the building system (CHEVALIER; LE TENO, 1996). Consequently, it is often not relevant to directly compare the construction products. In order to introduce environmental characteristics in the selection of building materials is often necessary to change the scale of the study: only those elements that have the same functional unit, the same quantities, the same lifetime, and the same technical features may be compared (ISO, 2006).

The comparison of building products with the same functional unit is limited to a few ones. In other cases, building products cannot be considered as alternatives for decision-making. The first set of building products which can represent an alternative to the decision-making problem are the building components. For instance, a wall that can be built with several sets of materials represents a building component, and each wall has the same functional unit. Thus, the building component scale will be the best one for comparisons, in most of the cases (LEMAIRE *et al.*, 2007).

As the purpose of implementing LCA data within BIM platform is providing quantitative environmental information to support environmental prioritizing of building elements or systems, functional unit should be as defined as possible - without losing the precision needed to ensure accurate results. When the functional unit is chosen and set properly, it can be used for the analysis of the same building components in different buildings typologies. Por essa razão, os componentes construtivos devem ser considerados de forma independente (por exemplo, a estrutura independente de vedação, cobertura, piso, etc., como uma função isolada). For this reason, the building components should be considered independently as a single function. Therefore, the potential impact on the lifecycle of any building component should not interfere with other ones (BUENO; FABRICIO, 2015).

Further important points are the geographic, temporal and regional scopes for data collection. Once the functional unit is defined, it is important to ensure that the same scope will be used for collecting data for all the alternatives of building components, especially among those with the same function. For instance, some of the most employed inventory databases can be used, as Ecoinvent (FRISCHKNECHT *et al.*, 2005) and GaBi (IKP-PE, 2002). Even if the both databases provide regional average data and are compatible with GaBi software, they have different scopes and methods for data collection, which can interfere with the final results. At this point, the focus of the discussion is not to determine which database would lead to more reliable results, but to state that the same database must be used within a whole class of building components, to ensure a fair comparison of the systems (BUENO; FABRICIO, 2015).

In almost every case, one or more processes in the product system provide more than one functional output, which can also be named as co-products. Such co-products may not be used for other processes in the same system, but in some other product system which has no relevance to the study. That means that the inputs and outputs of the process should be shared between their products and co-products. The ISO 14044 standard (ISO, 2006) presents a hierarchical pattern of different approaches for solving such problem. The choice is closely related to the modelling principle - consequential or attributional -, and the selection has to be made early in the scope definition, since it has influence on other study information such as the definition of the system boundaries (EC-JRC, 2010).

The system boundaries define which processes or activities (on-site, upstream and downstream processes) belong to the product system, and are required to perform the function as defined by the functional unit. The precise definition of system boundaries is important for the understanding of what the modelled system really is and how it should be interpreted in a broader context. The product system boundaries must be defined so that the flows that run through them are elementary and product flows, i.e. inputs and outputs should be traced back to their way out of technosphere and become part of the environment (EC-JRC, 2010).

4.3. Stakeholders and applications

Succar (2009) divides the structure of BIM platform in three different areas: Policies, Processes and Technology. Each of these areas has different stakeholders according to their definition and products, and some of these players have a central role in implementing the LCA within BIM. The roles played by stakeholders from different areas are delimited according to their expertise and knowledge field.

Regarding Policy field, its stakeholders should be responsible for creating guidelines and standardization for the collection and processing of LCI data and LCA scope definition, focused on the integration and application of such data within BIM platform. Moreover, the players in such field would also benefit from the use of the implemented BIM-LCA application – and data it generates – for the development of environmental performance policies in construction.

The Technology field should be involved in the practical implementation of the LCA data in BIM software. Furthermore, players included in this field would also be responsible for the development and interoperability of compatible LCA and BIM software, enabling the exchange of results.

Finally the most important and central players are those from the Process field, which are directly involved in the daily development of LCA data and BIM models and hence responsible for the practical results. In that field are included professionals from a) Environmental performance, responsible for data collection; b) Suppliers and manufacturers of building components and materials, responsible for providing production processes data; c) Architecture and engineering designers, responsible for the application of LCA data into BIM models and the interpretation of results, and d) Stakeholders and decision-makers, which are responsible for choosing building products based on the results derived by BIM-LCA assessment models. Figure 1 shows a summary illustration of the roles and interrelations among the aforementioned stakeholders.

4.4. LCA data inclusion in the BIM platform

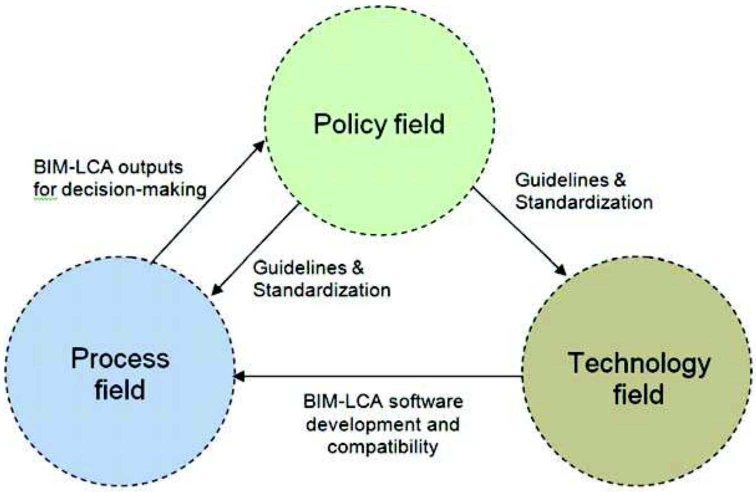
BIM is a set of policies, processes and technologies that, by their interaction, generate a methodology for critical data management of construction design and projects, in digital format, over the building life cycle (PENTTILÄ, 2006).

A BIM framework should be comprehensive enough to address all relevant issues of a building information model. However, at the same time, it must be concise enough to present the main issues systematically. The framework can be drawn so that the practical application effectively incorporate BIM technology in terms of ownership, relation, standards, use in different construction business functions throughout the project, organization and perspectives of the industry (JUNG; JOO, 2011).

BIM models are composed of"smart"objects - unlike CAD entities that comprise only some or no meta-data - (ISIKDAG, 2012) representing physical elements such as doors and columns with encapsulated"intelligence" (FISCHER; KUNZ, 2005).

According to Succar (2009), the implementation of BIM will change the components and relationships among the life cycle stages, their activities and

Figure 1: BIM-LCA Players, roles and interrelations. Source: Authors´ elaboration



tasks. The author sets the life cycle of a building within the BIM platform in three main phases: design phase, construction phase and operational phase.

The BIM implementation begins by deploying parametric 3D software based on objects. In the initial phase, users generate unidisciplinary models in the design, construction or operational phase. Deliveries include architectural design models and production models mainly used to automate the generation and coordination of 2D documentation and 3D visualization. Other results include basic data and light 3D models that do not have modifiable parametric attributes (SUCCAR, 2009).

The historical progress data can be automatically manipulated to produce knowledge for future projects and these expertise applications can be generated and actively used by information built into 3D objects (JUNG; KANG, 2007). This is how the LCA data could be applied, embedded in 3D building objects (Figure 2).

Applying that hypothesis to Revit® case, environmental impact datasets could be found in "Type Properties" menu, using the same interface as the "Analytical Properties", as illustrated in Figure 3.

The environmental data should consider the LCA impact categories and must be displayed as impact potentials in accordance with a given LCIA methodology. Figure 4 uses the Revit® case once more to illustrate how the environmental properties of a building component could be displayed in the software interface.

In this particular case, some of the LCIA impact categories from the Recipe 2008 methodology have been shown as an example of how the user would access the environmental data from construction materials. It is worth

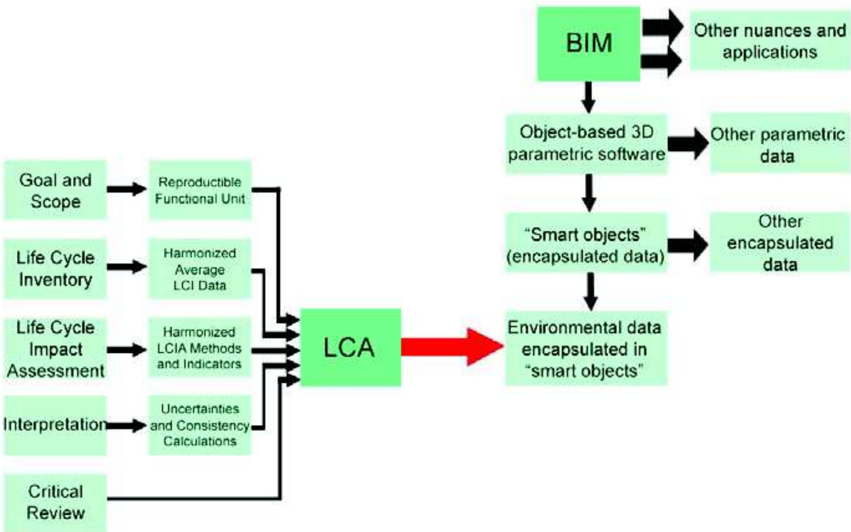


Figure 2: LCA implementation in BIM platform.
Source: Authors´ elaboration.

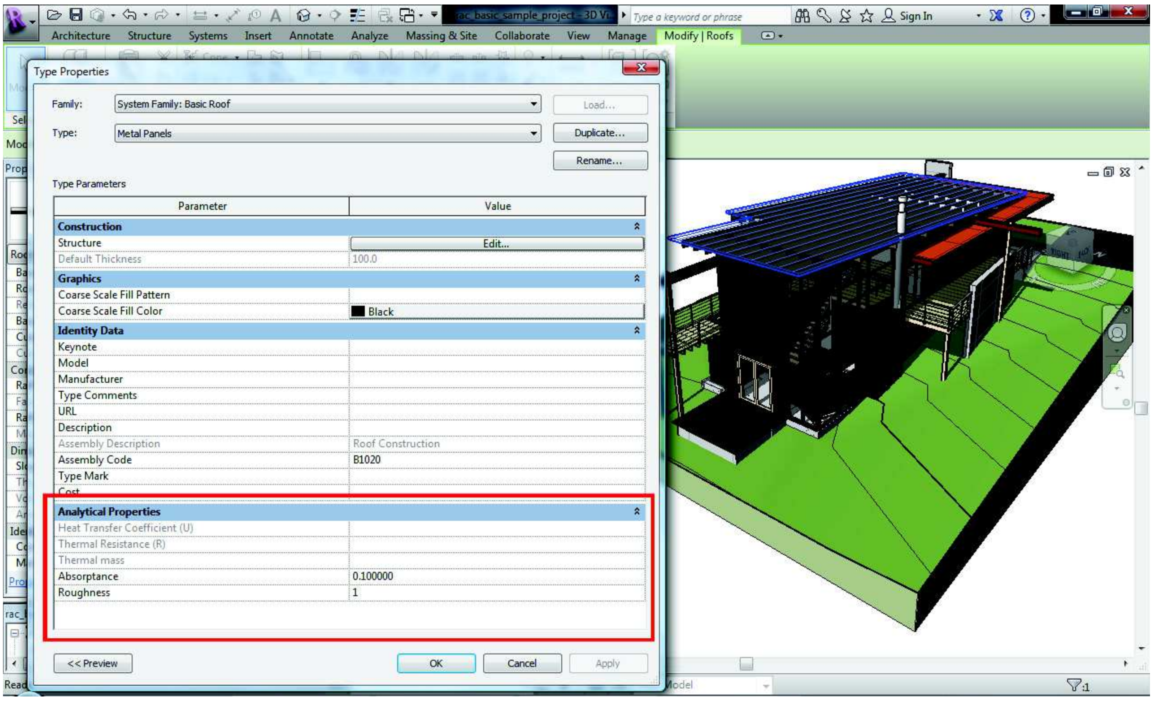


Figure 3: Investigation of the environmental data insertion in the Revit® interface.
Source: Revit Basic Sample Project.

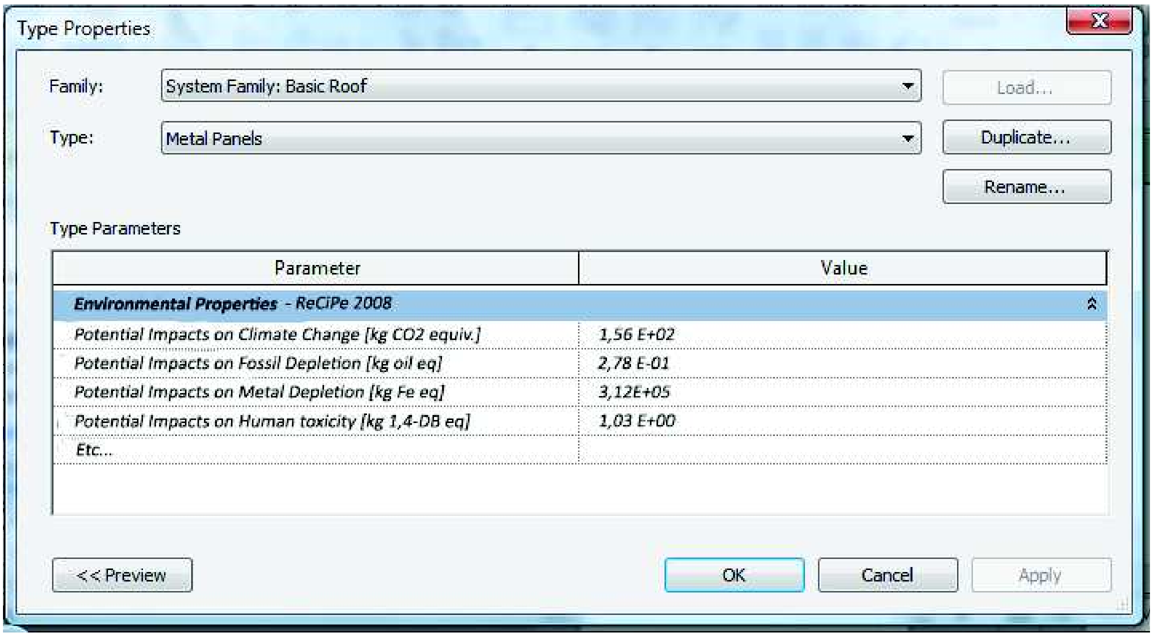


Figure 4: Propositional investigation of the environmental data inclusion in the Revit® interface.
Source: Authors´ elaboration

mentioning that environmental properties must be presented as impact potentials, i.e. after characterization process performed in LCIA phase of a LCA study. This is because the raw inventory data may lead the user - which, in most cases, is not familiar with the environmental impact assessment methods - to misleading conclusions.

A brief explanation is that different substances have different contributions to impact potentials and some of them, in small amounts, may contribute more to a given impact than large quantities of other substances (BUENO; FABRICIO, 2015).

Another important issue to be highlighted, which has already been approached by Monteiro and Martins (2013), is that while the quantification automatic retrieval is one of the potentially most important features of BIM models, a point still quite unexplored concerns how BIM models respond when the quantification becomes its primary use - as it would be in fact in the case of environmental quantities. These authors concluded that, although it is possible to adapt the model to extract quantities according to the specifications, adjustments have implications for other model applications, such as views or drawings, for instance.

Furthermore, when simulating dynamic processes in buildings, data modelling efforts usually require the modelling of construction geometry, its components and the relationships between them, as well as the modelling of the process that is under study. For example, to simulate a building life cycle, the flow of materials and information can be simulated as part of the modelling process, whereas a components model would just need to represent the construction as an artefact (OZEL; KOHLER, 2004).

4.5. Software applications

Some programs directed to LCA studies already have interoperability with BIM platform to facilitate the joint use of both tools. In this section of the paper, some of these applications will be briefly presented, in order to provide an overview of the available possibilities.

4.5.1. Autodesk® Green Building Studio®

Green Building Studio® is a cloud-based software, that allows users to perform energy analysis of complete buildings, optimization analysis of energy consumption and carbon emissions assessment, from the beginning of the design process.

This software is not specifically targeted to LCA studies however it can be used as a support tool for that kind of application.

Among the set of features provided by the software, the following can be found:

- Whole building energy analysis;
- Detailed weather data;

- Support for LEED and Energy Star certifications (the software provides score estimation for LEED rating system according to the performance of the simulated building, and provides a score estimation to obtain the Energy Star label, allowing the comparison of the efficiency of the simulated building against Similar constructions);
- Carbon emissions report;
- Daylighting analysis, which helps in the quantification in order to obtain specific credits in the LEED certification;
- Water use and related costs;
- Natural ventilation potential.

The Green Building Studio® is included in the Ecotect® Analysis software license, which is undergoing a transition process to become an enclosed application with the Revit® software package. Ecotect® Analysis is currently the desktop version of the software, while the Green Building Studio® is the web-based portion. Both programs can share the same gbXML file exported from the Revit® model, or other BIM applications.

4.5.2. Elodie

Developed by the *Centre Scientifique et Technique du Bâtiment* (CSTB), in France, Elodie is a software designed to provide the environmental performance assessment of a building over its life cycle. It is addressed to all stakeholders in the construction sector that seek to integrate those environmental considerations into their analysis.

Several design alternatives can be compared in this application:

- Identification of the building products and building inputs to a certain environmental impact potential and comparison of them with the impacts from the building operation phase;
- Energy performance and optimal environmental benefits assessment among the design solutions and constructive proposals;
- Determination of greenhouse gases emissions over the life cycle of the structure;
- Calculation of waste generation by the building operation over the several stages of its life cycle;
- Assessment and comparison of design options;
- Structural modelling aiming to meet the performance requirements of HQE environmental certification;
- Assessment of the environmental impact potentials from the construction site, as well as from building users transportation;

- Identification of the major contributions to environmental indicators in order to identify leverage points for improvements;
- Conducting simplified LCA study for the building according to the standard EN 15978 (CEN, 2011).

4.5.3. eToolLCD

The eToolLCD (Life Cycle Design) is an open use and web-based software aimed at the design and LCA of complete buildings. This application produces detailed reports with comparable data for environmental performance of buildings, which results are consistent with the international standards ISO 14044 (ISO, 2006) and EN 15978 (CEN, 2011).

To support the ongoing development of the software, any eToolLCD user for commercial purposes needs to "certify" the project. Essentially, this is a pay-as-you-go service on which eTool application provides a third part review of the assessment to ensure that it is completed correctly.

4.5.4. Lesosai

The Lesosai software allows the calculation of the environmental impacts from energy consumption, taking into account all the energy used in the building's operation as well as the impacts concerning energy consumption from the building materials and components life cycle.

This calculation is based on a building life cycle approach which uses the environmental impact indicators comprised in the Ecoinvent database, and the LCIA methodology in accordance with the Swiss standard project SIA2032 (CIS, 2010).

Among the features provided by the software are included:

- Import of XML files, which are usually generated by Autodesk Revit®, SketchUp and Archicad software (the latter two with the use of a plug-in);
- Own database, regularly updated by the producers and suppliers of building materials and components (www.materialsdb.org);
- Basic version of the environmental impacts calculation over the building life cycle, aimed mainly to Switzerland, France, Luxembourg, Italy, Germany and Romania.

4.5.5. LCADesign™ (Ecospecifier)

The LCADesign™, is an Australian LCA modelling software, developed by the National Research Center for Sustainable Built Environment.

The software is presented as a simplified tool for environmental assessment of buildings, which seeks to reduce the modelling time and effort to perform a complete LCA of buildings by using general data for the most commonly employed materials.

LCADetail™ is a subset of the program that is used by GreenTag™ for conducting LCA studies of products. When a LCA is carried out by this application, results output is not only in the form of a report with graphics and mass data tables, but a BIM file of the product impacts over its life cycle, which can be used in LCADesign™ to allow a LCA of a specific product can be performed.

4.5.6. Tally™

The Kieran Timberlake Innovations in partnership with Autodesk® Sustainable Solutions and PE International created this simplified application, which incorporates life cycle data required for analysis in the building design process: Tally™ software is a plug-in within the Revit® software interface. This application seeks the direct integration between LCA and BIM.

Tally™ software allows designers to link BIM elements and building materials to an environmental information database, and generate impact reports. Such reports answer a number of questions asked during the building design phase, including identifying where are the largest environmental impacts and how such impacts can be compared among the different options of materials and in relation to energy consumption operations.

Tally™ enables professionals working with Revit® to quantify the environmental impacts of building materials for the analysis of the whole building, as well as a comparative analysis of design options. While working in a Revit® model, the user can define relations between BIM elements and Tally™ Life Cycle Assessment database materials. The result is the LCA in demand, and an environmental information layer for decision making within the same software, time, pace and environment in which building design is generated.

4.6. Action Research: Assessment of LCA plug-in by BIM users

In order to evaluate Tally™ application, an action research was conducted with a renowned São Paulo building design office and some self-employed professionals, who work mainly in the BIM platform, and demonstrated interest in the application of LCA studies to support design decisions. Altogether 20 professionals from architectural design area and BIM application users participated in this research.

The questionnaire is fully presented in the methodological procedures section of this paper. The percentage grouping of objective responses to the questionnaire are shown in Figures 5 (Part I) and 6 (Part II), and will be discussed below.

Initially we discuss the Part I of the questionnaire responses (Figure 5), which refer to the interface friendliness and application ease of use. The first question, on how intuitive is the software operation, presented divergent responses, ranging from excellent (20%) and fair (80%). Among the justifications for application usage difficulties, the most frequent was the software availability only in English, which would make it difficult, in some cases, the recognition of the technical nomenclature of some building materials and components, and thus the definition of interrelations between construction and environmental databases.

Regarding the workshop duration to be enough for the perfect understanding and use of the software, the main finding of the interviewees was that the 4-hour workshop was enough for the application in a simplified design, but they probably would need more time devoted to the understanding of the plug-in features for application in a more complex project.

The third question deals with the easiness of the process of defining materials in the plug-in, which was considered fair by 40% of respondents and poor by 60% of them. The reasons presented demonstrate that the process itself was not considered difficult or complicated by most users but very laborious and time consuming because the materials have to be defined individually, one by one, in the process of relating materials and environmental databases. For the same reason, the software was classified as

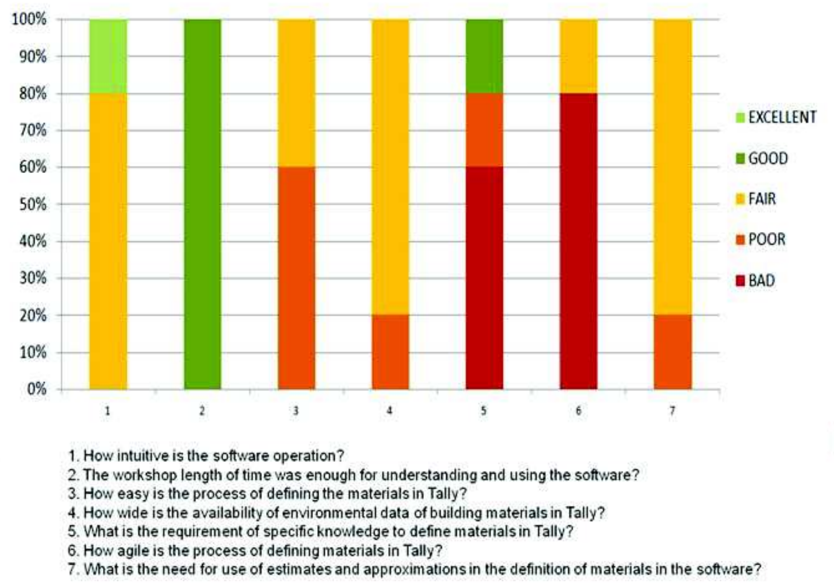


Figure 5: Part I – Interface friendliness and ease of use.
Source: Authors´ elaboration.

bad by 80% of respondents in the question number six, referring to the agility of the materials definition process.

On the availability of environmental data provided by the software, the justification of the respondents to the 80% fair and 20% bad scores, was the fact that the database does not provide environmental information compatible with the Brazilian reality, which would hinder the achievement of more realistic and robust results for such context. However, most of the users recognized that this issue goes beyond the capabilities of the software itself, and runs into the absolute lack of Brazilian lifecycle data availability for the vast majority of construction industry inputs.

Most of the respondents considered that the software requires at least some expertise in LCA to enable the correct definition of materials, adding to 60% of bad and 20% poor responses, demonstrating that users encountered difficulties and felt unprepared to exercise the correlations among databases and their associated specifications.

Finally, on the need for approximations and estimates for use of the software, users considered it predominantly as fair (80%), with 20% of bad scores, mainly justified by the limited diversity of materials available in the software library.

The second part of the questionnaire (Figure 6) is intended to assess the ability of an user - a building design professional, but little familiar with the LCA methodology - to interpret the results provided by the software in order to use such information for decision-making on the specification of building materials and systems in the design process.

The first four questions of the second part of the questionnaire aimed, therefore, to evaluate the previous knowledge of the respondents regarding

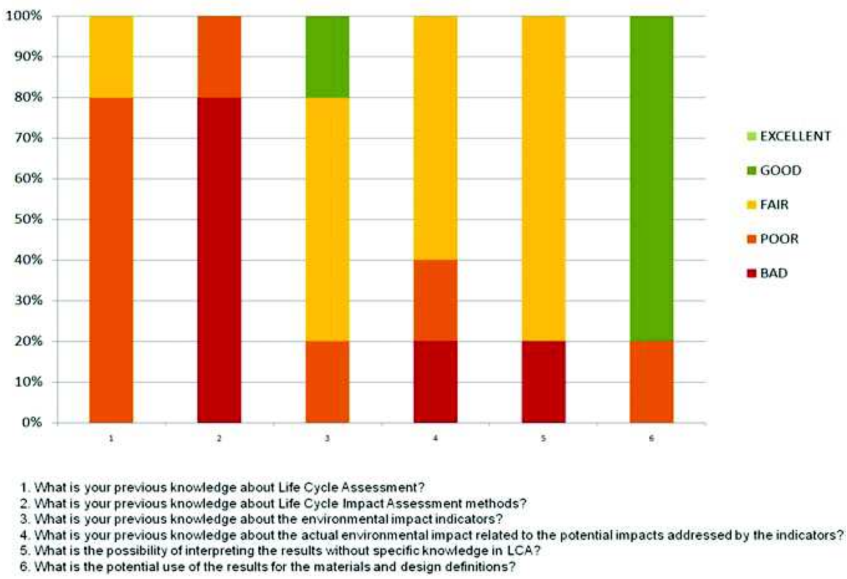


Figure 6: Part II – Interpretation of results. Source: Authors´ elaboration.

the issues related to LCA, LCIA and environmental indicators. What can be noticed when evaluating the answers is that, for all questions, users considered their prior knowledge on the subject between fair and bad, confirming the prerogative that LCA is still a new and relatively unknown field among building designers. At this point, it is important to stress that the participants of this research are part of a still minority group in the Brazilian market, which are already seeking the inclusion of environmental concepts in their designs, but yet, are not deeply familiar with the LCA concepts and methodology.

The fifth question concerns the possibilities of interpretation of the results without prior knowledge of LCA. Respondents considered it massively poor (80%) to very bad (20%). These responses reproduce the difficulties encountered by these users in the interpretation of results, given their shallow prior knowledge of the methodology. Nevertheless, although they have difficulties in interpreting the results, i.e. the output indicators, in the sixth question 80% of the users have stated that the software is good to assist in the decision-making regarding the choice of materials and design settings.

The apparent discrepancy of such latest findings demonstrate that, despite difficulties in the deepest interpretation of the indicators, users feel secure to make decisions based on quantitative assessments. However, in the case of more complex and less obvious results - with different best performance alternatives among the indicators - it is clear that the prior deeper knowledge on the indications becomes necessary so that the user can choose to have the best performance on a selected environmental aspect over another, a very common situation in the analysis of LCA results.

5. Conclusions

The environmental impacts from construction materials are often considered only as resources depletion in the buildings environmental assessment and certification applications (LEMAIRE, 2006). Building materials life cycle is rarely taken into account in such methodologies. That remark can be explained by the limitations of the Environmental Product Declarations (EPDs), which provide environmental information that does not allow direct comparison and choice of construction products. Thus the insertion of Life Cycle Assessment (LCA) data in models developed in the Building Information Modelling (BIM) platform would facilitate the implementation of such environmental assessment quantitative methodology in the construction field.

This article has covered an investigative approach of the possibilities for such integration and the available applications for such purpose, and should be further developed, especially regarding methodologies and scope for LCA inventory data collection and deeper assessment of the main available software, considering the improvement of such applications and the development of new alternatives.

Considering the stage of development and maturity of the two addressed disciplines, it can be observed that both are still rapidly developing and in an initial implementation stage, in which the scoping methods, the development of inventory data and its input mode within BIM platform are still in the early development stage, with no robustly consolidated methodological conclusions. Therefore the integration methods and computer programs presented in this paper are still innovative and quite incipient applications.

The final conclusion of the action research questionnaires discussion, for the evaluation of one of the most prominent applications, the plug-in Tally™, was that despite the simplifications and friendliness inherent to that application, users still have major difficulties not only in the software operation, but mainly in interpreting the LCA results. Such a conclusion shows that, alongside the development of methods and technologies for simplified application of LCA in the design process, it is also necessary to develop education and awareness strategies regarding the LCA concept and methodological principles.

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Author's note

The authors acknowledge FAPESP (São Paulo Research Foundation) for the financial support given to this research under the process number 2013/24046-0.046-0).

Editor's note

Date of submission: 07/29/2015
Acceptance: 05/16/2016

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