IOP Conf. Series: Materials Science and Engineering **442** (2018) 012010 doi:10.1088/1757-899X/442/1/012010

LCA-Based Comparison of the Environmental Impact of Different Structural Systems

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Abstract. Construction is one of the most impactful industrial sector because of the high consequences it generates on the society, the environment and the economy. The study presented herein aims to define a methodological framework that can be used for construction community stakeholders in order to conduct environmental sustainability comparisons among building systems at the design stage. An application of the methodology is performed by comparing structures having different building materials. Three alternative material options have been investigated: RC, steel, and wood. Each option has been designed to fulfill predefined structural, functional, and architectural requirements. Later, the environmental impacts of the structures have been assessed according to the four steps of the life-cycle assessment procedure (ISO 14040) and considering the four phases of a building life: extraction and processing of raw materials; construction; operation; end of life. LCA study is conducted for the three alternative structures with the help of SimaPro software, using both IMPACT2002+ and EPD2008 methodologies to quantify environmental impacts.

Keywords: Life Cycle Assessment methodology; reinforced concrete structure; steel structure; wood structure; construction industry sustainability.

1. Introduction

It is widely recognized that the construction and related industries have a significant global impact on the environment. Being a strategic economic sector, these industries attracts growing attention in terms of sustainability. Many assessment tools and new methodologies have been progressively developed to drive decision-making processes in the direction of achieving sustainability goals, focusing the attention on environmental issues. Life-cycle assessment (LCA) (ISO 14040, 2006) represents one of the most grounded and widespread methodology, which has the potential to analyse overall environmental factors related to the entire life-cycle of goods and processes. One of the main advantages of an LCA is that it quantifies the impacts on the environment not limited to energy or CO_2 emissions, but also use of resources, emissions and ionizing radiation. The use of the LCA in the environmental impact assessment in construction industry could be adopted for the selection of construction products and procedures. Although an LCA study of the entire building would seem to represent a system too complex to be assessed, by using a rigorous framework for life-cycle analysis, it could support the decision-making process, contributing to lower the environmental impacts. Literature offers several works dealing with the environmental assessment of buildings: most of the comparative studies, as (Peuportier, 2001), (Xing et al, 2008), (Menna et al, 2013) and (Asdrubali et al, 2013), focus on the life cycle assessment of buildings having different features, as volumes and functionality, and the “reference” unit is sometimes the building net area or volume unit. However, the required building performances should be explicitly set as basic parameters when defining the system boundary of an environmental sustainability evaluation by means of life cycle assessment. According to this, the paper presents a general framework that provides a set of requirements preliminarily defined for a comparative life-cycle assessment, and a case study where the approach is applied.

2. Proposed methodology

The main parameter driving the designer during the design phase of a buildings is its structural performance. This primary performance requirement is strictly related to many other initial choices made by a customer with reference to the final building/structure, for example, location, use, number of stories, available resources, and functional systems. Given this consideration, the present study proposes an approach for a sustainability comparative assessment among buildings, summarised in Figure 1, which defines a set of “building system requirements” for the building element/system, taking in count functional, architectural, structural, and economic performances, as well as other factors (see Figure 1, steps 1-2). The requirements are interconnected because one specific requirement can affect the others. For instance, the definition of the use of a structure/building (residential, office, strategic infra-structure etc.) primarily affects the architectural, structural, and economic features linked to the decision making at the design phase. Moreover, some of the requirements of Figure 1 (steps 1-2) are site-specific, and depend on the climatic zone, hazards, and local constraints related to the building site.

The proposed framework allows the comparison of different design options, at design stage, leading to a final comparison at the level of the construction product system. In this way, the identification of the contribution of one or more sub-assembly options in the environmental impacts of the final product is possible.

These requirements first depend on building use and location in terms of live loads, hazards, and environmental condition. Starting from these requirements, the feasible options are identified, which take into consideration several additional constraints, such as common and local construction techniques and materials, overall cost, and national standards establishing minimum performances (Figure 1, step 3). After the design parameters are computed and the considered options are designed, the sustainability assessment is performed by means of the common sustainability tools (Figure 1, step 4), allowing the examination of all the desired sustainability aspects.

According to this methodology, the comparative sustainability assessment among building system can be considered scientifically and technically reliable.

For this study, only environmental aspects of the sustainability assessment is considered (step 4). Environmental sustainability can be examined by a variety of assessment tools. LCA represents one of the most commonly used and most valuable; to calculate life-cycle environmental impacts, the LCA process is conducted by following four steps according to ISO 14040 (ISO 14040, 2006) and ISO 14044 (ISO 14044, 2006): (1) goal and scope definition; (2) life-cycle inventory (LCI) analysis; (3) life-cycle impact assessment (LCIA); and (4) results.

The general standard for an LCA is then applied to the "building system", for which a generic system boundary has to be set to properly compute the environmental impact related to the entire building life-cycle. EN 15978 (EN 15978:2011) provides indication to the definition of the system boundary for performing LCA applications in construction works.

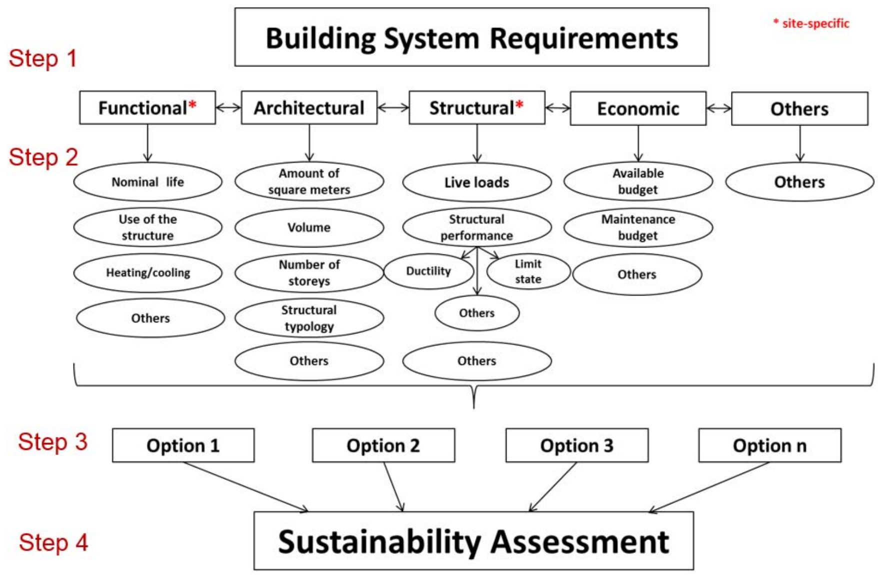

Figure 1: Proposed approach to building structures sustainability

3. Case study

The above-described methodology is applied to a case study, performing the sustainability assessment of three structural options for residential building. In particular, the study aims to the comparison of the environmental impact of materials and processes related to the complete life-cycle of a reinforced concrete (RC), steel, and wood structure, ideally located in the municipality of Rome, Italy. The LCA is only applied to the structural frame of the building because it is assumed that non-structural elements and systems do not vary within the different options. Figure 2 shows the application of the methodology for the case study. Hereafter, architectural, functional, and structural requirements, equal for the three construction options, are discussed.

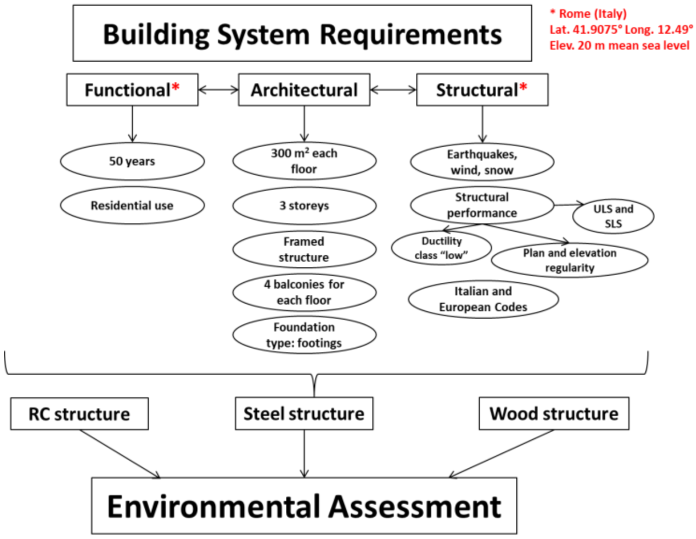

Figure 2: Proposed approach applied to the case study

3.1 Building system requirements

Three sub-categories of building system requirements are considered for the case study (Figure 2): architectural, functional and structural. Architectural requirements include: structural plan dimensions, equal to 12x25 m^2 (300 m^2 each floor); structural typology, framed structure composed by three 4 m spans in the y direction and five variable-dimension (4.7 m – 5.5 m – 4.6 m – 5.5 m – 4.7 m) spans in the x direction; number of storeys, equal to three; number of apartments, equal to two for each floor, having 2 balconies each. Functional requirements include: the use, which is residential building; and the nominal life, equal to 50 years. Structural requirements include: loads (dead loads, snow, wind, seismic actions, and live loads); structural codes (NTC 2008 (D.M. 14.01.2008) and the related Circolare n°667/2009(Ministerial Circular n.617, 02.02.2009), Eurocode 3 (EN 1993, 2005) for the steel structure and CNR-DT 206/2007 (CNR-DT 206/2007) for the wood structure); analysed limit states (ultimate limit state, ULS, and service limit state, SLS).

3.2 Design and verification of structures

The design of the RC, steel, and wood structures have been fulfilled by means of the common design software Edilus v.26.00, developed by ACCA Software S.p.A (User Manual, 2013), which is helpful for design and verification of new and existing structures according to a Eurocode-like approach (CEN (2004) Eurocode 8). The design phase of the three considered structures consists of the definition of the geometry and mechanical properties of the structural members belonging to the buildings. In detail, the RC structure consists of C25/30 concrete and B450C reinforcing steel classes, with a cross section of 30x50 cm^2 for the beams and columns and 35x50 cm^2 for the knee beams of the stairs. The cast-in-situ RC slabs are 22 cm high and the joist beams are oriented in one direction. The steel structure is comprised of S275 steel elements, with IPE270 elements for the principal beams, IPE200 for the secondary beams and HEA320 for the columns and flanged joints between the beams and columns and between the main and secondary beams. The steel-concrete slabs are made of S235 A55/P600 HI-BOND corrugated sheets and 6.5 cm high RC cover slabs. The wood structure is comprised of LL GL32h glued laminated wood class, with a cross section of 16x36 cm^2 for the beams, 20x44 cm^2 for the columns, glued S275 steel bars for the connecting beams and columns, and S275 plates for the connecting columns and the foundation elements. The wood slabs are comprised of 14x28 cm^2 wood joists with 80 cm of axle spacing, 4 cm of concrete slab, and 3.5 cm of wooden floorboards. Figure 3, 4 and 5 show the structural models.

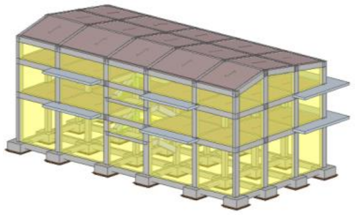

Figure 3: R C structure

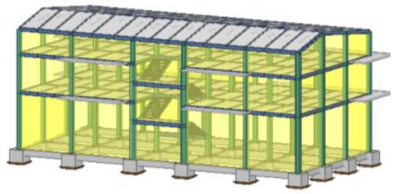

Figure 4: Steel structure

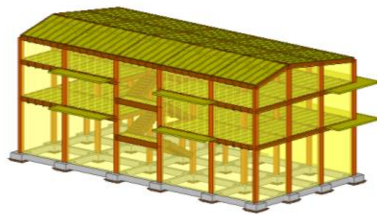

Figure 5: Wood structure

The first three vibration modes of the three structures are listed in Table 1, taking into account the x and y ULS seismic actions that indicate the period, horizontal acceleration (Sa(T)), and participating mass (in kg and in %) of each mode.

Table 1: Dynamic characteristics of the three structures

Mode	Spectrum	Period (T) s	Mode Spectrum Period (T) s	Horizontal spectral acceleration, Sa(T) m/s^2	Participating mass, $N{\cdot}s^2/m$=kg	Participating mass, %
RC structure	1	ULS x	0.464	1.454	817784	76.5
	2	ULS y	0.416	1.454	763844	71.5
	3	ULS y	0.065	1.615	138831	13.0
Steel structure	1	ULS y	0.861	0.774	544880	67.1
	2	ULS x	0.755	0.883	496393	61.1
	3	ULS y	0.066	1.600	138186	17.0
Wood structure	1	ULS y	0.619	1.077	275093	52.6
	2	ULS x	0.573	1.164	192176	36.7
	3	ULS y	0.076	1.578	143941	27.5

3.3 Life-Cycle Assessment

The forth and last step of the methodology, set out in Figure 2, is the sustainability assessment of the three building options. To this aim, LCA models have to be built. The entire "building" is chosen as Functional Unit (FU) for this analysis. In particular, the estimated impacts are related to the materials and processes needed to build the structural system. The system boundary is shown in Figure 6, and includes: the pre-use phase, extraction and the production of materials, and construction phases; the use phase, ordinary maintenance of structural elements; and the End-of-Life (EoL) phase, building demolition, and material disposal. Mechanical demolition is chosen in the EoL phase, and it is assumed that the materials are sent for recycling, landfill, and/or to an incinerator according to the percentages declared by national institutions.

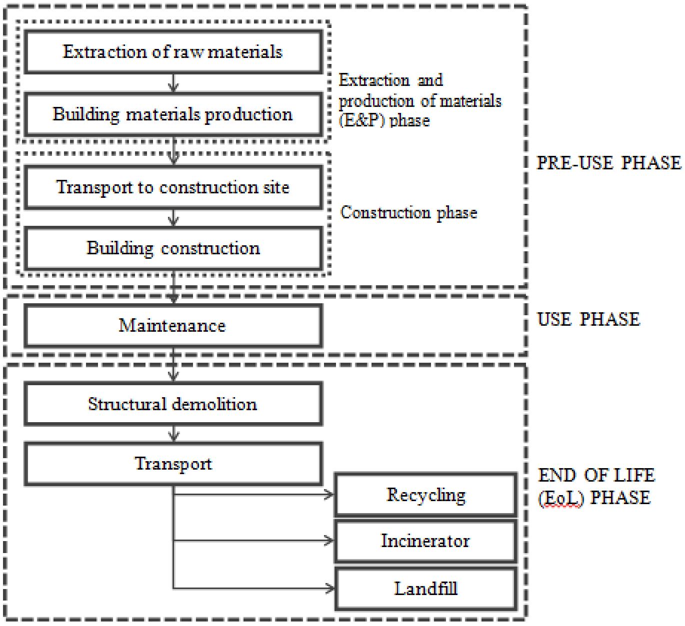

Figure 6: System Boundary of the case study

For each stage of the system boundary, the LCI analysis and LCIA are developed, and performed using the SimaPro 7.3 software (SimaPro 7, 2010), which is an efficient tool, useful to collect sustainability data and to analyse and monitor the sustainability performance of products/services. Moreover, SimaPro software allows the access to international databases and impact assessment methodologies, as Ecoinvent 3.0 (Ecoinvent Centre, 2007), the international database chosen as main source for the life-cycle inventory. Two methodologies for the impact assessment are selected: IMPACT2002+ (Humbert et al, 2012) and EPD (IEC, 2008). The IMPACT 2002+ methodology (Humbert et al, 2012) is used for the LCIA, with impacts evaluated for 15 midpoint categories, grouped into four damage categories: human health, measured in DALY (disability-adjusted life years); ecosystem quality, measured in PDF*m^2*yr (the potentially disappeared fraction of species over a certain amount of m^2 during a certain amount of year); climate changes, measured in kg-equivalents to a reference substance; and resources, measured in MJ (Humbert et al, 2012).

Each phase of the building life-cycle is described in the following section.

3.4 Case study results and discussion

3.4.1 Pre-use phase—extraction and production of materials (E&P phase)

The computation of the amounts of structural materials required for producing the beams, columns, joints, slabs, stairs, foundations, and balconies of each structure is fulfilled at E&P stage. All the processes before the construction phase are also considered, i.e. zinc coating for steel elements and wood treatments. All the materials, except concrete, are modelled according to Ecoinvent database; the data concerning concrete are modified using more refined Italian data collected by detailed environmental product declarations (EPD). According to the Ecoinvent database, structural steel is composed of 37% recycled steel (from energy-optimizing furnaces) and 63% new steel (from basic oxygen furnaces). Table 2 lists the amount of materials and processes for RC Structure, Steel Structure, Wood Structure, as well as the data sources.

Table 2: Amounts of materials and processes and related data sources

Material/Process	UdM	RC Structure	Steel Structure	Wood Structure	Data
Concrete C25/30	m^3	251.01	118.07	63.62	Average data by AITEC
Steel B450C	kg	28186.57	10547.93	4284.56	Reinforcing steel, at plant/RER U (Ecoinvent)
Steel S235-S275-8,8	kg		74265.15	24926.73	Steel, low-alloyed, at plant/RER U (Ecoinvent)
Bricks	kg	85363.2			Brick, at plant/RER U (Ecoinvent)
Glued laminated timber GL32h	m^3			138.69	Glued laminated timber, outdoor use, at plant/RER U (Ecoinvent)
Zinc coating	m^2		830		Powder coating, steel/RER U (Ecoinvent)
Powder coating	m^2		830		Zinc coating, pieces/RER U (Ecoinvent)

During this first stage, LCA results show that the wooden structure provides the highest contribution to ecosystem quality, while the steel option has the greatest impact on human health, climate change, and resources. Focusing on components, the steel material is responsible for the highest impact of a steel structure, while glued laminated timber is responsible for the greatest impact of the wooden structure on ecosystem quality.

3.4.2 Pre-Use Phase – Construction

For modeling the construction phase, transportation of materials from plants to construction sites and all the processes needed to build the structural systems are considered. Concrete and reinforcing steel plants are assumed to be available within 30 km distance from the construction site (Vitale et al, 2014). Steel elements are available from the Riva production plant in Patrica (FR) (87.5 km from Rome) and wooden elements are available from the Rubner Holzbau production plant in Calitri (AV) (249 km from Rome).

The LCA analysis of the Construction Phase leads to worse results for the wooden structure: indeed, such buildings affect the human health, the ecosystem quality, the climate, and resources, mainly due to the transportation phase.

3.4.3 Use Phase

Only ordinary maintenance is considered in the use-phase, being the study focused on the structural part of the building. With regard to the RC structure, steel reinforcement spalling on 5% of the surface of exposed beams and 5% of exposed columns is assumed. The steel elements of the steel structure are assumed to be subjected to zinc (ISO 14713-1:2009) and a powder coating during production to prevent environmental corrosion. Consequently, according to UNI EN ISO 14713 (ISO 14713-1:2009), given the typical consumption of this kind of coating (EPD, 2010), (ISO 12944, 1998) it is assumed that only limited maintenance would be required and, consequently, powder coating on just 20% of the total metallic surface is taken into account. For the glulam structure, a maintenance plan is necessary for steel connections and the glulam elements exposed to UV radiation. The presence of powder coatings on the surfaces of all the steel connections and the annual application of a wood-impregnating solvent with a long oil-high penetration alkyd resin on exposed surfaces of balconies, ridge beams, and columns are therefore assumed.

Such analysis leads to show that RC and steel structures require less maintenance than wood versions. Therefore, the ordinary maintenance of glulam structures has the greatest impact due to the need to frequently apply preservatives. Nevertheless, the impacts related to the use phase are negligible, respect the other phases.

3.4.4 End of Life (EoL) Phase

The EoL phase includes structure demolition and material disposal. Mechanical, conventional demolition is chosen for each structure, and is assumed to be carried out by one excavator with a hydraulic hammer (for foundation demolition) and jaw (for structure demolition and inert crashing), one wheel loader, and 28 m^3 lorries to remove demolition waste from the site. The RC structure demolition would need three 28 m^3 lorries carrying inert waste for 17 journeys and one such lorry carrying steel waste for one journey. The demolition of the steel structure would require two lorries carrying inert waste for 6 journeys and two carrying steel waste for 6 journeys. Finally, demolition of the wood structure would need one lorry carrying inert waste for 3 journeys, one carrying steel waste for 1 journey, and two carrying wood waste for 7 journeys.

After demolition, it is assumed that material separation would be carried out at the construction site and all the materials loaded to lorries and sent to other destinations 30 km away. The separated materials are sent for recycling, landfill, and/or to an incinerator according to national or European reference amounts. The recycled materials are computed in SimaPro as an avoided product. According to ANPAR (ANPAR 2012) and ISPRA data, 65% of inert waste is sent for recycling and 35% for landfill. Recycled inert materials are considered to be avoided gravel. According to ArcelorMittal (Constructalia, website), 65% of reinforcing steel is recycled and 35% is sent to landfill. Given that reinforcing steel is composed of 37% recycled steel, 28% (i.e. 65% minus 37%) of steel leaves the system boundary and is considered to be avoided new steel (from basic oxygen furnaces) (ISO/TR 14049:2000). Also according to ArcelorMittal (Constructalia, website), 98% of steel from steel beams and columns is recycled and 2% is sent for landfill. Given that low-alloyed steel is composed of 37% recycled steel, 61% (i.e. 98% minus 37%) of steel leaves the system boundary and is considered to be avoided new steel (from basic oxygen furnaces). According to TRADA reports (TRADA, 2008), 16% of glued laminated timber is recycled, 4% is sent to an incinerator, and 80% for landfill.

Results on Impact Assessment of the EoL phase show that demolition and transportation phases' contributions are negligible respect to the disposal phase. Steel structure has the lowest impact on all the four impact categories (human health, ecosystem quality, climate change, and resource use), being the recycling steel percentage, which is higher than the percentage of the other materials, the main parameter influencing the results.

3.4.5 Global Impact Assessment

In this section, results regarding the environmental impacts are shown for each life-cycle phase of the three buildings, in terms of midpoint and endpoint categories. For the following figures 7 and 9, for each category, impact values are divided by the maximum value achieved among the three buildings and are plotted in percentage, in order to effectively illustrate the building environmental performance comparison

Figure 7 reports the aggregated results of the LCA analysis over all the phases in terms of the midpoint categories related to the IMPACT 2002+ method. Results in terms of endpoint categories are shown in figure 8, when considering all the life-cycle stages of the buildings. As figures show, the greatest impact on human health is due to steel and wood structures, the highest impact on ecosystem quality and resource consumption is due to wood structure, and the greatest impact on climate change is caused by RC structure. Figure finally shows that RC structure has the least impact on each damage category, except climate change.

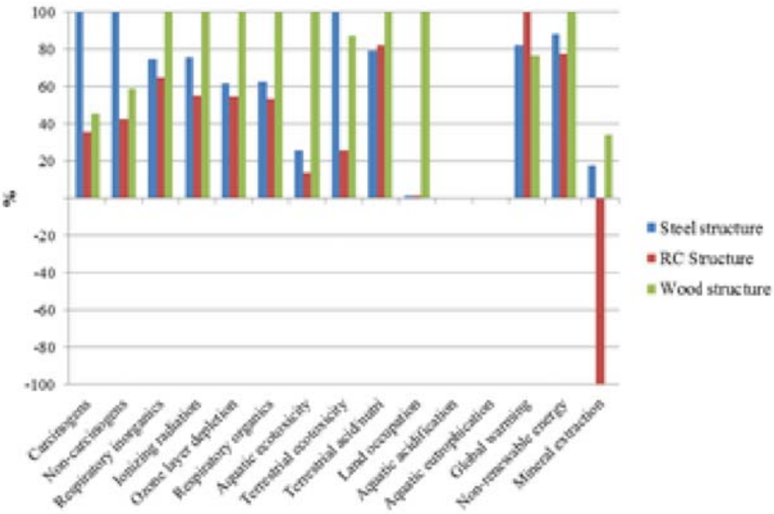

Figure 7: Comparative LCA results in terms of midpoint category according to the IMPACT2002+ method

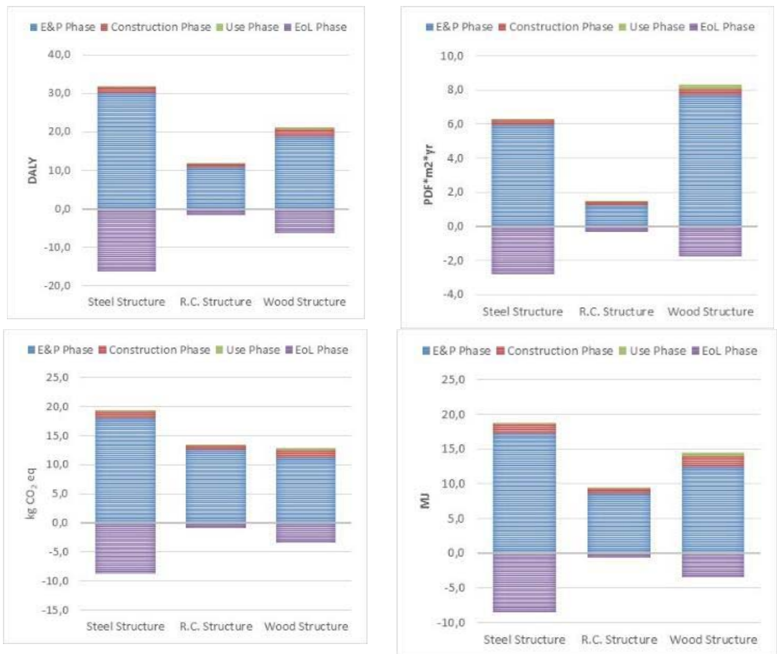

Figure 8: Comparative LCA results for each structural life-cycle phase in terms of endpoint category according to the IMPACT2002+ method: Human health (top-left); Ecosystem quality (top-right); Climate change (bottom-left); Resources (bottom-right)

A further elaboration of the environmental sustainability assessment has been provided for the case study. Indeed, data on the environmental impacts according to the EPD method (IEC, 2008) have been also computed and reported in Figure 9. In particular, the EPD method requires elaboration on some of the midpoint categories of the IMPACT 2002+ method. The EPD method provides impact assessment values regarding: global warming, ozone layer depletion, photochemical oxidation (equivalent to respiratory organics), acidification, eutrophication, non-renewables, and fossils (equivalent to non-renewable energy). Also according to this different Impact Assessment methodology, results show that the RC structure has the highest impact on global warming, followed by steel structure (80%) and then wood structure (75%). For all the other categories, a wood structure is responsible for the greatest impact, always followed by steel and RC structures.

Finally, Figure 10 shows the environmental impact according to the EPD method, considering each structural life-cycle phase. For the three structures, the greatest impact is generated by the extraction and production of building materials phase. Impacts due to transportation, construction, and maintenance amount to less than 10% of the impact due to extraction and the production of materials. The EoL phase's impacts equate to 20-50% of the extraction and production of materials phase. These results are similar to the ones shown in Figure 8.

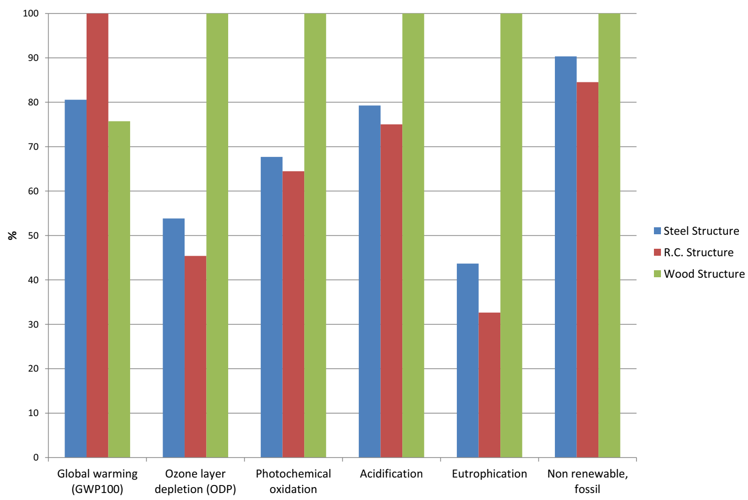

Figure 9: Environmental impact according to the EPD method

Figure 10: Environmental impact for each structural life-cycle phase according to the EPD method: Global warming (GWP) (top-left); Ozone layer depletion (ODP) (top-middle); Photochemical oxidation (POPC) (top-right); Acidification (AP) (bottom-left); Eutrophication (EP) (bottom-middle); Non-renewable, fossil (bottom-right)

4 Conclusions

In the present paper the authors have proposed a methodological approach to effectively perform a comparative environmental sustainability assessment of building structures, using an LCA-based analysis. The methodology has been applied to a case study, dealing with three alternative structural material options: RC, steel, and wood, and the related environmental impacts were quantified. Each option was designed to fulfil predefined structural, functional, and architectural requirements.

Authors can discuss some conclusions. Firstly, the environmental assessment of buildings has been analysed in different studies, but the presented one fixes external constraints on the minimum design performances, that should be considered for a comparative sustainable assessment. By comparing the different options, results revealed that RC structure is an environmentally worthy building solution. Indeed, RC structure has the highest impact only for one (climate change) out of four damage categories, according to IMPACT2002+, and one (climate change) out of six categories, according to EPD results, providing the lowest impacts for all the other categories. Steel structure is able to provide the widest benefit related to recycling. The study have revealed that there is no option that produces the best LCA-based environmental performance in all the impact categories. Indeed, the proposed methodology can support the decision-making process helping the designer to define the most sustainable alternative with respect to one of the environmental categories analyzed.

Moreover, authors want to point out that, besides the sustainability assessment methodology, the obtained environmental results depend on the case study considered and on the used databases. Future studies could include the enrichment of the proposed framework with energy performance indicators in the use-phase.

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