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Building Information Modelling for Whole-Building LCA: BIM4LCA

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Abstract. Combining sustainable design strategies and building information modelling (BIM) can change traditional practices and efficiently lead to high-performance designs but is still impaired by deficient software interoperability. Automatic extraction is one of the most cited ways that BIM models can support environmental analyses. However, the reviewed literature does not confirm validation of such procedure by lifecycle assessment (LCA) experts and register incipient procedures to systematically increase implementation of BIM for LCA. This paper explores contributions offered by BIM to facilitate and improve whole building LCA to verify the hypotheses that (1) automatically extracting bills of materials from BIM models with level of development (LOD) 300 positively contributes to LCA processes (BIM+LCA); and (2) embedding environmental parameters and calculations directly into the model to extract calculated impacts instead of pure material quantities (BIM4LCA) can significantly enhance such contribution. We selected one case study to support analysing the variations between baseline (manual quantity survey from design documents) and BIM-supported automatic extraction of bill of materials, and the suitability of the model's LOD to LCA purposes. Revit Architecture 2016 was used for modelling architectural, structural, plumbing and HVAC elements. We demonstrated that LOD 300-modelling is aligned to the accuracy level currently practiced in whole building LCA and that BIM models can indeed be prepared to facilitate LCA (BIM4LCA) through a low complexity, high effectiveness operational measure. This procedure provides reasonably quick feedback to support decision-making and enhance environmental performance of new building designs, until "Extraction, Transformation and Loading" (ETL) technologies or full interoperability become mainstream practice in the AECO industry.

1. Introduction

Strategies outlined for building sustainability permeate different fields of action and involve multiple agents. From the designers' perspective, one of the most important barriers to overcome is the lack of understanding of the environmental performance of solutions as they are incorporated into a project, especially in the early development stages. Limited information available in the work environment and familiar format to the designers prevents the iterations necessary to test and modify propositions until an optimized and satisfactory environmental performance is achieved.

Building information modelling (BIM) is a process of generating, managing, exchanging and sharing multidisciplinary construction information in an interoperable and reusable way [1], which offers benefits in all phases of a project's life cycle [2] [3] [4].

The combination of sustainable design strategies and BIM becomes particularly useful for assessing sustainability aspects and supporting the corresponding decision making during project development [5] [6]), especially with regard to material selection, reduction of material consumption, and increase in recycled content [7], with a significant potential for saving time and resources [8] and to radically transform traditional practices [9].

Life cycle assessment (LCA) is critical to achieving globally set targets for reducing the impacts of buildings. The use of such a procedure in design practice is one of the main missing pieces to enable rapid environmental accountability of design decisions and to guide decision making in the search for advanced solutions. BIM can help and should be explored in this regard.

Currently, LCA faces structural challenges, related to, for example, deficient or outdated databases; lack of appropriate models for impact assessment; and intrinsic uncertainty related to unavoidable normative decisions made along the LCA. Such limitations are out of this paper's scope, as LCA application in building design face challenges of its own.

Despite the widespread acknowledgment that the environmental impacts of a building are mainly determined by decisions made in the initial design stages [10], *if* performed, such assessment usually occurs after building design completion, when changes are expensive and difficult to implement. Improvement opportunities are dramatically reduced. In the event that improvement opportunities are pursued, the lack of interoperability among the different (specialized and design) tools managed over LCA application to buildings impair that the main conceptual benefit of BIM-supported design processes is harvested, that is: design solution optimization after multiple cycles of sharing, quantification and analysis of multidisciplinary information, within a single environment. In traditional LCA, once the objective is defined, the analyst inspects the design and construction documents manually to determine the material inputs, estimate the operational energy consumption, and then transfer them to some specific calculation software [10] [11]. If there are changes to the solution, the material listing must be reprocessed each time, in an obviously labour-intensive task.

As the inventory analysis step concentrates most of the time and effort undertaken in conducting a LCA, tools that automate data collection are particularly beneficial. If the objects that make up the BIM model already contain the necessary environmental information, much of the material data can be exported automatically from the model [12]. This environmental information needs to be taken from life-cycle inventory databases that have been lifted into the evaluation context. This is one of the major limitations intrinsic to the LCA technique and, therefore, outside the scope of this work.

Integration of LCA-BIM would allow to quickly estimate relevant environmental impacts [13] and return this information to the designer to base and refine their material and component specifications iteratively in project development. However, this is still not a feasible practice, mainly due to the lack of environmental information about the materials and components stored in the database; and interoperability between design tools and environmental analysis of buildings [14] [2].

While this ideal scenario does not materialize through programs and/or plug-ins, intermediate solutions can facilitate the environmental assessment process. The simplest of these is the automatic extraction of information from the model, such as quantitative materials, for example. The main impact of the automatic quantitative material extraction procedure occurs at the LCA inventory analysis stage, specifically during the data collection of the building. If there are changes in the project model, the material quantities are updated automatically, without repeating the time-consuming task of collecting data manually from 2D projects.

Despite studies confirming this possibility, when conducting a systematic review of the literature, [15] did not find validation records of this procedure by LCA analysts, and the emphasis of the work remains in the perspective of developments in the BIM realm. To help to bridge this knowledge gap, in this paper we aim at (1) confirming that the level of development (LOD) 300 is enough and compatible with current whole building LCA (wbLCA) practice, in the quest to integrate BIM and LCA, and (2) illustrating how the automatic extraction features of information models can facilitate its accomplishment.

2. BIM and its integration to LCA

3D solid-state building modelling was developed in the late 1970s and early 1980s. The current generation of BIM tools for architecture projects have developed from the capabilities of object-based parametric modelling and were initially developed for mechanical systems. Parametric objects can be characterized as objects that have data and associated rules that compose integrated geometries, without inconsistencies, and that allow automatic modification. They allow different levels of aggregation, and can be linked to or receive, disseminate or export sets of attributes [16].

BIM models can be characterized by the level of development in which they are. The level of development (LoD) describes the minimum dimensional, spatial, quantitative, qualitative, and other data included in a model element to support the authorized uses associated with such LOD's. It is a measure that reflects the maturity of information and its wealth and is present throughout all phases of the project [17].

The American Institute of Architects (AIA) developed its first set of Development Level (LOD) definitions in 2008, which were updated and complemented in 2013 [18]. The AIA's LOD Schema comprised LOD 100, 200, 300, 400 and 500. Each LOD specifies a type of model and the level of information it contains [17], facilitating the exchange of information among the agents involved in the design process. The AIA later on licensed the use of its latest LOD definitions to define the BIMForum LOD Specification (BIMForum, 2017). LOD 350 was added to better address information required for effective trade coordination, whilst LOD 500 was no longer addressed, for being related to field verification rather than indicating progression to a higher level of geometry or information (BIMForum, 2017). According with this updated interpretation of the LOD definitions:

- LOD 100 elements are *not geometric* presentations. They may be symbols or other generic representations of information that can be derived from other model elements. Any information derived from LOD 100 elements must be considered *approximate*.
- LOD 200 elements are graphic representations of *generic placeholders* for volume, quantity, location, or orientation info. Any information derived from LOD 200 elements must be considered *approximate*.
- LOD 300 elements are graphically represented as *specific systems, objects or assemblies:* quantity, shape, size, location, and orientation *can be measured directly*, without having to refer to non-modeled information such as notes or dimension call-outs.
- LOD 350 elements are enhanced beyond LOD 300 by the addition of information regarding coordination interfaces with other building systems. For example, an LOD 350 masonry wall element would include jamb conditions, bond beams, grouted cells, dowel locations, and joints.
- LOD 400 elements are modelled at *sufficient detail and accuracy for fabrication* of the represented component.

The purpose established for BIM models (for example, cost estimation, energy simulation, creation of manufacturing drawings) defines their LOD [18]. Even within the overall aim to support LCAs, a model's LOD may vary depending on the pre-set purpose and scope (Table 1). Similarly, different integration levels between LCA-BIM are possible (Figure 1)), and each one may find its way in serving different design process stages and types depending on the expected LCA feedback.

Table 1. LCA/BIM granularity, LOD and adequate LCI data sources for different life cycle 'assessment snapshots'

Life cycle assessment snapshot [Design process stage (RIBA (2013)]	Concept	Developed Design	Technical design
Level of Development (LOD)	LOD 100	LOD 200 –LOD 300	LOD 300
LCA/BIM granularity [Building, Element, Material]	n.a	Element level – Material level	Element – material level
LC phase included [Product A1–A3, Construction A4–A5, Operation B1–B7, End of life C1–C4]	n.a.	Product LOD 200/300 Construction LOD 200 Operation LOD 200 EOL LOD 100	Product LOD $\geq$ 300* Construction LOD $\geq$ 300/350* Operation LOD $\geq$ 300* EOL LOD $\leq$ 200
LCI data source	n.a	**Background** (contextualized average database) **Foreground** (sectoral (market average) EPDs)	**Background** (contextualized average database) F**oreground** (primary/product-specific EPD)

* benefit of higher LOD still to be validated. At LOD 100, elements are not geometric representations.

3. Method

This study is illustrated by one selected case: a demonstration project with 1,005.21 m^2 (gross floor area) experimentally designed to achieve, at least, the net zero energy status. The integrated design process was guided by high environmental performance targets, such as high level-certification by both US LEED BD+C: New Construction v2009 and Brazilian PROCEL rating system. It also provided experimental support for innovative technologies, including low-energy and resource use optimization strategies, onsite renewable energy technologies and storm water management, low-energy air conditioning system, living roofs and façade, earth construction, online resource use and indoor monitoring, among other best practices. The building's materiality is summarized in Table 2. The building is described in detail by [19].

The research was developed in two parts: firstly, a comparative study between manual quantification processes from design documents (reference) and automatic extraction of quantitative BIM model; followed by an exploratory study to verify the possibility of improvements in the second procedure. The comparative study comprised five steps:

- Analysis of the documentation of the design disciplines considered (architectural, structural, plumbing and HVAC) for the selected case study;
- Definition of the reference quantile (baseline) from the review of the survey done manually by [19] for LCA of the same case study;
- Creation of a model in LOD 300, using the tool BIM Revit Architecture 2016;
- Automatic extraction of quantitative data from the information model (BIM + LCA stage);
- Comparison of the results of the two procedures – reference versus BIM-supported – for quantifying materials; and
- Advanced use of information modelling resources to insert environmental parameters directly into the BIM objects (BIM4LCA stage). The resulting process mapping, in BPMN notation, could not be displayed due to limited paper length.

The assumptions for reference quantification and BIM modelling of the case study followed the standards ISO 14040 [20], ISO 14044 [21] and EN 15978: 2011 [22]. The system boundary for life cycle modelling in this study covers modules A1 to C2, shown in grey in Figure 1. Transport for end-of-life treatment was considered, but waste processing and final disposal were not included in the analysis scope [19].

For the baseline quantification, we reviewed the survey by [19] for the same case study. The inventory analysis consisted of the collection of specific data regarding the study model, taking into

account the established system boundaries. The collection was made from the architectural, structural, electrical, plumbing and HVAC design documentation, which characterized a product somewhere between basic design and construction documents. The portion of elements in each subsystem that could be manually quantified and modelled later on varied across design disciplines (Figure 2).
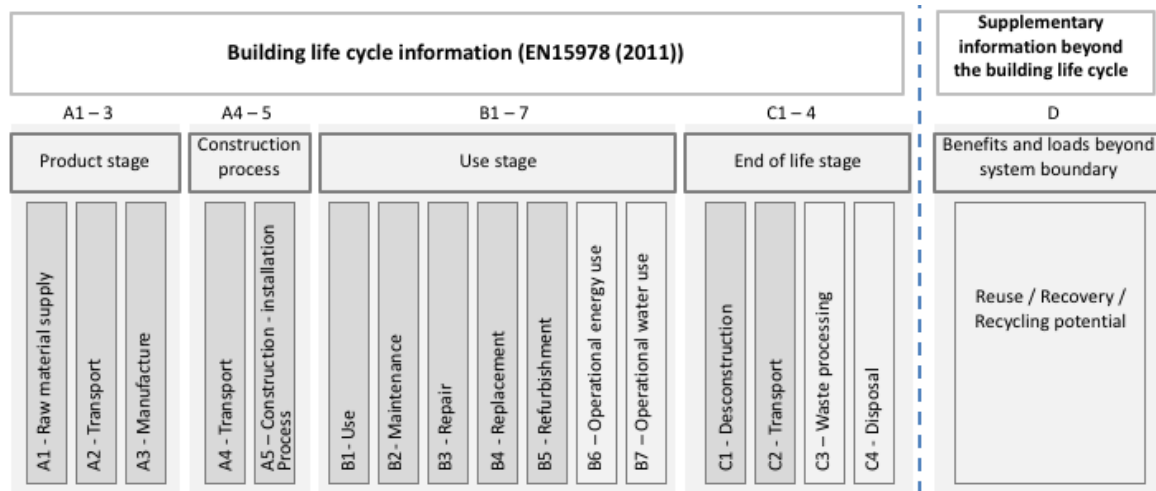

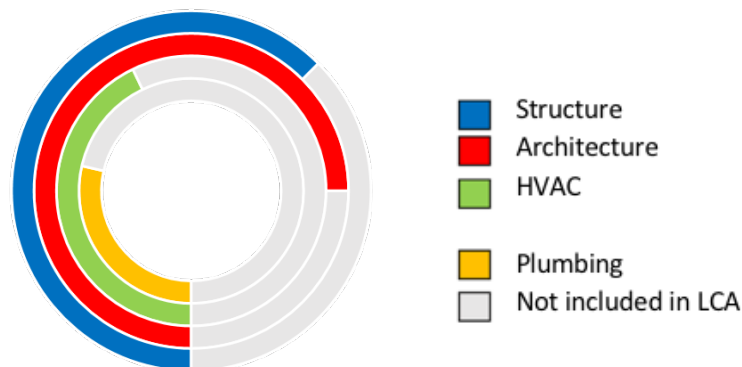**Figure 1.** Life cycle stages within our study boundary.

Figure 2. Share of elements modelled in Revit and considered in the LCA. Adapted from [23]. Elements considered in the manual survey observed the variations indicated in Table 2.

Only the gross building elements were computed: walls (without coatings), floors, structural systems, roofs, doors, windows, plumbing and air conditioning systems. Mechanical and hydraulic equipment, stairs, furniture and floor finishes, as well as items unavailable in the life cycle inventories databases, such as specific wall coatings and flooring systems, or excluded by the applied cut-off rule (<5% of the total impact AND mass <1% of the total estimated building mass), like the reused wood, were excluded.

Autodesk Revit Architecture 2016 supported the information modelling process, which strictly replicated the content, calculation approach and product system adopted by [19], for comparison sake. Even though Revit software allows for detailed modelling of the building elements, the LOD was, in fact, determined by the information available in the project documentation, mostly developed at the basic design level, i.e.: with all its interfaces solved, in order to allow a preliminary evaluation, yet without clear and objective technical information on all elements, systems and components of the enterprise. The structural system modelled disregarded details such as screws and holes at the intersections between metal profiles or the modelling of the building foundations. Similarly, HVAC ducts and plumbing pipes

were modelled with the dimensions specified in the design but excluded connexions. Finally, the electric system was not modelled since design documents only contained memoir and quantitative tables, and lacked graphic description of the corresponding lighting points, switches, switches and electrical wiring. Considering these limitations, all building design disciplines were therefore modelled on LOD 300, ensuring accuracy as to the shape, size and orientation of BIM objects.

4. Results and discussion

For most of the subsystems analysed, automatically extracted bill of materials (BIM + LCA) average values were slightly higher than those calculated by the baseline procedure. This suggests that manual quantification from analogic design documents slightly underestimates quantities, but elements probably simplified or disregarded in the reference survey were captured in the digital model.

Discrepancies relatively to the baseline were acceptable in quantity survey practice (under $\pm$10%) for 84% of the material entries (see Table 2), but predominantly discrete (below 5% for 60% of the items). Notable exceptions referred to the sewage pipes, which showed automatically extracted quantities of PPR (80%) and PVC (29%) substantially higher than the respective baselines. This difference is explained by the nearly absent (sewage) design documentation, which greatly impaired manual quantification. Plastic components can be important contributors to a building's overall environmental impacts and should not be neglected. Sewage elements were then included directly in the model, to fill in incomplete designs blanks, a valuable opportunity that manual surveyors would not have.

Table 2. Automatically extracted (BIM) vs. baseline (manual) material quantification. Positive variation indicates an automatically extracted value higher than the baseline. Adapted from [23].

Subsystem	Item	Unit	Variation BIM/baseline
Structural frame	Steel structure	kg	+3%
	Steel rebar	kg	+5%
	Concrete with cement CPIII-32 fck 30	m3	+1%
	Concrete with cement CPIII-32 fck 60	m3	-12%
Facade	Steel panel	kg	+7%
	Poliurethane	kg	+1%
	Glazing	kg	-2%
Roof	Green roof	m2	-1%
	Waterproofing system	m2	0%
Internal partitions	Gypsum board	kg	+8%
	Wood laminated board	m3	+3%
	Wood	m3	+9%
	Aluminum	m2	-7%
Ceiling	Gypsum board	kg	+9%
External paving	Pervious concrete	m3	0%
Pumping	Copper pipes (domestic hot water)	kg	-3%
	Galvanized steel pipes (water)	kg	-2%
	PVC pipe (water)	kg	+1%
	PVC pipe (sewage)	kg	+29%
	PPR pipe (water and sewage)	kg	+80%
HVAC	Galvanized steel duct	kg	+7%
	Glass wool	kg	+3%
Electrical	Galvanized steel conduit	kg	-4%
	PVC insulation + protection layer for copper wire	kg	+5%
	Copper wire	kg	+2%

It became clear that LOD 300-modelling is aligned to the accuracy level currently practiced in whole building LCA. Information beyond LOD 300 refer to coordination interfaces with other building systems, that were suppressed from the LCA for practicality sake. Unless LCA is so ingrained in the design practice that it is recurrently used to optimize design as it – and its LOD – evolves, it seems unrealistic to assume that information for fabrication (LOD 400) will be available at the time an LCA would be typically carried out. Furthermore, overdetailing the model solely for LCA purposes seems to simply not be worth it at the moment, given the limited inventory data in countries like Brazil, and the (data, model and scenario) uncertainties inherent to LCA elsewhere. Consolidation of the present quest for new purposes for information models that aggregate value to project design, construction and post-delivery phases might be a driver of change in this regard.

Due to the paper length limitation, it is not possible to detail the object parameter edition (BIM4LCA mode) and also include the BPMN process maps contrasting the baseline and BIM-supported LCA procedures. Those maps showed that whilst the agents involved remain unaffected, the main alterations occur in the design process itself and in the data collection procedure for LCA, basically in activities rearrangement and in addition/modification of the information exchanged. Inserting new object parameters which embed different environmental categories impact coefficients and directly calculates impacts on the BIM platform itself eliminates steps and interfaces found in the conventional evaluation. The model can be generated in accordance with the goals and objectives of the LCA, previously established from design outcome. Integrated project team work adds to automatic data extraction to make LCA more accurate and consistent.

Although the case study served well the purpose to verify the LOD compatible with a wbLCA, the fact that only one building was used to illustrate and support our analyses is a limitation of this study. For the case studied, total time for model preparation and extraction of impact listings was equivalent to the time needed for manually surveying materials and carrying out the LCA. However, LCA specialization demand changed, with more objective participation of the LCA specialist. More practical examples would be useful to produce robust inferences of the time and effort balance.

5. Conclusions

In this article we have demonstrated that LOD 300 is compatible with the level of accuracy currently practiced in whole-building LCA. It is possible that lower LODs can be worked on in design and preliminary study steps, but this assessment was not part of the scope of this article. However, the need to employ higher LODs is less likely, but may be useful for carrying out, for example, a detailed environmental audit of a specific project, guided by information inputs that best describes it.

Automatic extraction of material quantities from the BIM model indeed saves time and data collection effort and reduces risk of errors relatively to the manual process, without obstructing the design process. Preparing the model to facilitate LCA (BIM4LCA mode) enables automatic extraction of impact listings rather than a mere bill of materials. Though operationally simple, this procedure provides rapid feedback – albeit unidirectional – and supports more robust decision making regarding environmental performance of buildings, while complete interoperability or even the use of ETL technologies do not become common practice in AECO.

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