Investigating the effectiveness and robustness of performing the BIM-based cradle-to-cradle LCA at early-design stages: a case study in the UK

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Abstract

Life Cycle Assessment (LCA) has been used to provide a 'roadmap' for a building design to mitigate their adverse impacts on the environment. Due to the increasing trend of using Building Information Modelling (BIM) tools in the building design and construction industry, integrated BIM-based LCA approaches have gained importance in early-design stage decision-making processes. However, the ability of these tools to seamlessly integrate into the building design process remains a gap in the field. This paper aims to address this knowledge gap by proposing and applying an evaluation framework developed to assess current integration practices within the workflow of an LCA plugin for BIM; eToolLCD.

Therefore, an educational building case study in the UK was used to compare assessment results from both conceptual and detailed-design stages produced using eToolLCD to those produced through a 'traditional' LCA approach using SimaPro8. The scope in both approaches considered solely the vertical envelope of the building within a cradle-to-cradle system boundary. Findings from the comparison of both tools highlight that the minimum difference was around 8% for the Global Warming Potential impact category while significant variations were detected for other categories. The outcomes of this study are expected to primarily contribute to identify main opportunities as well as potential technical challenges and limitations of the implementation of the LCA-based plugin and ultimately the proposal of potential future development routes.

Introduction

Significant amounts of energy and material consumed within the architecture, engineering, and construction (AEC) sector account for 36% of global energy use and nearly 40% of total direct and indirect CO_2 gas emissions; thus, notable efforts to reduce these have been made. As a green building strategy, the evaluation of the environmental impacts of buildings in the context of lifecycle thinking emphasises the importance of the role of Life Cycle Assessment (LCA) in building design. LCA, widely adopted and preferred decision support tool, evaluates energy-related and environmental loads of activities and processes within a defined building system (Cavalliere et al., 2018; Asdrubali et al., 2013).

Within the context of buildings, the implementation of a detailed LCA is complex due to the long lifespan of the building materials and the intricate networks of materials embedded in different building layers in each life cycle stage of the overall building. As such, the majority of studies in this field have mainly focussed on on a specific stage, such as the production of materials, construction, and building operation rather than the whole lifecycle. Furthermore, several studies have specifically addressed a single impact category with a particular focus on energy and carbon-related assessments (Hossain and Ng, 2018; Koezjakov et al., 2018) rather than more comprehensive impact assessment categories.

In regard to scope, several studies have been conducted under the 'cradle-to-grave' system boundary. This is defined in the ISO14040 series and addresses the impacts from the raw material acquisition stage to the end-of-life (EOL) stage. However, this model excludes the potential of building materials beyond their EOL, where they become construction and demolition waste (CDW), and therefore limits the comprehensiveness of LCA. To evaluate the potential recovery opportunities from CDW and assess impact of alternative disposal and treatment routes within the context of the closed-loop examination, a new system boundary known as cradle-to-cradle (C2C), covering reuse, recovery, and recycle (3R) potentials of the materials, has been proposed (Ng and Chau, 2015; Silvestre et al., 2014).

Early design stages are critical to minimise impacts of buildings through their whole lifecycle. However, the continuous design changes that may occur at early-design stages, present a particular challenge for conduction of traditional LCA studies given time and resource constraints (Basbagill et al., 2013). Building Information Modelling (BIM) has been investigated a possible means by which to address this issue and assist in the decision-making process in the assessments (Anton and Diaz, 2014; Najjar et al. 2017; Bueno and Fabricio, 2018; Santos et al., 2019). While some of these integrative strategies have proven useful and resulted in a growing range of commercial tools, a few limitations still persist linked to technical problems such as interoperability issues and a lack of efficient data exchange, as well as socio-economic factors, such as knowledge gaps in the correct applicability and interpretation of results.

Therefore, the seamless integration workflow between these tools remains a gap in the field (Wastiels and Decuypere, 2019; Cavalliere et al., 2019; Bueno et al., 2018; Peng, 2016). To address this gap, this paper presents a framework for the evaluation of one of the current integration practices within the workflow of an LCA plugin for BIM; eToolLCD. The work focusses on the investigation of technical challenges as well as formulating further development pathways towards achieving seamless integration.

BIM-based LCA integration strategies and studies

Numerous studies have focused on the integration between BIM and LCA tools with the aim of reducing the time spent for inputting data and performing multiple analyses in early design stages. While several strategies have been developed, there are still various difficulties to overcome, and further exploratory studies are therefore needed to formulate an effective and seamless integration workflow (Santos et al., 2019). In the literature, three main approaches to the integration practices are defined; (i) using variety of software programs to conduct assessments, (ii) linking the bills of quantities generated by BIM software with a tool in which embedded life cycle inventory (LCI) database, and (iii) including the environmental properties in the BIM objects (Zuo et al., 2017; Anton and Diaz, 2014; Basbagill et al., 2013). In reference to these approaches, Wastiels and Decuypere (2019) describe five different strategies, defined through reviewing existing tools and analysing feedback from experts. Table 1 briefly explains the key features of the strategies, which are analysed below.

Table 1: Different strategies in the integration workflow (Wastiels and Decuypere, 2019)

1	**Bill of quantities (BoQ) export:** Extraction of BoQ from BIM to the external LCA software. - Manuel link, data intensive traditional LCA - Unsuitability to iterative design process
2	**IFC import of surfaces:** Extraction of BIM model including geometry and material quantities to external LCA software via IFC file format -The imported data includes geometric parameters and material specific information -Suitability to iterative design process
3	**BIM viewer for linking LCA profiles:** Data extraction via IFC file to BIM viewer to attribute LCA profiles in there. Then the data sent to the LCA software. - LCA data attributed in 3D model - The link can be maintained for further process
4	**LCA plugin for BIM:** Direct link to LCA profiles and calculations via plugin - Automatic link, time-efficient, instant results - Open for the developments
5	**LCA enriched BIM objects:** LCA information included in BIM objects, the analysis can be done via plugin or external software with extracting data -Automatic/semi-automatic link - Real-time information -High potential to centralise all the data within the BIM objects

Strategies 1, 2, and 3 have a number of disadvantages including interoperability issues between different programs, license costs and time requirement for the whole process, which limits their future applicability. In respect to the future applicability, strategies 4 and 5 are considered promising workflows based on their potential for open development; however, dependency on the availability of LCA data in plugin/software is a major drawback as this can result in significant variations in the results.

Strategy 4 based on specialised BIM-plugins is evaluated as a 'black-box' assessment, the current developments and considerable works on its assessment possibilities makes Strategy 4 as one of the most cutting-edge integration pathways (Bueno and Fabricio, 2018). Strategy 5 can assist in the maximisation of the potential of BIM through the provision of useful information for the assessments. As such, several researchers in the field have identified it as the target level that is needed rather than focusing on the development of new plugins required to support Strategy 4 (Santos et al., 2019; Anton and Diaz, 2014) instead of focusing on development of new plugins as Strategy 4 (Soust-Verdaguer et al., 2017). However, in the context of continuous design changes, strategy 5 may involve a more laborious process in which users have to change BIM objects in the model rather than changing the LCA profile in the LCA software.

Recent studies mostly have focussed on strategies 4 and 5. A study by Santos et al. (2019) presented a BIM-LCA/LCC framework to perform LCA and LCC analysis within a BIM-based environment via IFC4 schema and explored the information exchanges and process for the proposed framework. The authors highlighted that the current IFC4 schema needs further development to support a complete LCA. Another study by Mora et al. (2018) tested two BIM-based plugins, Tally and One Click LCA, using a small residential building for comparing the results. This work emphasised the importance of the identification of materials which is associated with database quality and availability in plugins, and the congruence of information between the tools. The results from both tools show considerable variations mainly due to the regional context of LCI databases and different material selections and calculations in each tool.

Similarly, Kose (2018) compared Tally and One Click LCA in a hospital building. In this study, the significance of semantic detail level of BIM models during the data extraction was highlighted to prevent possible faults on data mapping process. The comparison of results here also showed that different environmental impact values were obtained from tools due to variations in methodologies; however, the BIM-based LCA workflow was more accurate and promising in terms of reducing data loss and time spent during the data extraction, compared to the traditional LCA process. As a further example of using Strategy 4, recent studies (Röck et al., 2018; Bueno et al., 2018) developed an automated link between Revit and MS Excel worksheet via Dynamo interface, linking manufacturer-based LCA information with BIM objects to assist decision-making process at early-design stages. While the performance of the workflow produced satisfactory results at those stages, common data structure and naming convention had to be specified to complete data exchange. Moreover, the workflow considered not be suitable for detailed-design stages due to the requirement of reproducing the nodes in Dynamo for different subcomponents. Another study by Najjar et al. (2017) evaluated the performance of Tally, and highlighted the necessity for further developments in the automated data extraction process to avoid the need to redefine the materials in each analysis.

In expanding and complementing this work, this research focusses on evaluating the effectiveness of using BIM-based LCA tools to early-design stage assessments with the aim of assisting the decision-making process by simplifying the implementation process.

Methodology

This study concentrates on the investigation of the effectiveness of using eToolLCD, a web-based commercially available LCA tool developed by two engineers (eToolLCD, n.d.), for LCA of buildings at early-design stages. In accordance with LCA methodology, this study proposes a framework to test the tool's effectiveness and robustness by comparing it with a 'traditional' LCA processes. For the purpose of this study, effectiveness is defined as the ability of the tool to provide accurate enough results; robustness means that the data transfer from BIM to the tool is free from errors, and the ability of the tool in obtaining some hotspots of the process as well as providing some meaningful results. A case study approach was therefore adopted to undertake a comparative analysis of both conceptual and detailed-design stages assessment results produced using eToolLCD and a 'traditional' LCA approach using SimaPro8, a commercially available LCA software developed by PRé (SimaPro, n.d.). The LCA in both approaches was performed within the cradle-to-cradle system boundary. Table 2 shows the LCA modules considered in this study.

Table 2: Included LCA modules (EN 15978:2011)

Product Stage	A1 A2 A3	Raw material extraction Transportation Manufacturing
Construction Stage	A4 A5	Transport to the site Assembly/Installation
Operational/Use Stage	B1	Use
	B2 B3 B4	Maintenance Repair Replacement
	B5 B6 B7	Refurbishment Operational Energy Use Operational Water Use
End-of-Life Stage	C1	Deconstruction, Demolition
	C2 C3 C4	Transport to waste site Waste processing Disposal
Beyond the System boundary	D1	Recycling
	D2 D3	Reuse Recovery
Included stages highlighted in grey		

As described below, the case study was a higher education building and the study period was defined as 75 years (Grant and Ries, 2013). The functional unit for the analysis assessed the environmental impacts of the vertical building envelope per 1 m^2 gross floor area over the 75-year period. CML-IA impact assessment methodology was conducted including the following categories; global warming (GWP100, kg CO_2 eq), ozone layer depletion (ODP, kg CFC-11 eq), photochemical oxidation potential (POCP, kg C_2H_4 eq), fossil resource abiotic depletion (ADP^1, MJ), mineral resource abiotic depletion (ADP^2, kg Sb eq), acidification potential (AP, kg SO_2 eq), eutrophication potential (EP, kg PO_4---eq), ecotoxicity potentials (kg 1,4-DB eq) for freshwater (FAETP), marine aquatic (MAETP), and terrestrial (TAETP), and human toxicity potential (HTP, kg 1,4-DB eq). However, FAETP is not available in eToolLCD, and MAETP, TAETP and HTP are based on Australian Indicator set with different units (uDAY, uDAY, and uDALY, respectively).

Study Design

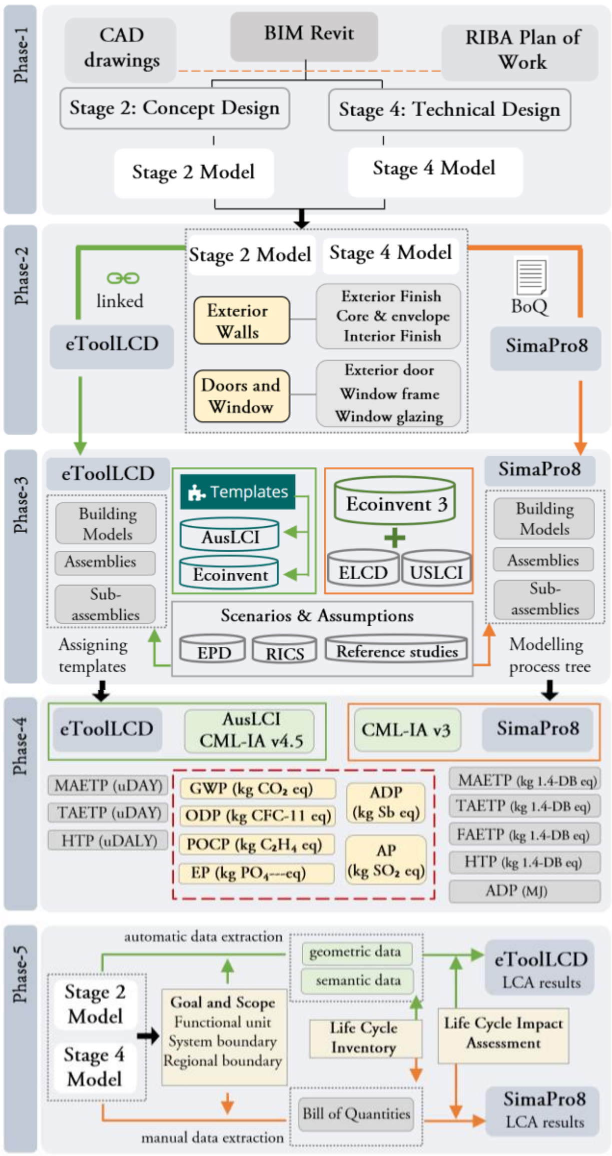

Figure 1: Schematic workflow of this study

The proposed framework was based on five-step approach. Figure 1 illustrates the schematic workflow of this study.

Phase-1: The selected case study building was modelled as two different versions to meet the requirements for Stage 2 and Stage 4 models within the RIBA Plan of Work 2020.

Phase 2: The scope of the study was specified, building elements and components to be included in the study were defined. Bill of Quantities (BoQ) was extracted from Revit as preparation for manual input process for SimaPro8. Both models were linked with the prepared project templates in eToolLCD.

Phase 3: Based on the specified building elements, the predefined templates in eToolLCD were modified to match the building components, then assigned to the imported Revit components. According to the BoQ, two different process trees including all assemblies and subassemblies were created in SimaPro8 for both models.

Phase 4: For both tools, the CML-IA baseline impact assessment methodology was chosen. Because the conversion factors for the units of MAETP, TAETP, and HTP could not found, they were not included.

Phase 5: The strengths and limitations of eToolLCD were defined by evaluating its workflow.

Case Study Building

The case study building was selected from the higher education non-domestic stock. This sector is considered to be one of the major contributors to the UK's total emissions (HESA, 2013), where few studies have been conducted within the LCA context (Hossain and Ng, 2018). The scope of this study is limited to assessing vertical envelope of the building (external walls, windows and external doors), and the building had recently undergone a deep-retrofit process. Thus, impacts from operational energy and water use (B6, B7) were not considered, and new refurbishment interventions (B5) were not included within the specified 75-year lifetime study scope. The building consists of 6 storeys and a basement with total 9951 m^2 gross floor area. External walls were cladded by facing bricks and installed to the existing concrete frame by steel framing system (SFS). The building façades each include different glazing ratios which range between 17.5% to 52% of each façade area.

Case Study Modelling Process

In accordance with the RIBA Plan of Work (2019), two different Revit models of the building were developed to represent the conceptual design (Stage 2) and detailed-design stage (Stage 4) models. For the Stage 2 model, a conceptual massing model was developed to allow data extraction through the eToolLCD. All the vertical surfaces of mass instances were converted to building elements and components. Figure 2 illustrates both Stage 2 and Stage 4 models of the building. In regard to level of details for the models, as the Stage 2 model represented the simplified version of the actual building, aluminium panels were not modelled. One size of aluminium mullion and major external wall types used in the building were applied to simplify the modelling process. The Stage 4 model represents more detailed version of the building. Table 3 shows the main differences between the models in regards the bill of quantities.

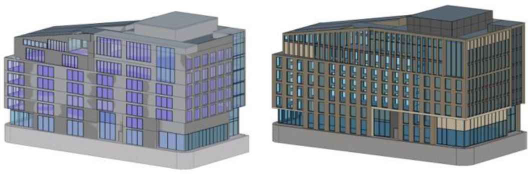

Figure 2: (a) Stage 2 model, (b) Stage 4 model

Table 3: Main differences between the models

Building Elements and Components	Stage 2	Stage 4	Difference
Gross Floor Area	9951 m^2	9951 m^2	0%
External Wall Area	3474 m^2	2876 m^2	19%
Window Surface Area	791 m^2	824 m^2	4%
Curtain Wall Panels			
IGU panels	654 m^2	607 m^2	7%
Aluminium mullions	511 m^2	412 m^2	21%
Aluminium panels*	-	1327 m^2	200%
GRC panels	-	151 m^2	200%
External Doors Surface Area	37 m^2	37 m^2	0%
**Aluminium sill and reveals are also included in this category*			

Scenarios and Assumptions

In accordance with the default scenarios for UK projects specified by RICS (2017) for transport to the building site and scenarios for waste processing proposed by Rose (2019) based on the existing waste management logistics in the UK, Table 4 shows the transportation inputs for main materials in both tools.

Table 4: Transport Scenarios

Materials	A4 (km by road)	C2 (km by road) *		C2 (km by sea)
Insulation	300		100	-
Gypsum, GRC unit	300		100	-
Metals, Plastics	300		25	200
Glazed units	300	25	25	200
Bricks, tiles, ceramic	300		100	-
Concrete, mortar	50		100	-
* transportation for both waste sorting and processing site				

For the allocation for waste treatment of each materials, Table 5 shows the defined scenarios for main materials in both tools. For operational stage inputs, high maintenance scenario and longer service life were assumed; thus, annual cleaning for glazing unit, and aluminium frame and mullions was assumed. Service life of glazing units, aluminium frame and mullions, and gypsum plasterboard were assumed to be 45, 80, and 50 years, respectively. Replacement of weather sealings over 20-year periods were considered (Carlisle et al., 2015).

Table 5: Waste treatment scenarios for main materials

Materials	Recycling	Landfill	Ref.
Mixed Plastics (PE, PP, etc)	46.2%	53.8%	1
Steel - Iron - Aluminium	92%	8%	2
Concrete *	90%	10%	2
Reinforcement steel	92%	8%	2
Concrete hollow blocks *	90%	10%	2
Brick *	90%	10%	2
Glazed unit *	90%	10%	2
Rockwool *	75%	25%	2
Insulation (EPS) *	46.2%	53.8%	1
GRC units *	90%	10%	2
*eToolLCD does not allow to assign recycling rate for them			
(1) DEFRA, UK Statistics on Waste 2019, (2) EPD documents			

Traditional LCA Approach

Figure 3 illustrates the schematic overview of the traditional approach taken in this study.

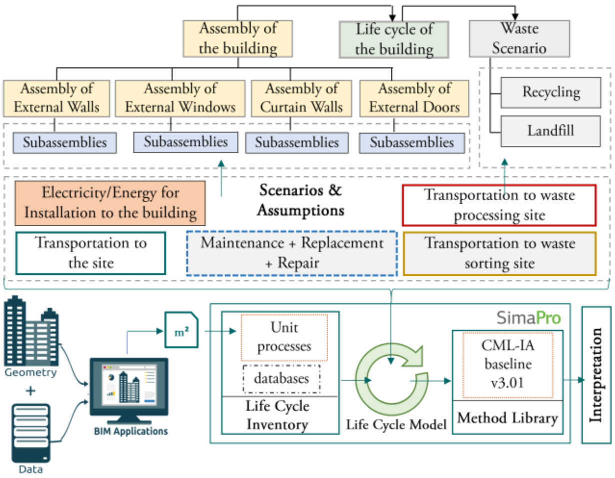

Figure 3: Schematic overview of the SimaPro workflow

In this study, SimaPro 8.0.3.14 Faculty license was used. The workflow in this approach starts with an inventory of the building materials based on the BoQ, then follows the modelling of a process tree in SimaPro. This model describes all the relevant processes within the building lifecycle defined in the study scope. The remaining part is based on manually linking the building components with predefined materials and/or processes in the LCI datasets. Within the regional context, LCI data for the materials were mostly based on the Ecoinvent 3 library. The USLCI library was used for some materials (cold/hot rolled and galvanised steel, etc.) due to the lack of a better option in Ecoinvent 3. The workflow was based on creating a process tree for the building and manual data input according to the BoQ of materials.

Integrated BIM-based LCA Approach via eToolLCD

Figure 4 illustrates the schematic workflow of eToolLCD. In this study, eToolLCD Researcher Subscription was used for the analysis. This process depends on linked Revit model elements and components with eToolLCD Templates. This includes a high level of detail, inputs and assumptions and provides a transparent and user-friendly data arrangement process. Users need to match their model specifications to the corresponding templates. The template also allows users to make modifications to create the best matching options for model elements and components (Hermon, 2019). For example, although the material in the selected template has been calculated in a different size or quantity than the building element in the Revit model, the quantity and/or size of the material can be adapted based on the BoQ in the model.

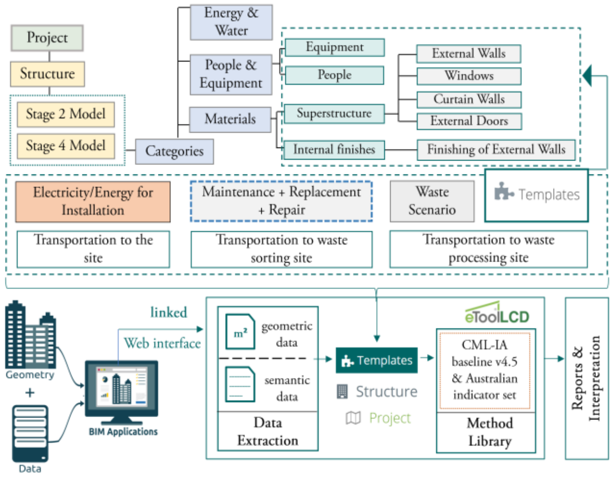

Figure 4: Schematic overview of eToolLCD workflow

Figure 5 shows an example for a Template system.

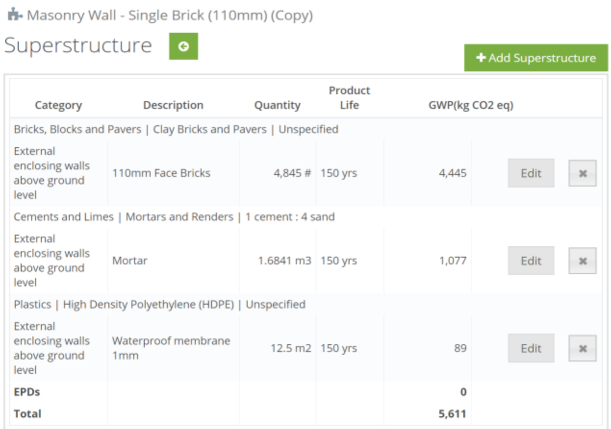

Figure 5: Example of eToolLCD Template

Results and Discussion

The results from both Stage 2 and 4 models were produced by each tool separately, then, a comparative analysis was carried out. To find out how the study results differentiate from the closest examples of case studies, studies conducted by Junnila (2003) for three office buildings were chosen based on their suitability to the scope of the study. However, it is worth mentioning that the comparison of the studies using LCA is in general literature considered to be problematic as the analyses are performed using different tools and methods, and based on regional variations (Hossain and Ng, 2018).

SimaPro Results

The overall LCA results of both models for all impact categories are given in Figure 6. The results indicate that both models had relatively close results with a maximum 17% difference for GWP, AP, ADP[1], and POCP impact categories. Whereas the minimum difference (10%) between the models was found in AP and ADP[1]. The most significant variations were found to be MAETP (-206%), then following by in FAETP (63%) and HTP (51%). Overall, the Stage 2 model was more 'impactful' in LCA terms than the Stage 4 model for all impact categories except ADP².

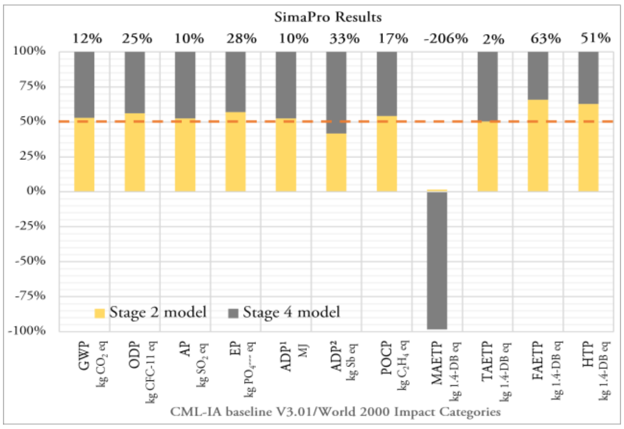

Figure 6: SimaPro Results

In an aim to understand the reasons for differing degrees if variation and agreement in the results, a more in-depth analysis focussing on the life cycle stages was undertake (Figure 7).

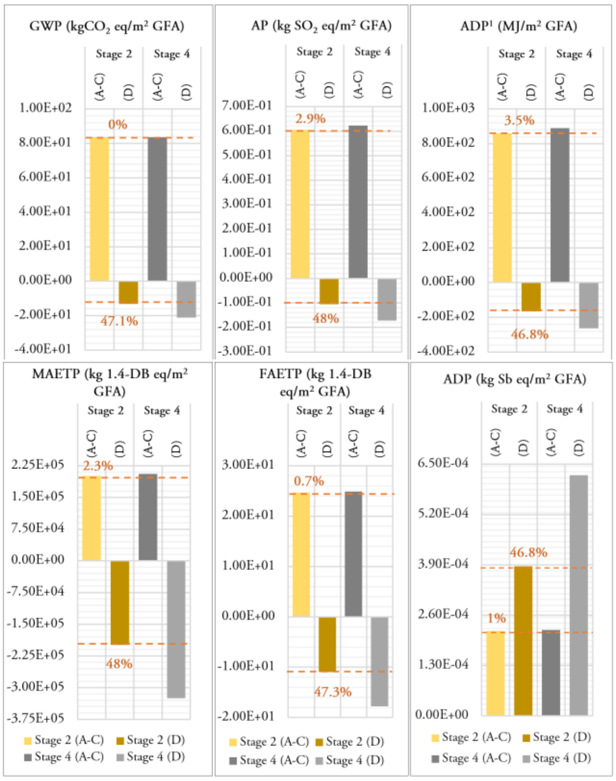

Figure 7: The detailed SimaPro results

For Module (A-C), while Stage 2 and 4 results are the same for GWP, there are slight differences (a maximum of 3%) between the models for other categories. As can be seen, impact of Module (D1:recyling), mostly benefits from aluminium recycling, for all categories it is the driving factor for the difference between overall/aggregated results.

eToolLCD Results

Figure 8 shows the overall LCA results for both models regarding the specified impact categories.

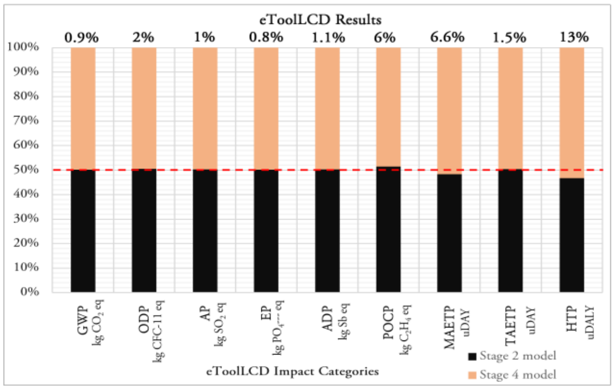

Figure 8: eToolLCD results

Results show a maximum 14% difference in the overall figure; however, especially in EP, and GWP, the difference is below 1%. With the exception of MAETP and HTP, the Stage 2 model has more impactful results than the Stage 4 for the remaining categories.

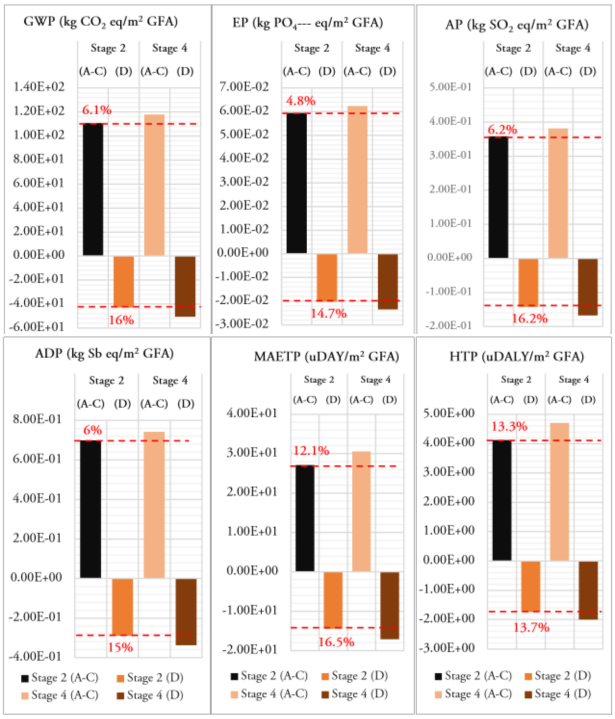

Figure 9: The detailed eToolLCD results

As illustrated in Figure 9, even though the Stage 4 model has used more impactful materials, in large part due to the difference in aluminium panels used between the models, the benefits from aluminium recycling helps to not only make up to differences but also reduce impacts of Stage 4 model in overall results for all categories except for HTP and MAETP. This distinction for both categories mainly stems from the GRC panel, used only in Stage 4 model, then glazing (frame+IGU) whose recycling benefits could not be defined in eToolLCD due to lack of assigning recycling scenario option for window templates and GRC units as a limitation of the tool. It is normally expected that the Stage 4 model achieve more recycling benefits from aluminium. The aggregated result for MAETP in Stage 4 model results were expected to be lower than the Stage 2 model results. However, due to limitations in defining recycling scenarios for some materials in eToolLCD, the findings did not correspond to the expected results.

Comparison of the LCA results

Specified categories with common units in both tools include GWP, EP, POCP, AP, ODP, and ADP[2]. Figure 10 shows the comparative results for these categories for both tools compared to case studies. Regarding the envelopes, Study A has a double glass façade system as exterior walls. Study B has a masonry wall system with bricks, steel-profile support, and insulation. The exterior wall system of Study C is concrete sandwich panels.

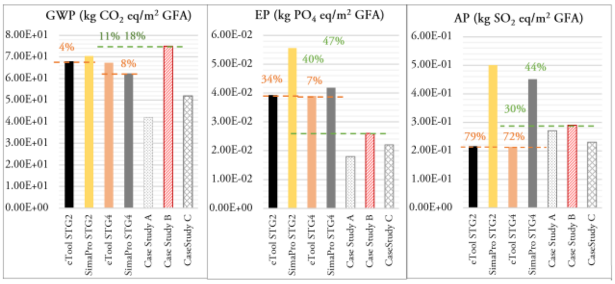

Figure 10: Comparative results

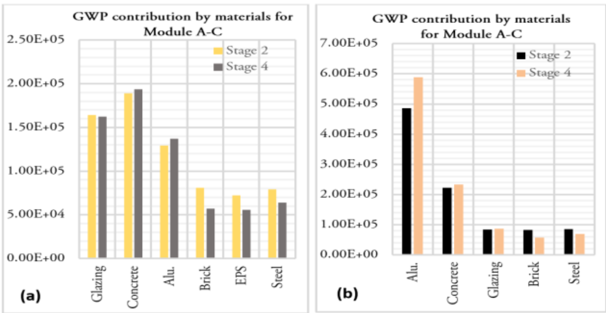

Figure 11: (a) SimaPro, (b) eToolLCD contributions

In Figure 10, there is a 4% and 8% difference in GWP results between Stage 2 and 4 models, respectively. Stage 4 results also are relatively close to the Case Study B, which has similar features to the building used. The relative consistency in GWP results found in this study echoes several in the literature which states the similarity on GWP results performed by different tools within the same study scopes (Hossain and Ng, 2018). However, the results of material impact contributions for Module A-C did not correspond for both tools. Figure 11 illustrates the differences in GWP category amongst others. This discrepancy likely stems from the variations in datasets for manufacturing process of materials and therefore highlights the importance and complexity of LCI sources.

Conclusion

This study has found that the traditional approach is highly susceptible to user mistakes due to manual data extraction, which required that a significant amount of data be handled and mapped. Data specification in BIM models tends to be insufficient to construct a detailed LCA model, with numerous assumptions required, resulting is increased uncertainty and reduced robustness of the model. The eToolLCD works directly by linking the Revit model and thus completes data extraction automatically, which considerably reduces the time and resources required, however, it does not address the issue of accurate specification of the model and reduces visibility of model assumptions. However, as expected, implementation time and process via eToolLCD were substantially quicker and simpler than via SimaPro8.

Overall, whereas the geometric data extraction from BIM to eToolLCD was found to be robust and synchronous for both developed-conceptual and detailed-design stage models, the level of semantic data extraction is still in its infancy, and the extracted semantic definitions of building elements are currently insufficient to achieve robust integration even for the detailed-design stage model. eToolLCD exports the data of building components instead of materials and it allows to users to match the components with the predefined templates.

In regards to the validation of the results, a consensus on result comparison for benchmarking is still lacking in the literature (Anand and Amor, 2017), and considers the variations on results to mostly stem from the underlying LCI database and the tools used to perform assessments as well as model assumptions. As a limitation for the reference case studies, a more recent study corresponding with scope of the research and the building used in this study could not be identified. In comparing the results from both models in eToolLCD, it is evident that even though very few inputs for scenarios and some modifications in templates to match with the design specifications are required, within the proposed framework the tool was found to be well suited for early-design stage use in terms of getting consistent and quicker results as well as performing multiple analyses aligned with the continuous design changes. Moreover, it seems quite promising to help the decision-making process by obtaining some of the hotspots in the assessment process.

It should be noted that these findings were based on a study scope that included only SimaPro8 and eToolLCD and may therefore differ for other tools and users. Regarding the aim of this study, the inherent limitations in the accuracy of LCA model, and the nature of the comparative analysis, this study does not provide a standard to determine which tool is closer to provide more accurate and robust results, truly reflecting overall lifecycle impact of the building. The framework presented here represents a first step of the research and is therefore limited in terms of the building elements and components included, the exclusion of operational impacts, and limiting the focus to only recycling benefits. Furthermore, the validation of the proposed framework is currently limited to a single case study. For further research, the proposed method will be applied to additional case study buildings and will be extended to include a larger range of different LCA plug-ins to investigate how they assess the effect of circular use of building materials in early design stages.

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