BIM in LCA/LCEA Analysis: Comparative analysis of Multi-family House and Single-family

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Abstract

The use of Building Information Modelling (BIM) in the Architectural, Engineering, and Construction (AEC) industry has increased lately due to the awareness of this methodology's potential to improve the performance and efficiency of projects and reduce errors. Similarly, there is a growing concern with energy consumption and environmental impact of buildings. If BIM is integrated with other methodologies that assess the environmental impact of buildings and its energy consumption, such as Life Cycle Assessment (LCA) and Life Cycle Energy Analysis (LCEA), it is possible to achieve higher levels of sustainability of the urban environment.

This paper (i) identifies which information LCA tools require and how to incorporate it in BIM objects, (ii) determine how that information can be incorporated in the BIM model, and (iii) perform an energy and environmental analysis of two different buildings and compare the results obtained in order to understand the impacts of designer's choices on the building's performance. The authors not only identify which information is required for an automatic LCA analysis of BIM-based projects, but also assess which phases and materials contribute the most for the environmental impact of buildings.

Keywords

BIM; LCA; LCEA; multi-family house; single-family house

1. Introduction

The building sector accounts for 40% of energy consumption and 36% of carbon dioxide (CO2) emissions in Europe, with a similar scenario in the United States (Commission 2015). As the building sector is the main contributor of greenhouse gas (GHS) emissions and a huge consumer of raw materials, it is extremely important to develop adequate legislation for construction, in order to achieve the Kyoto emission targets. In the case of EU, the goal is to achieve a 20% energy efficiency target, 20% share of energy from renewable sources until 2020, and reduce greenhouse gas emissions by 80-95% by 2050, compared to the levels of 1990 (Commission 2012).

If methodologies such as Life Cycle Assessment (LCA) and Life Cycle Energy Analysis (LCEA) are employed in the Architectural, Engineering, and Construction industry (AEC) the EU will more likely achieve these targets. The LCA methodology predicts how a building will perform during its lifespan, considering its entire life-cycle (environmentally focused) (ISO 2010). LCEA assesses the energy consumption of the whole project (energy efficiency focused), considering: (i) embodied energy, which is the amount of energy due to the process of production, construction, transportation, and possible renovations; (ii) operating energy, which is the amount of energy used to maintain the indoor air quality (IAQ) and thermal conditions of the inside environment through heating and cooling, as well as lighting and operating appliance; and (iii) demolition energy of the building, which is the energy required to demolish the building and dispose of the material (Cabeza et al. 2014). As the operating energy is responsible for about 80-90% of total energy consumption and environmental impact (EI) of a standard building during its lifecycle, it becomes crucial to choose the solutions that will enhance the energy performance of the building from the very first phase of the project (Asdrubali et al. 2013). This must be taken into account when we are performing an LCA or LCEA of a project, in order to achieve a sustainable construction.

Nonetheless, in order to fully use the potential of methodologies such as the ones described above in the AEC industry, an integrated approach capable of supporting all life cycle phases and gathering and processing a high volume of information is needed. Building Information Modelling (BIM) might be the solution for that problem. BIM is a methodology that enhances the collaborative aspect amongst all different fields of expertise throughout the project design and enables a more efficient management of a building's operation cost (Costa and Grilo 2015). The potential of BIM in the field of energy simulation and building performance has also been recognized lately, with applications ranging from photovoltaic (PV) simulation, waste management, energy rehabilitation of existing buildings, etc. (Ahn et al. 2014; Cheng and Ma 2013; Gupta et al. 2014).

Despite the growing amount of published papers in the last years regarding BIM synergies with energy and building performance (Hiyama et al. 2014; Marzouk and Abdelaty 2014; Woo and Menassa 2014), so far, the literature in BIM-LCA only analyses the theoretical advantages of this integration (Antón and Díaz 2014; Díaz and Antön 2014), with only three papers having a more empirical approach (Basbagill et al. 2013; Jalaei and Jrade 2014; Jrade and Abdulla 2012). Identifying this need for additional BIM-LCA discussion, the current paper focuses the integration between BIM and LCA/LCEA tools, and reports an energy and environmental analysis of two different buildings and compares the results. The rest of the paper is structured as follows: section 2 describes the methodology used; section 3 identifies the required information for BIM-based LCA/LCEA; section 4 presents a pilot case study conducted to test existing tools for energy analysis and environmental performance of buildings, and in section 5 conclusions are presented.

2. Methodology

As mentioned above, the aim of this paper is to briefly discuss the integration of LCA/LCEA with BIM methodology and conduct an LCA study resorting to a pilot case study. As a result of this BIM and LCA/LCEA integration, this paper contributes to: (i) the efficient use of LCA and simulation methods in design processes, (ii) promotion of performance-based methods within designers, contractors, and providers of facility maintenance and energy services, and (iii) the improvement of product information management throughout the construction life cycle.

The first part of this paper describes the LCA and LCEA methodology and what type of generic information should be included in the BIM model. In this sense, the authors initially search for existing standards in the field of LCA and then identify the key information required to conduct an LCA study, and that should be included in the LCA databases.

In the last part of this paper, an LCA/LCEA is conducted using BIM-based software, using the pilot case study method. Two different solutions representing the residential buildings are analysed and compared: a single-family building and a multi-family building. Revit software is used to create the BIM models, while Revit Energy Analysis tool is used to conduct the energy analysis and Tally tool to perform the LCA study of the above mentioned solutions.

The results of the Revit Energy Analysis are based on the geometry and materials of the BIM model and automatically consider some predefined options based on ASHRAE standards (e.g. Occupancy Schedules and number of people living in the dwellings). The authors only specify the Analysis mode ("building elements"), the HVAC system ("Residential 14 SEER/8.3 HSPF Split Packaged Heat Pump"), the location ("Lisbon, Portugal"), and the building type ("single" or "multi-family"). The obtained results are then imported to Tally in order to consider the environmental impact of operation phase, and the impact assessment method used is TRACI 2.1.

3. BIM and LCA/LCEA tools Integration

3.1. Definition of LCA/LCEA

According to AIA (Bayer et al. 2010), the LCA methodology have almost 50 years, when researchers demonstrated their concerns over the resources depletion and energy waste, searching for new ways of sustainable lifestyle (Adalberth 1997; Bekker 1982; Sharma et al. 2011). LCA's potential started to be noticed only in 1997 with the International Organisation for Standardisation (ISO) publishing a set of standards promoting the adoption of LCA method and presenting a framework for conducting an LCA analysis, with four phases (ISO 2010):

- The scope of an LCA: depends on the subject and the intended use of the study,
- The life cycle inventory analysis phase (LCI phase): consisting of the inventory of input/output, involving collection of the data necessary to meet the goals of the defined study,

- The life cycle impact assessment phase (LCIA): provides additional information to help assess a product system's LCI results,
- Life cycle interpretation: the results of an LCI and/or an LCIA are discussed as a basis for conclusions, recommendations, and decision-making in accordance with the goal and scope definition.

Although LCA method has been used in a variety of sectors for a long time, it was studied only in the last decade in the AEC sector (Antón and Díaz 2014; Buyle et al. 2013; Díaz and Antön 2014; Jrade and Abdulla 2012). As LCA is a very consistent tool to evaluate environmental impacts, the AEC industry is increasingly incorporating this method and suitable product selection into decision making processes in order to optimise the whole construction process (Asdrubali et al. 2013).

In addition to the LCA method, there are other methods that assess the environmental impacts of constructions, such as Life Cycle Energy Analysis (LCEA) and Life Cycle Cost Analysis (LCCA). Unlike the LCA methodology, LCEA is more focused on the energy inputs of a building during its life cycle, including the embodied energy, operating energy, and demolition energy (Cabeza et al. 2014), and the sum of all the energy consumed in the building is the life cycle energy (Ramesh et al. 2010). Designers that resort to LCEA are able to identify the phases that have the highest energy demands, having the possibility to make more appropriate material choices. LCEA can also quantify GHG emissions through the primary energy of the building by multiplying it by a factor. However, LCA tools provide more precise results (Ramesh et al. 2010), as in this methodology, the product’s environmental impact is assessed from the beginning of the analysis.

In order to successfully design a sustainable building with better performance, the designer not only should use BIM, as it is a methodology that has the ability to analyse different scenarios faster than the traditional methodologies, but also take into account a great diversity of different simulations, such as (Krygiel and Nies 2008): (i) Building orientation, (ii) Building massing, (iii) Daylighting, (iv) Water harvesting, (v) Energy modelling, (vi) Renewable energy, and (vii) Materials. As such, the designer must be aware which type of information fed into the BIM model will have a greater impact on the results of the LCA analysis.

3.2. Information required for LCA/LCEA tools

One source for LCA/LCEA tools databases is the Environmental Product Declaration (EPD), legislated and harmonised with the EN 15942:2011. EPDs have the purpose of facilitating the communication of a product’s environmental performance for business-to-business (B2B) (Standards 2011). LCA can use generic, average, or specific data (Silvestre et al. 2015), with EPDs fitting in the last category. Specific data is the data collected at the manufacturer’s plant. However, the product’s impacts can differ from other similar products (Silvestre et al. 2015). This is easily explained, as for the same products different manufacture processes can be used. If a manufacturer intends to develop an EPD of a product, the following information must be provided (Standards 2011): (i) General information of the product; (ii) Parameters describing the environmental impacts of the product; (iii) Parameters describing the resource use and primary energy use of the product; (iv) Parameters describing the resource use, secondary materials and fuels, and use of water of the product; (v) Information regarding waste categories of the product; (vi) Output flows of the product; (vii) Additional technical information; (viii) Additional information on release of dangerous substances to indoor air, soil, and water during the use phase.

In order for BIM-based tools to perform an automatic or semi-automatic LCA of a project, BIM objects must therefore contain the information described above. If manufacturers include that information in BIM objects, there will be no need to connect to specific LCA databases, promoting the open access to environmental information, as most LCA databases are paid. Also, it will be much faster and simpler to execute an LCA study in this situation, as designers will not need to learn how to work with additional tools. However, there are some data that designers should add in the BIM objects that are site-specific (e.g. energy and water used, site location, transportation from factory to site, etc.). In order to include the required data in BIM-based objects, manufacturers and designers can resort to parametric modelling, which allows to incorporate the information regarding different specialities in a single object, as well as defining parametric relations and constraints (Lee et al. 2006). International guides for a BIM object library should be used in this process, such as NATSPEC BIM Object/Element Matrix and NBS BIM Object Standard.

4. Pilot Case Study: multi-family house vs single-family house

The purpose of this pilot case study was to understand the effect of designer's choices in the environmental impact of the building and to compare the energy consumption and environmental impact of a multi-family house with a single-family house, according to Figure 1. As such, the authors used Autodesk Revit to develop the BIM model, Revit Energy Analysis for energy simulation, and Tally for environmental assessment of the projects, as explained in Section 2.

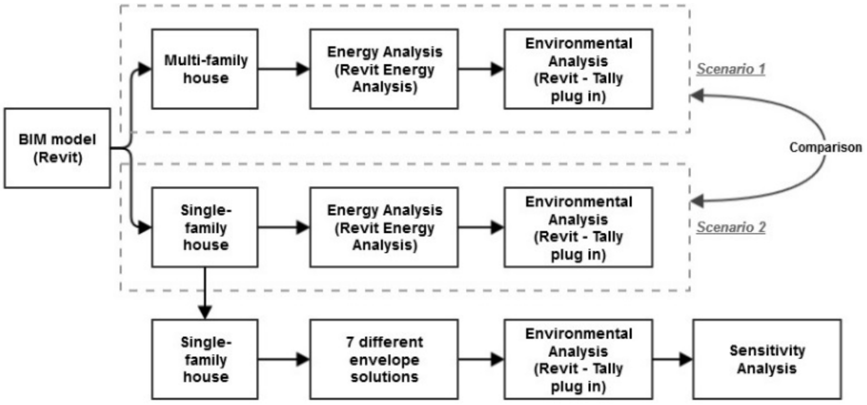

Figure 1 – Pilot Case Study methodology

The initial step was to model two simple buildings in Revit (Figure 2 and Figure 3), both with same envelope solutions, in order to guarantee that the results obtained are independent of material choices. After the development of both BIM models, the authors used the Revit Energy Analysis option to simulate the energy consumption (The second step of this Pilot Case Study was to analyse the environmental impacts due to materials selection, by examining the results of seven different envelope solutions (Figure 1.) Unlike the first step, in which the authors' objective was to compare the energy and environmental analysis of different types of buildings, in this step the authors seek to understand the impact of designer's choices of materials, using a single scenario (single-family house).

Table 1) and Tally plug-in to perform the LCA of these projects (

Table 2), assuming a 60-year lifetime. Unfortunately, Tally plug-in did not recognise the chosen materials in Revit, only the construction solution, as this tool only works with GaBi's database. Extra work was therefore required in order to select the corresponding materials in Tally's database. This could compromise the accuracy of the expected results, as the tool users can select only the available materials. Nonetheless, as the purpose of this paper is to compare two scenarios with the same materials solutions, this software limitation will not jeopardise the expected results (both in Revit and Tally).

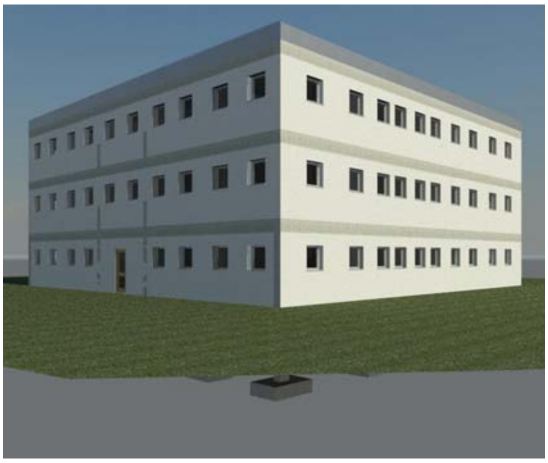

Figure 2 - 3 floor multi-family house (3D view)

Figure 3 - single-family house (3D view)

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Table 1 - Revit Energy Analysis results (multi-family house vs single-family house)

	Multi-family house	**Single-family house**	**Units**
Area	1,120.00	100.00	m2
Electricity Use	88.00	90.00	kWh/m2/year
LC Electricity Use	2,956,800.00	270,000.00	kWh
	270.0	24.7	kWh/day
PV low efficiency	46,514.00	11,243.00	kWh/year
PV medium efficiency	93,029.00	22,487.00	kWh/year
PV high efficiency	139,543.00	33,730.00	kWh/year

Table 2 – Tally results (multi-family house vs single-family house)

	Row Labels	Sum of Acidification Potential Total (kgSO2eq)	Sum of Eutrophication Potential Total (kgNeq)	Sum of Global Warming Potential Total (kgCO2eq)	Sum of Ozone Depletion Potential Total (CFC-11eq)	Sum of Smog Formation Potential Total (kgO3eq)	Sum of Primary Energy Demand Total (MJ)	Sum of Non-renewable Energy Demand Total (MJ)	Sum of Renewable Energy Demand Total (MJ)
Multi-family house	End of Life	75	41	174960	0.00	2550	575515	569443	6046
	Maintenance and Replacement	3114	366	319574	0.01	17084	3840682	3309445	531238
	Manufacturing	5364	468	1285760	0.10	48229	10458306	9612019	846288
	Operations	12200	630	2635708	0.00	142650	59812579	36338720	23473859
	Total	**20754**	**1506**	**4416001**	**0.12**	**210514**	**74687083**	**49829627**	**24857430**
Single-family house	End of Life	-2	4	39813	0.00	149	42730	41394	1329
	Maintenance and Replacement	282	34	26429	0.00	1457	339942	291080	48862
	Manufacturing	567	49	192020	0.02	5358	1033348	940644	92704
	Operations	1100	57	222181	0.00	13750	5201615	3060519	2141097
	Total	**1948**	**143**	**480442**	**0.03**	**20715**	**6617635**	**4333636**	**2283992**

As it is possible to observe from

Table 2, Tally provided six different Environmental Impact categories: Acidification Potential, which causes fish mortality, forest decline, and the deterioration of building materials; Eutrophication Potential, which can cause an undesirable shift in species composition; Global Warming Potential, which causes an increase of the greenhouse effect; Ozone Depletion Potential, which leads to higher levels of UVB ultraviolet rays; Smog Formation Potential, which leads to respiratory issues and damage to ecosystems; and Primary Energy Demand, which measures the total amount of primary energy extracted (non-renewable plus renewable resources). In general, the environmental impacts from the multi-family house are about 10 times higher than the single-family house, being almost proportional to the area of the building.

The Global Warming Potential (GWP) is one of the most relevant impacts, and in both cases it is mostly due to operational energy consumption. However, for the single-family house the weight of the operational phase is lower than for the case of the multi-family house. On the other hand, the manufacturing processes contribute more to the GWP of the single-family house than the GWP of the multi-family house. So, we might argue that there is an economy of scale in terms of manufacturing (as an example we can refer that there are several construction elements, such as foundations, roof, etc., that are not proportional to the number of floors) but in terms of operational energy consumption the same logic does not apply, as the multi-family house has higher relative energy consumption (what might be related to the relevant energy consumption of the common/social spaces).

It is also important to understand which kind of materials have higher environmental impact, and if these materials represent a considerable portion of the building's mass. Table 3 and Figure 4 display the environmental impact of all materials used in the single-family house, throughout the different project phases. For this purpose, it is meaningless to display both scenarios (multi-family house and single-family house), as our real concern is only to analyse the environmental impacts due to materials selection, not to compare the two scenarios.

Table 3 - Tally (single-family house material's EI)

	Building Phases	Sum of Acidification Potential Total (kgSO2eq)	Sum of Eutrophication Potential Total (kgNeq)	Sum of Global Warming Potential Total (kgCO2eq)	Sum of Ozone Depletion Potential Total (CFC-11eq)	Sum of Smog Formation Potential Total (kgO3eq)	Sum of Primary Energy Demand Total (MJ)	Sum of Non-renewable Energy Demand Total (MJ)	Sum of Renewable Energy Demand Total (MJ)
Single-family house	**End of Life**	**-2**	**4**	**39813**	**0.00**	**149**	**42730**	**41394**	**1329**
	03 - Concrete	17	2	3676	0.00	304	61060	58499	2561
	04 - Masonry	4	1	792	0.00	65	13189	12642	547
	05 - Metals	-19	0	-3730	0.00	-200	-39564	-39987	423
	07 - Thermal and Moisture Protection	-5	0	39061	0.00	-40	12243	10165	2072
	08 - Openings and Glazing	-1	1	-518	0.00	-28	-12902	-8244	-4658
	09 - Finishes	3	0	532	0.00	48	8704	8320	384
	Maintenance and Replacement	**282**	**34**	**26429**	**0.00**	**1457**	**339942**	**291080**	**48862**
	03 - Concrete	0	0	0	0.00	0	0	0	0
	04 - Masonry	5	0	654	0.00	29	7244	6854	391
	05 - Metals	235	31	16334	0.00	990	246946	211625	35321
	07 - Thermal and Moisture Protection	2	0	180	0.00	7	1088	770	318
	08 - Openings and Glazing	10	1	1943	0.00	120	35210	23277	11933
	09 - Finishes	30	1	7318	0.00	312	49453	48554	899
	Manufacturing	**567**	**49**	**192020**	**0.02**	**5358**	**1033348**	**940644**	**92704**
	03 - Concrete	181	7	40938	0.00	2402	290957	277781	13177
	04 - Masonry	19	1	11139	0.00	295	138240	130311	7928
	05 - Metals	283	33	25320	0.00	1725	364925	324893	40031
	07 - Thermal and Moisture Protection	53	7	105754	0.02	544	158259	143472	14787
	08 - Openings and Glazing	12	1	2455	0.00	147	47947	31358	16589
	09 - Finishes	19	1	6413	0.00	246	33021	32828	192
	Operations	**1100**	**57**	**222181**	**0.00**	**13750**	**5201615**	**3060519**	**2141097**
	Grand Total	**1948**	**143**	**480442**	**0.02**	**20715**	**6617635**	**4333636**	**2283992**

As expected, concrete was the material with the highest mass percentage of the building, having a relatively low environmental impact/mass ratio (except in the manufacturing process). On the other hand, metal-based materials and insulation materials have a very high environmental impact/mass ratio, particularly on GWP, Acidification Potential, and Eutrophication Potential, despite their low representativeness in the total mass of the building. If designers are aiming for sustainable solutions, the selection of insulation material and its thickness is an extremely important aspect for the environmental impact of a building. It is relevant to mention that the higher the insulation thickness, the less thermal loss, leading to a decrease of operational energy consumption. So, for a sustainable solution to be reached, it would be advisable to perform a multi-objective optimisation of both (environmental vs energy consumption).

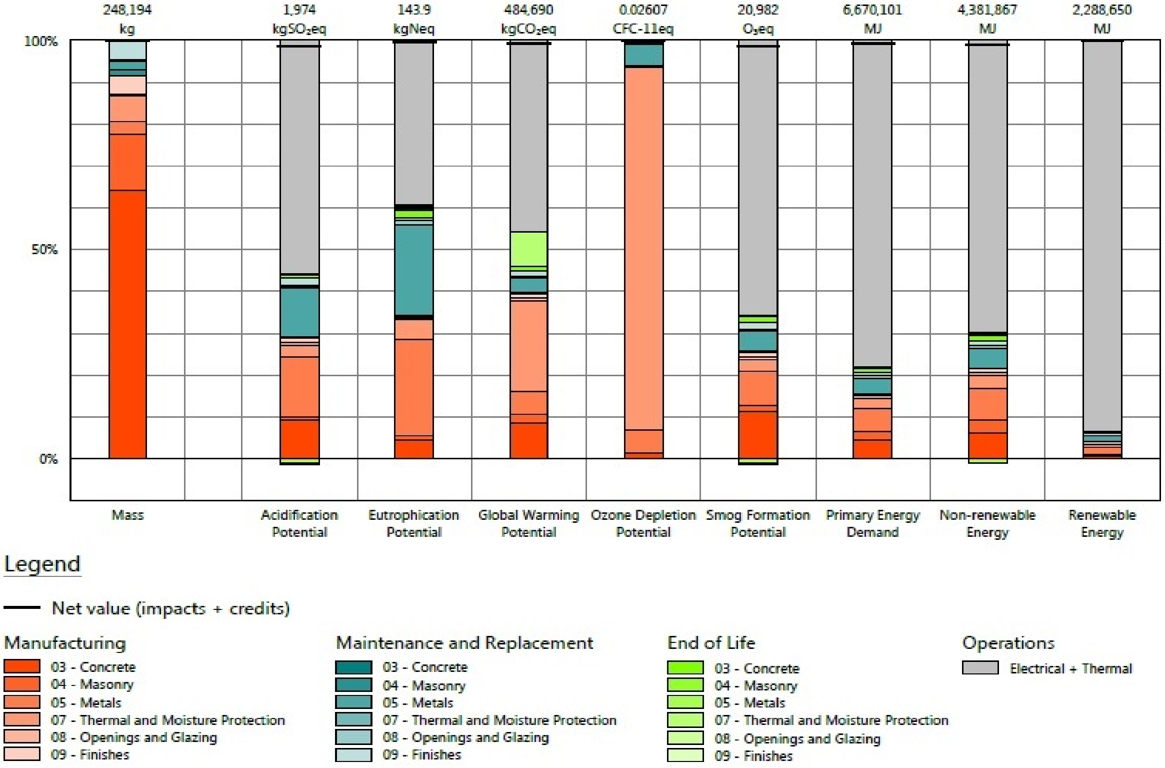

Figure 4 - Tally (single-family house material's EI)

However, in order to demonstrate how the designer's choices can profoundly affect a building's environmental impact, the authors decided to use the scenario of a single-family house and select different Revit and Tally solutions for the envelope. As observed in Figure 5, the original option (studied earlier) is one of the best sustainable solutions for most environmental impact categories. Also, wood-based solutions (option 3 and option 5) are the ones in which renewable resources can suppress most of the required Primary Energy Demand. Interestingly though, these two solutions also seem to be amongst the least environmentally friendly solutions (option 3 – wood roof: 1st in Acidification Potential, 1st in Eutrophication Potential, and 1st in Primary Energy Demand; and option 5 – timber floor: 2nd in Eutrophication Potential and 2nd in Global Warming Potential). However, if we examine Figure 6, we can conclude that most of those environmental impacts result from the End of Life potential use (recycling/reuse/recovery) of wood-based solutions, assuming that these materials are still in good condition. They are also the only ones with a positive energy return at the end of life (through burning processes). Regarding Smog Formation Potential, Acidification Potential, and demand from non-renewable resources, option 6 (full concrete envelope) comes as the least environmentally friendly solution.

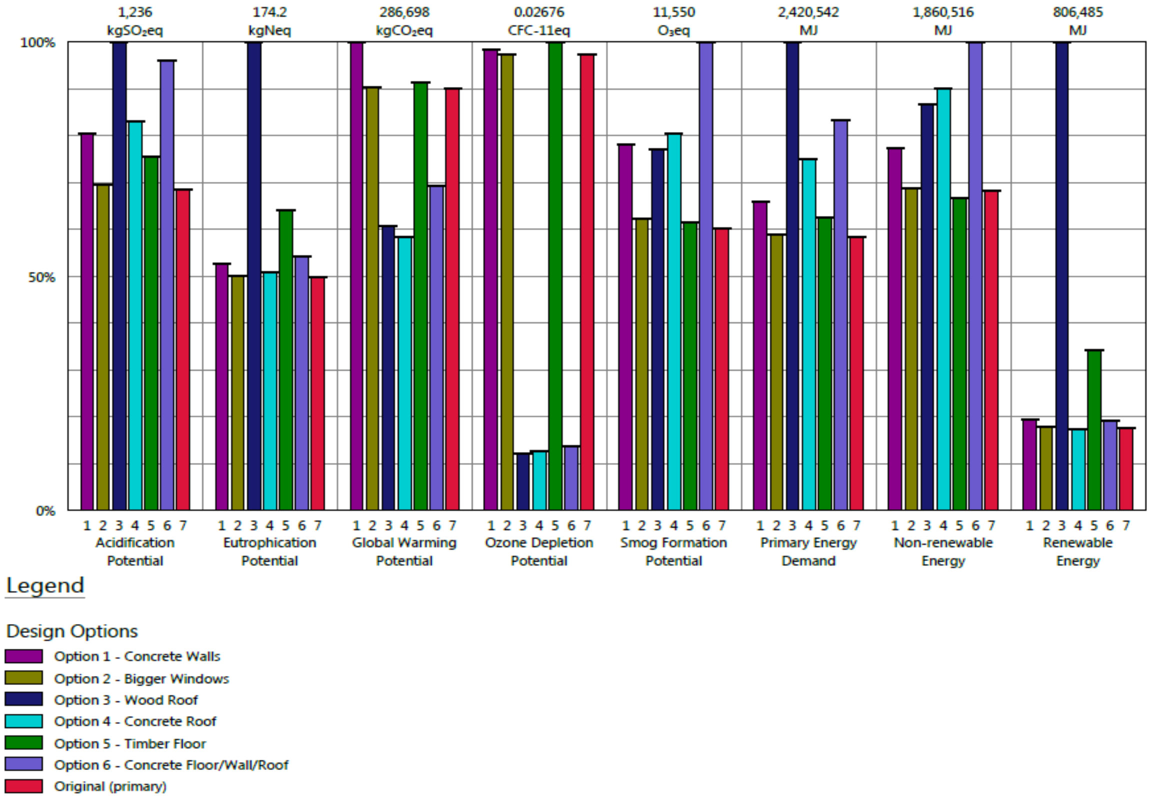

Figure 5 - Tally LCA analysis of single-family house (7 different options)

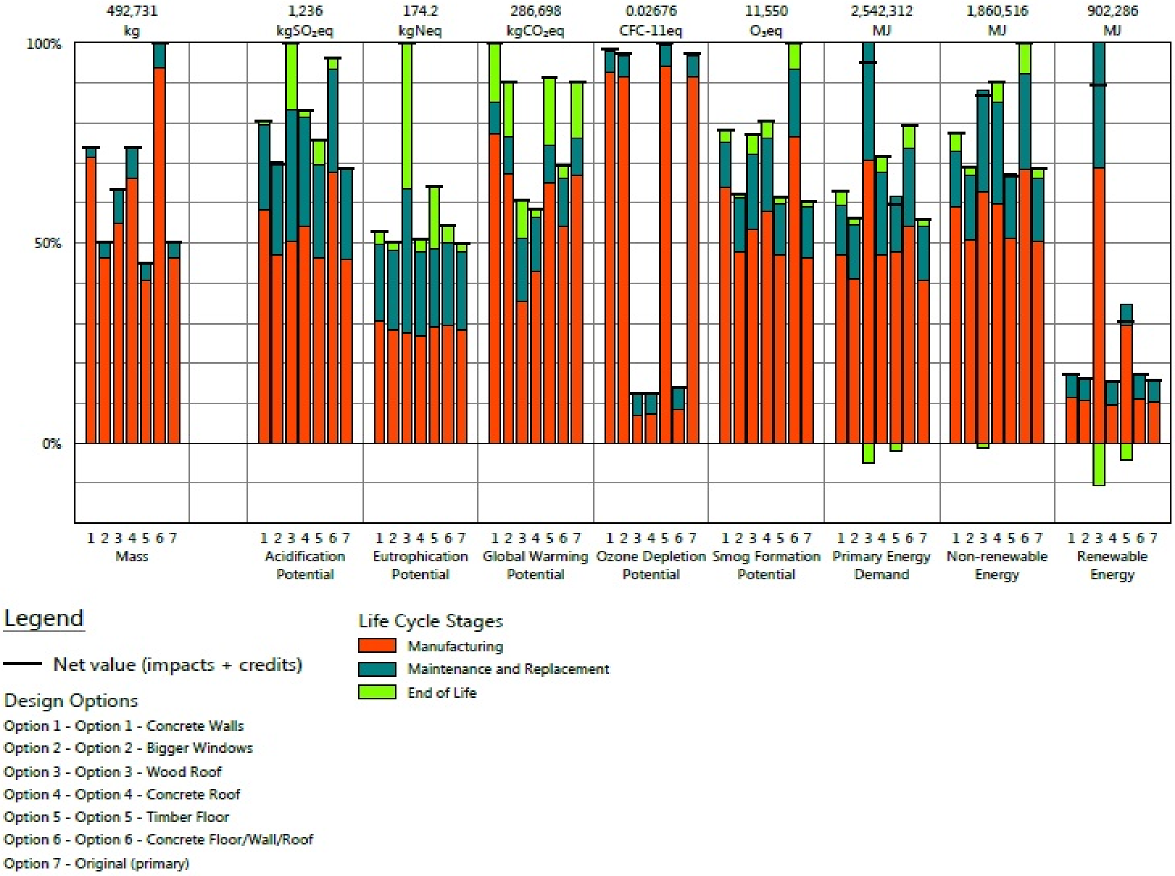

Figure 6 - Tally LCA analysis of single-family house (Life Cycle Stages)

5. Conclusions

The first purpose of this paper was achieved through the analysis of existing ISOs and ENs, in which EPDs were identified as one of the main sources for LCA's databases. As such, in order to develop a BIM-based LCA automatic simulation tool, BIM-based objects must contain some crucial information that is requested by EPDs (see Section 2). The LCA plug-in used in this article, in spite of identifying Revit elements present in the project, did not recognise the object's information, as it works with GaBi's databases. This means that all information used by this tool must be manually added by the user after designing the architecture and type of solutions in the Revit. The second goal was achieved by performing Revit Energy Analysis, in order to obtain the expected energy consumption of both multi-family house and single-family house, and then by performing an LCA by using Tally. As mentioned above, the authors had to manually add the energy consumption of the selected scenario (provided by Revit Energy Analysis) with the purpose of obtaining results due to Operational phase, and also manually add the materials chosen to be used in the construction of the building, from a pre-defined list.

Despite the innovative environmental approach of Tally plug-in, designers will be greatly limited by existing options. However, the designers must also bear in mind that Tally plug-in represents only a quick and approximate analysis of a building's environmental impact. The authors initially assessed that both multi-family house and single-family house had a similar energy consumption (kWh/m^2), with multi-family house having about 10 times greater area, higher energy consumption, and greater environmental impact in most categories. The authors concluded that there was a positive correlation (in most cases) between energy consumption and environmental impact of buildings. Lastly, after the analysis of several envelope solutions for the single-family house scenario, the authors identified some effects due to the designer's material choices. Wood-based solutions are those in which renewable resources can potentially suppress most of the required Primary Energy Demand. Wood-based solutions are also those with higher End of Life potential use, leading to greater environmental impacts due to recycling/reuse/recovery processes. Option 6 (full concrete envelope) is one of the worst solutions, being on top of Smog Formation Potential, Acidification Potential, and demand from non-renewable resources. This is explained by the concrete's manufacturing environmental impact, which is very high compared with other materials.

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