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# Methodology for Life-Cycle Sustainability Assessment of Building Structures

by M. C. Caruso, C. Menna, D. Asprone, A. Prota, and G. Manfredi

*This study aims to define a methodological framework that could guide construction community stakeholders in conducting environmental sustainability comparisons among building systems at the design stage. The study proceeds on the basis that the design of new structures starts with specific requirements, including national technical standards. An application of the proposed framework for the comparative life-cycle assessment (LCA) concerning a residential building is presented; three different structural materials are compared—namely, reinforced concrete (RC), steel, and wood. Starting with functional, architectural, and structural requirements, the building is designed and verified to take into account how structural solutions change depending on each building material. A cradle-to-grave LCA study is conducted for the three alternative structures using SimaPro software; both IMPACT2002+ and EPD2008 methodologies are used to quantify environmental impacts.*

**Keywords:** comparative sustainability assessment; life-cycle assessment (LCA); reinforced concrete structure; steel structure; sustainability; wood structure.

## INTRODUCTION

The construction and related industries are widely recognized as having a significant global impact on the environment. Furthermore, as a strategic economic sector and the primary pillar of social communities, these industries are attracting growing attention in terms of the sustainability of constructions. As far as environmental issues are concerned, many assessment tools have been progressively employed and developed to effectively drive decision-making processes in the direction of achieving sustainability goals. Some methodological frameworks analyze single or multiple aspects of environmental scenarios that are related to construction activities. These frameworks now form part of national/international standards and legislations, and can be mandatory or voluntary (Protocollo ITACA,<sup>1</sup> LEED,<sup>2</sup> SBTool,<sup>3</sup> HQE,<sup>4</sup> DGNB,<sup>5</sup> BREEAM,<sup>6</sup> GBC,<sup>7</sup> CASBEE<sup>8</sup>).

The life-cycle assessment (LCA) (ISO 14040<sup>9</sup>) has the potential to analyze overall environmental factors related to the entire life cycle of a building, and is increasingly employed in the engineering community. The main advantage of an LCA is that it makes it possible to quantify the impacts on (or damages to) the environment not limited to energy or CO<sub>2</sub> emissions, but also use of other renewable and non-renewable resources, covering the emission of many organic and non-organic compounds into the air, water, and soil, as well as ionizing radiation. Given these features, an environmental impact assessment in the construction industry using an LCA could be usefully adopted for: 1) the development of tools

and databases related to the impact of products, technologies, systems, and processes; 2) the selection of construction products; and 3) the evaluation of construction systems and procedures. It could be argued, however, that while an LCA of a single construction component or process can be effectively conducted according to process/manufacturing data, an entire building/structure would represent a system that is too complex to be assessed, with a very long lifespan that makes it difficult to conduct an LCA due to multifaceted procedures, hypotheses, data collection, and interpretations. Nevertheless, moving the LCA focus from single components to entire buildings and structures would significantly contribute to sustainability from the design phase onward, orienting the decision-making toward genuinely low-impact solutions. In fact, widening the scope of an LCA—that is, expanding the boundary of the system to the entire building, would allow consideration of indirect effects and interlinked correlations of the environmental impact caused by the multiple processes and products within a building system. This complexity would not emerge when considering the results of multiple LCAs of single components instead of the findings of a single LCA on an entire building.

Nevertheless, if an entire building is treated as a single, complex object to be analyzed, any LCA would require a rigorous framework, particularly when a comparative study between multiple options needs to be conducted for optimization purposes. In fact, when an LCA analysis is focused on an entire building, different design options (that can affect part or the complete set of building components) could be evaluated and then developed. On this basis, the environmental impact of the resulting configurations of a complete building could be compared, with the ultimate aim being to identify the design option that is able to minimize the full environmental impact.

Many pieces of work in the available literature follow this research direction and contain studies dealing with LCAs of entire buildings, and with different basic materials and methodological approaches. Gerilla et al.,<sup>10</sup> for instance, studied the environmental emissions of an energy consumption generated by the life phases of wood and reinforced concrete (RC) residential buildings in Japan with the same floor areas and design lifetimes. They also computed the

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level of emissions per year per square meter of the floor area. Peuportier,<sup>11</sup> meanwhile, used a comparative assessment to compare the environmental impact of different buildings with different floor areas but the same air conditioning and illumination properties. Xing et al.<sup>12</sup> performed a comparative LCA between a steel and an RC office building with different floor areas, while Asdrubali et al.<sup>13</sup> investigated the environmental impacts generated by three RC buildings of different volumes, using one square meter of usable floor area per year as a functional unit (FU). Different studies have also focused on various structural typologies. Pajchrowski et al.,<sup>14</sup> for example, assessed the environmental impact throughout the life-cycle of four equivalent buildings made of two different building materials, wood and masonry, while Guggemos and Horvath<sup>15</sup> compared the environmental effects of the construction phase of steel-framed and concrete-framed office buildings.

Nevertheless, within these kinds of study, the required building performances, such as structural capacity or design life-time, are sometimes not explicitly provided for and do not play a central role in the comparative assessments. According to the authors of these studies, this is a key factor that should be taken into account when defining the system boundary of an LCA analysis, especially when focusing on an entire building. In fact, comparing different design options can only be properly conducted when they satisfy some of the minimum requirements of designers. In other words, a comparison between the environmental performance of different design options can be properly carried out by: 1) designing different building configurations and adopting each of the options to be compared; 2) verifying that each building configuration satisfies some performance requirements, for example, structural properties, thermal insulation properties, and space availability; 3) performing an LCA of the different building configurations of a standardized LCA framework; and 4) interpreting and comparing the results according to such a framework.

Although the studies listed previously contain very useful information and valuable outcomes regarding the environmental impact of different solutions (in the design stage), it is notable that the “design-to-analysis” approach often lacks a common and rigorous framework. As such, the design constraints required to perform a robust environmental analysis and/or comparison to support the overall decision-making process are not properly defined. For instance, to conduct a comparative LCA among buildings made of different structural materials, constructions should have the same floor area, volume, and overall performance. This means that the investigated buildings should be designed to assure that a minimum number of accepted performances is guaranteed.

To this end, a framework for comparative life-cycle assessment of building structures is proposed, which establishes a set of preliminarily requirements related to the context-sensitive nature of this kind of studies and to the macroscopic scale of the building system. The approach is applied for the assessment of the life-cycle environmental impacts of three residential buildings made of three different structural materials. The three residential buildings have

identical volumetric and architectural features and requirements. One of the major requirements concerns the fixed structural performance of the three options, which means that the building structures are designed in accordance with the Italian structural code and calculations are based on the same loads and hazard intensity. The environmental impact of the buildings is assessed according to the LCA procedure (ISO 14040<sup>9</sup>).

## RESEARCH SIGNIFICANCE

Several works dealing with the environmental assessment of buildings have been recently conducted in the research community for sustainability purposes. Most of the comparative studies focus on the life-cycle assessment of buildings having different volumes, functionality, use or structural typology and the reference unit is sometimes the building net area or volume unit. However, the required building performances (structural capacity or long-term performance) should be explicitly set as basic parameters when defining the system boundary of an environmental sustainability evaluation by means of life-cycle assessment. To this end, the authors propose a general framework that provides a set of requirements preliminarily defined for a comparative life-cycle assessment. The approach is applied to a case study where the structural materials are considered as a design option.

## ANALYTICAL PROCEDURE

During the design stage, the component/building structural performance is the main “parameter” that drives the designer, along with the subsequent need to satisfy structural codes and guidelines. 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, final use, number of stories, available resources, and functional systems. Accordingly, the usual building design process moves from optional choices that must inevitably be taken into account in the structural performance assessment performed by the designer. Given these considerations, and from the perspective of a sustainability comparative assessment, in this proposed approach, a set of “building system requirements” is defined for the building element/system, accounting for functional, architectural, structural, and economic performances, as well as other factors specifically defined by the end users of the buildings (refer to Fig. 1, steps 1 to 2). These requirements are interconnected (in the horizontal direction of Fig. 1, step 1) because the choice of one specific requirement can affect the others. For instance, the definition of the use of a structure/building (residential, office, strategic infrastructure, and so on) primarily affects the architectural, structural, and economic features linked to the decision-making at the design phase. Moreover, some of the requirements depicted in Fig. 1, steps 1 through 2 are site-specific, and depend on the climatic zone, hazards, and local constraints related to the position of the building. Within this framework (which is essentially based on performance requirements), the comparative evaluation of different design options at the design stage with reference to structural and/or non-struct-

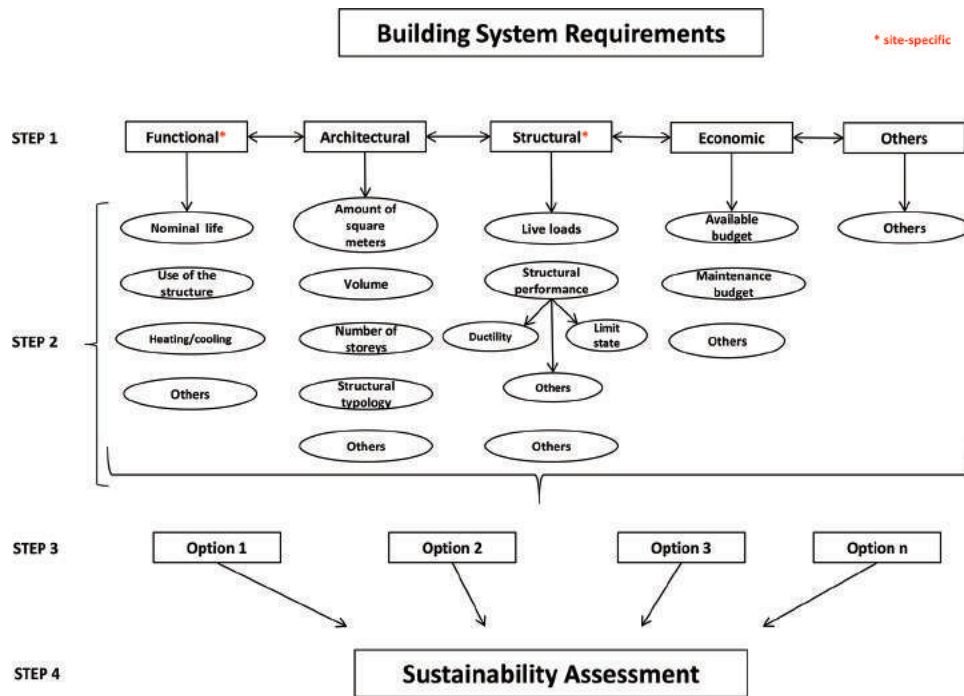


Fig. 1—Proposed approach to building structure's sustainability.

tural elements (named as the subassembly level) can be effectively performed at the level of the final product system (assembly level), that is, the entire building/structure. In this way, the environmental effects associated with one or more subassembly options can be effectively regarded at a global level that is representative of the final product.

These requirements first depend on building use and location in terms of live loads, hazards, and environmental condition (very aggressive, aggressive, and nonaggressive). The feasible options are identified based on these requirements, and take into consideration several additional constraints, such as common and local construction techniques and materials, overall cost, and national standards establishing minimum performances (Fig. 1, step 3). Once the minimum design parameters are computed for all the options, and the different building configurations are designed, the building sustainability assessment is performed using common sustainability tools (Fig. 1, step 4). In this way, the proposed framework defines the system boundary that should be built to compare different products within a given building structure.

A sustainability assessment can examine environmental, social, and/or economic aspects. However, for this study, the focus is only on environmental issues as the main objective of the comparative analysis based on the presented methodological framework (step 4). Environmental sustainability can be examined by a variety of assessment tools, and the LCA is 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<sup>9</sup> and ISO 14044<sup>16</sup>: 1) goal and scope definition; 2) life-cycle inventory (LCI) analysis; 3) life-cycle

impact assessment (LCIA); and 4) results (Fig. A1, available in the Appendix\*).

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. A general system boundary can be described as follows, taking into consideration the different levels of the environmental analysis: 1) life-cycle stages (including the material manufacturing, construction, use and maintenance, and end of life stages); 2) building industry (including the building, product, and material levels); 3) LCI (including emissions from material manufacturing and resources used for this purpose, and emissions from energy combustion in the complete life-cycle); 4) phase of the design process (including design development stage); and 5) life-cycle impact categories, including, for instance, global warming potential (GWP).

The system boundary definition for LCA applications in the construction industry is described in detail in EN 15978,<sup>17</sup> which provides a standard for measuring the environmental sustainability of buildings and classifies the life-cycle stages into four modules (Fig. A2). The detailed information is available in the Appendix.

## CASE STUDY

The described methodological approach is implemented in this paper to perform a sustainability assessment of three structural options for a residential building. The focus is mainly on the structural requirements (Fig. 1, steps 1

\*The Appendix is available at [www.concrete.org/publications](http://www.concrete.org/publications) in PDF format, appended to the online version of the published paper. It is also available in hard copy from ACI headquarters for a fee equal to the cost of reproduction plus handling at the time of the request.

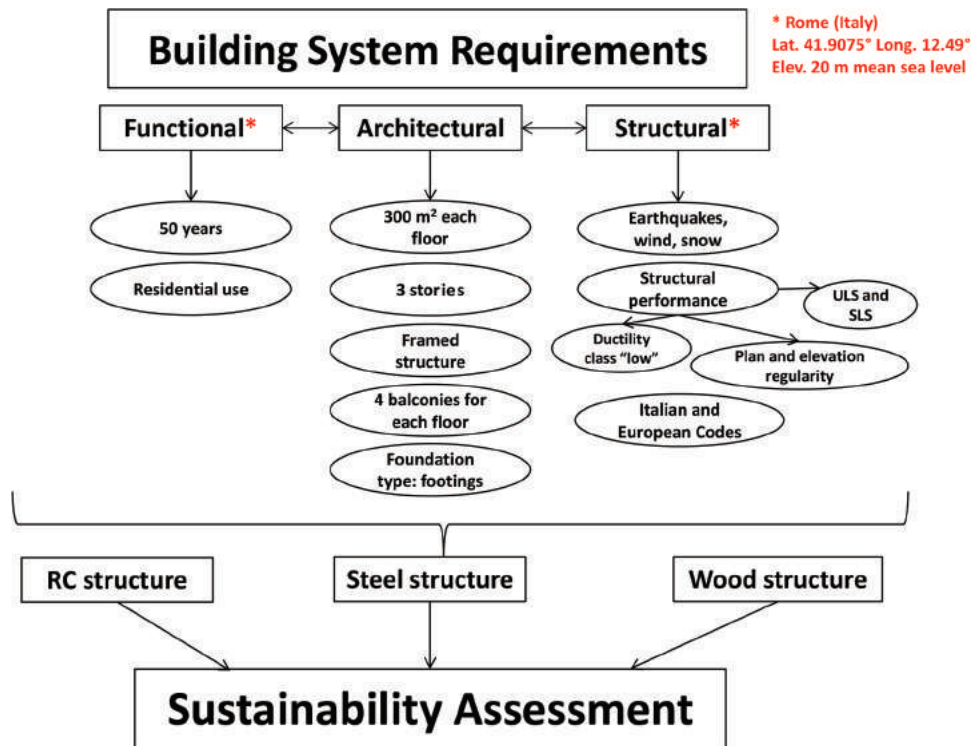


Fig. 2—Proposed approach applied to case study.

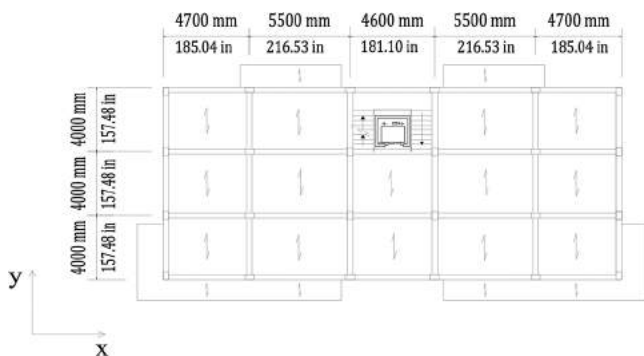


Fig. 3—Floor plan.

through 2). This reflects the concept that the structural factors represent the first prerequisites evaluated by designers. The environmental performances are thus affected by this “extended” system boundary. In particular, the scope of the study is to compare the environmental impact of materials and processes related to the complete life-cycle of an RC, steel, and wood structure. The building is ideally located in the municipality of Rome, Italy (lat. 41.9075 degrees; long. 12.49 degrees; elevation 20 m mean sea level) in ordinary environmental conditions. The LCA is only applied to the structural frame of the building, and assumes that non-structural elements and systems do not vary within the different options. This assumption is introduced only for the sake of the simplicity of the analysis and should be verified and possibly removed in real cases. Indeed, non-structural components could vary with the adopted structural system, and this would affect the overall environmental impact. Figure 2 shows how the analytical procedure is modeled for the case study. The same architectural, functional, and

structural requirements are considered for the three material options and are fully described in the subsequent paragraphs.

### System requirements

The LCA is based on the definition of the building system’s requirements, which can be divided into three subcategories: 1) architectural; 2) functional; and 3) structural.

The following properties are defined for the architectural requirements (refer to Fig. 2 as a reference): the structural plan dimensions are 12 x 25 m<sup>2</sup> (39.37 x 82.02 ft<sup>2</sup>) (300 m<sup>2</sup> [3229 ft<sup>2</sup>] each floor), with three 4 m (157.48 in.) spans in the y-direction and five variable dimensions (4.7, 5.5, 4.6, 5.5, 4.7 m; [185.04, 216.53, 181.10, 216.53, 185.04 in.]) spans in the x-direction (framed structure), according to Fig. 3. The building is composed of three stories: 1) the ground floor (4.5 m [177.16 in.] interstory from the top of the foundations); 2) the first floor (3 m [118.11 in.] interstory); and 3) the mansard floor (3 m [118.11 in.] top interstory, 2 m [78.74 in.] eaves interstory). Each floor hosts two 130 m<sup>2</sup> (1399 ft<sup>2</sup>) apartments with two 1.4 m (55.12 in.) balconies each. The foundation system is composed of RC footings and connection beams framed in two orthogonal directions. Stairs are connected to the structures and composed of knee beams. Figure 3 shows the complete floor plan.

The building use and nominal life of the structure are set as functional requirements. The structure is a residential building, and has a nominal life of 50 years. This period is also used as an input in the LCA-based environmental analysis of the building.

In terms of structural requirements, the following factors are set as design parameters. The considered loads are snow, wind, seismic actions, and live loads (Table 1), and these are determined based on the geographical location

of the building. Dead loads are also considered in design process of the three alternative buildings. Contrary to live and environmental loads, dead loads only depend on the single structure characteristics and are combined with the

ones listed in Table 1, complying with the Italian code indications. The structures are designed and verified according to the Italian structural code, NTC 2008,<sup>18</sup> and the related Circolare n°667/2009.<sup>19</sup> In this paper, Eurocode 3<sup>20</sup> is also considered for the steel structure and CNR-DT 206/2007<sup>21</sup> for the wood structure. The structures are designed and verified against the ultimate limit state (ULS) and service limit state (SLS) in accordance with the Italian code. Contrary to Eurocode stating that the structure shall be designed to have adequate structural resistance, serviceability, and durability, in the building design process of the case study, durability issues are taken into account through the SLS and ULS verifications as well as through maintenance and material qualification requirements, following the Italian code indications, Chapter 11.<sup>18</sup> In particular, structural materials were chosen according to the durability requirements and were subjected to specific treatments, as reported in the Pre-use phase (for

**Table 1—Load values at ULS**

Load type	Value	Units
Snow	480 (0.0696)	N/m <sup>2</sup> (lbf/in. <sup>2</sup> )
Windward	815 (0.1182)	N/m <sup>2</sup> (lbf/in. <sup>2</sup> )
Downwind	-490 (-0.0711)	N/m <sup>2</sup> (lbf/in. <sup>2</sup> )
Earthquake	0.118	a <sub>g</sub> /g, PGA
Internal live loads	2000 (0.2901)	N/m <sup>2</sup> (lbf/in. <sup>2</sup> )
Roofing live loads	500 (0.0725)	N/m <sup>2</sup> (lbf/in. <sup>2</sup> )
Staircase and balcony live loads	4000 (0.5801)	N/m <sup>2</sup> (lbf/in. <sup>2</sup> )

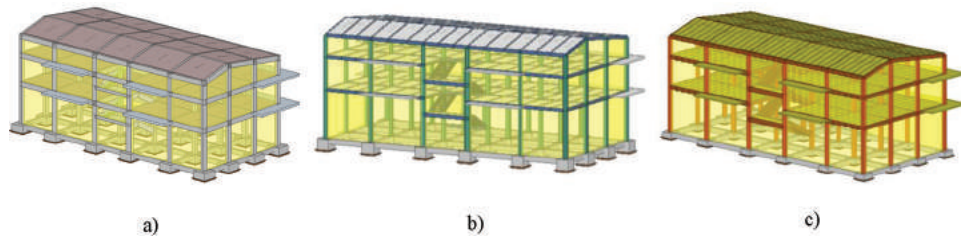


Fig. 4—(a) RC structure; (b) steel structure; and (c) wood structure.

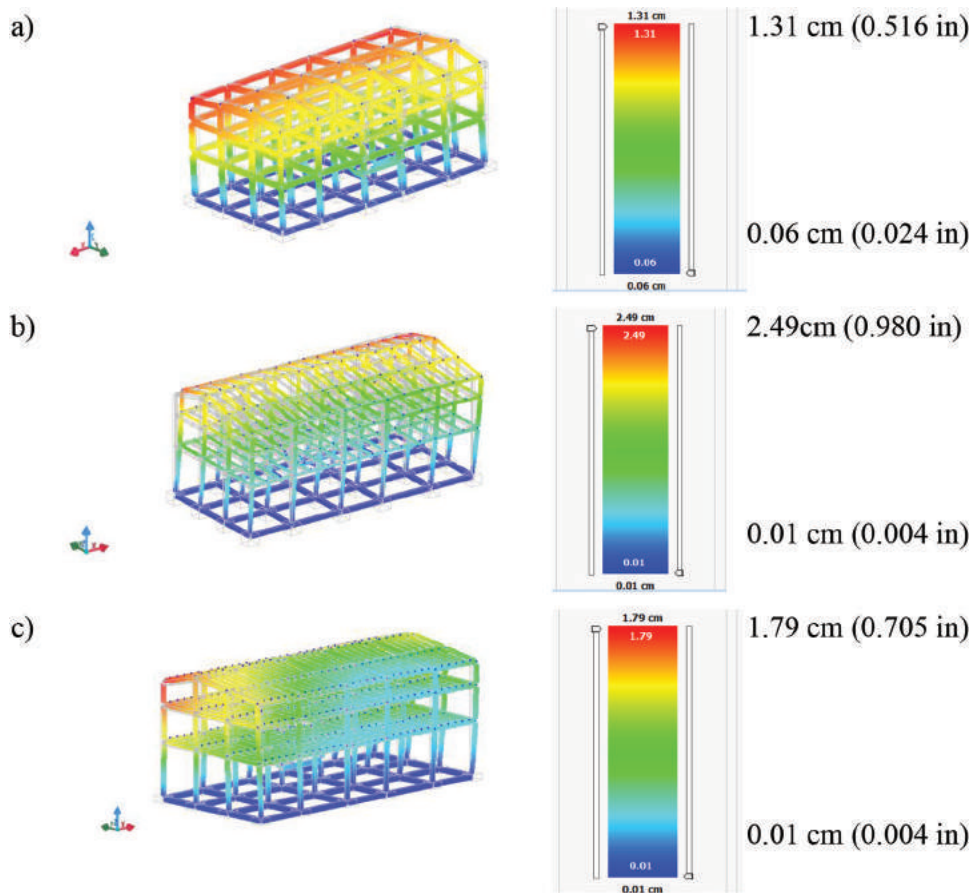
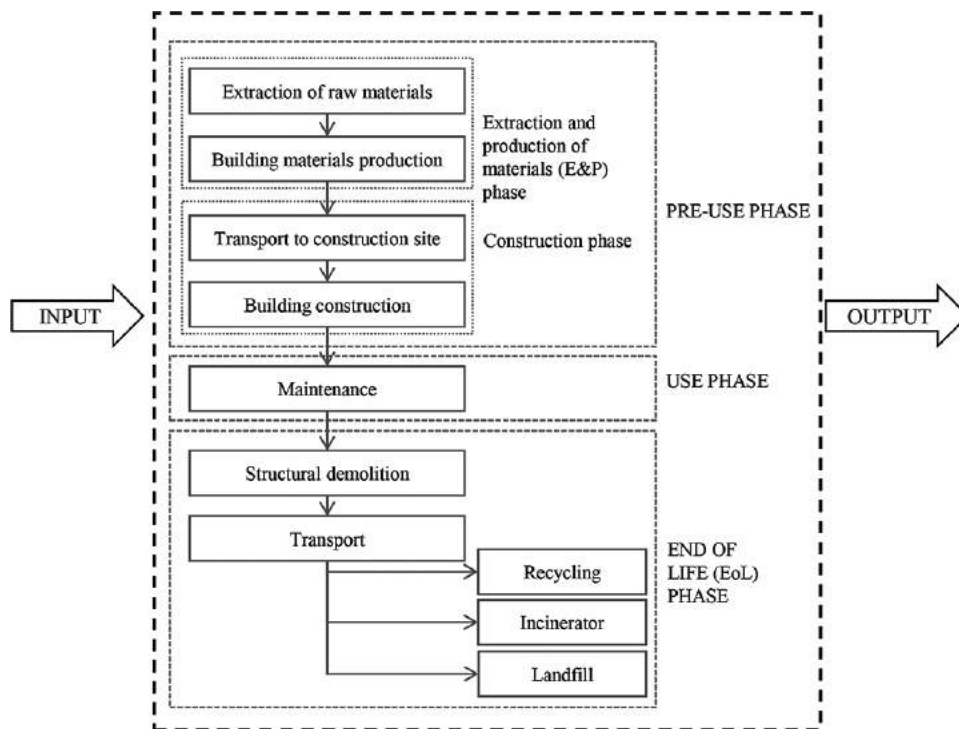


Fig. 5—SLS displacements under positive/negative x-direction earthquake: (a) RC structure; (b) steel structure; and (c) wood structure.

**Table 2—Vibration modes**

	Mode	Spectrum	Period $T$ , s	Horizontal spectral acceleration $S_d(T)$ , $m/s^2$ (in./s <sup>2</sup> )	Participating mass, $N \cdot s^2/m$ = kg (lb)	Participating mass, %
RC structure	1	ULS x	0.464	1.454 (57.244)	817,784 ( $1.802 \times 10^6$ )	76.5
	2	ULS y	0.416	1.454 (57.244)	763,844 ( $1.684 \times 10^6$ )	71.5
	3	ULS y	0.065	1.615 (63.583)	138,831 ( $0.306 \times 10^6$ )	13.0
Steel structure	1	ULS y	0.861	0.774 (30.472)	544,880 ( $1.201 \times 10^6$ )	67.1
	2	ULS x	0.755	0.883 (34.764)	496,393 ( $1.094 \times 10^6$ )	61.1
	3	ULS y	0.066	1.600 (62.992)	138,186 ( $0.305 \times 10^6$ )	17.0
Wood structure	1	ULS y	0.619	1.077 (40.402)	275,093 ( $0.606 \times 10^6$ )	52.6
	2	ULS x	0.573	1.164 (45.827)	192,176 ( $0.424 \times 10^6$ )	36.7
	3	ULS y	0.076	1.578 (62.126)	143,941 ( $0.317 \times 10^6$ )	27.5



*Fig. 6—System boundary of case study.*

example, galvanization of steel elements and surface treatments on glued laminated timbers). In addition, a maintenance plan was considered during the use phase of the structures to avoid durability issues. A structural assessment for the seismic condition has been performed using a dynamic linear analysis.

**Structural design and verification**

The RC, steel, and wood structures have been designed using the common design software Edilus v26.00, developed by ACCA Software S.p.A.<sup>22</sup> Edilus is a structural analysis software for design and verification of new and existing structures according to a Eurocode-like approach<sup>23</sup>; this software guides the user to conduct the design of the structure by following a step-by-step procedure, including the definition of generic building characteristics, geometry, cross sections, loads, material properties. Then, software checks if demand is lower than available members’ strength

to verify the compliance with the structural code considered (in our case the Italian structural code<sup>18</sup>). For the case study, the design consisted of the definition of the geometry and mechanical properties of the structural members that belong to the three different buildings. In relation to Fig. 2, the requirement that must be satisfied for the comparative assessment between the different options consists of a set of structural performances posed by the structural code. In detail, the RC structure consists of C25/30 concrete and B450C reinforcing steel classes, with a cross section of 30 x 50 cm<sup>2</sup> (11.81 x 19.68 in.<sup>2</sup>) for the beams and columns and 35 x 50 cm<sup>2</sup> (13.78 x 19.68 in.<sup>2</sup>) for the knee beams of the stairs. The cast-in-place RC slabs are 22 cm (8.66 in.) 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

**Table 3—Material and process amounts and data sources**

Materials/processes	Unit of measure	RC structure	Steel structure	Wood structure	Data
Concrete C25/30	m <sup>3</sup> (in. <sup>3</sup> )	251.01 (15.318 × 10 <sup>6</sup> )	118.07 (7.205 × 10 <sup>6</sup> )	63.62 (3.882 × 10 <sup>6</sup> )	Average data by AITEC
Steel B450C	kg (lb)	28186.57 (62.141 × 10 <sup>3</sup> )	10547.93 (23.25 × 10 <sup>3</sup> )	4284.56 (9.45 × 10 <sup>3</sup> )	Reinforcing steel, at plant/RER U (Ecoinvent)
Steel S235-S275-8,8	kg (lb)	—	74265.15 (163.73 × 10 <sup>3</sup> )	24926.73 (54.95 × 10 <sup>3</sup> )	Steel, low-alloyed, at plant/RER U (Ecoinvent)
Bricks	kg (lb)	85363.2 (188.19 × 10 <sup>3</sup> )	—	—	Brick, at plant/RER U (Ecoinvent)
Glued laminated timber GL32h	m <sup>3</sup> (in. <sup>3</sup> )	—	—	138.69 (8.463 × 10 <sup>6</sup> )	Glued laminated timber, outdoor use, at plant/RER U (Ecoinvent)
Zinc coating	m <sup>2</sup> (in. <sup>2</sup> )	—	830 (8934.04)	—	Zinc coating, pieces/RER U (Ecoinvent)
Powder coating	m <sup>2</sup> (in. <sup>2</sup> )	—	830 (8934.04)	—	Powder coating, steel/RER U (Ecoinvent)

secondary beams. The steel-concrete slabs are made of S235 A55/P600 HI-BOND corrugated sheets and 6.5 cm (2.56 in.) high RC cover slabs. The wood structure is composed of LL GL32h glued laminated wood class, with a cross section of 16 x 36 cm<sup>2</sup> (6.30 x 1 4.17 in.<sup>2</sup>) for the beams, 20 x 44 cm<sup>2</sup> (7.87 x 17.32 in.<sup>2</sup>) 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 14 x 28 cm<sup>2</sup> (5.51 x 11.02 in.<sup>2</sup>) wood joists with 80 cm (31.50 in.) of axle spacing, 4 cm (1.57 in.) of concrete slab, and 3.5 cm (1.40 in.) of wooden floorboards. Figures 4(a), (b), and (c) show the structural models.

Table 2 lists the first three vibration modes of the three structures, considering both the x and y ULS seismic actions that indicate the period, horizontal acceleration, and participating mass of each mode.

Figure 5 shows the results of one of the considered displacement scenarios at the SLS under seismic action. As expected, the displacement response is different for each structure; the RC structure (Fig. 5(a), maximum top displacement equal to 1.31 cm (0.52 in.) in the direction of the seismic action) is stiffer than the wood (Fig. 5(c), maximum top displacement equal to 1.79 cm [0.70 in.]) and the steel structures (Fig. 5(b), maximum top displacement equal to 2.49 cm [0.98 in.]). The displacement analysis herein reported represents an indication on the displacement performance of the buildings at the SLS. However, in the approach of Fig. 1 the structure displacements (either at SLS and ULS) could be set as further structural requirements to link this parameter to the safety of the occupants and serviceability of the building.

### LIFE-CYCLE ASSESSMENT

Once the minimum design parameters were set for the three building options, we built sustainability assessment models of these options based on the LCA methodology, following the scheme set out in Fig. A1 (in the Appendix). According to the first phase of the LCA, the FU and system boundary were defined. The FU chosen for this analysis was the entire building. In particular, the estimated impacts were related to the materials and processes needed to build the

structural system. The system boundary is shown in Fig. 6 and includes: 1) the pre-use phase (E&P, extraction, and the production of materials and construction phases); 2) the use phase (ordinary maintenance of structural elements); and 3) the EoL phase (EoL, building demolition, and material disposal). In the EoL phase, mechanical demolition is chosen and it is assumed that the materials are to be sent for recycling, landfill, and/or to an incinerator. The amounts of these materials were assumed according to national rates. Stages from A1 to A7 were all considered according to EN 15978<sup>17</sup> (Fig. A2). In module B, only the B2 stage (ordinary maintenance) was taken into account, because use consumptions depend on the non-structural parts of buildings, and these were not analyzed in the case study. Moreover, the structures do not need extraordinary maintenance (repair, replacement, or refurbishment), because they are designed with a nominal life of 50 years (equal to the life-cycle period). All the stages of Module C were considered, except C2, because the same distance to the waste management site hypothesis was adopted. Module D was considered for the amounts of products going for recycling.

The LCI analysis and LCIA were developed for each of the building life-cycle phases reported in Fig. 6.

The LCI analysis and LCIA were performed using the SimaPro 7.3 software.<sup>24</sup> SimaPro is an efficient tool<sup>24</sup> that is useful to collect sustainability data and to analyze and monitor the sustainability performance of products/services. It has been used in several environmental studies available in the open literature.<sup>25,26</sup> The software includes a set of international databases and impact assessment methodologies. Ecoinvent 2.2 international database<sup>27</sup> was chosen as main source for the life-cycle inventory. It is a wide environmental database, including compositions, production processes, disposal scenarios of most of the existing materials, industrial processes and construction materials. IMPACT2002+ methodology<sup>28</sup> and EPD<sup>29</sup> methodology were selected for the impact assessment phase of the study. For the sake of brevity, the complete description of the impact assessment methodologies is reported in the Appendix. The IMPACT 2002+ methodology<sup>28</sup> was used for the LCIA, with impacts evaluated for 15 midpoint categories that were grouped

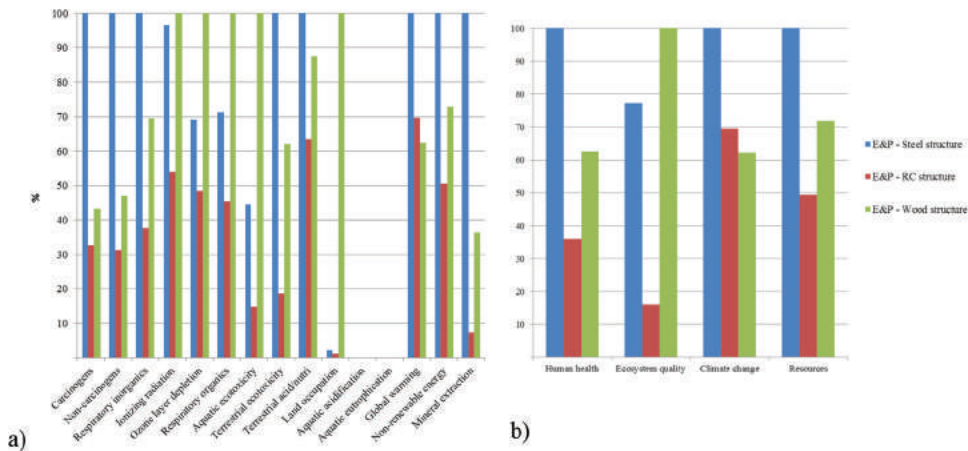


Fig. 7—Environmental impact for extraction and production of raw materials phase: (a) environmental impact for each midpoint category; and (b) environmental impact for each endpoint category.

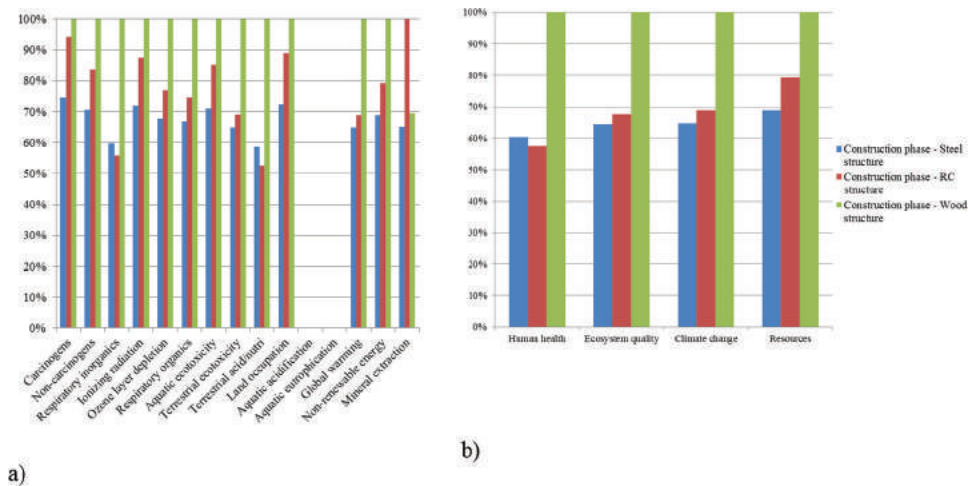


Fig. 8—Environmental impact for construction phase: (a) environmental impact for each midpoint category; and (b) environmental impact for each endpoint category.

into four damage categories: 1) human health, measured in DALY (disability-adjusted life years); 2) ecosystem quality, measured in PDF\*m<sup>2</sup>\*yr (the potentially disappeared fraction of species over a certain amount of m<sup>2</sup> during a certain amount of year); 3) climate changes, measured in kg-equivalents to a reference substance; and 4) resources, measured in MJ.<sup>28</sup> The details of the Impact Assessment methodologies are summarized in the Appendix. The building life-cycle phases are described in the following, along with the related environmental impact determined from the LCA analysis.

## RESULTS AND DISCUSSION

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

In this phase, the amounts of structural materials required for producing the beams, columns, joints, slabs, stairs, foundations, and balconies of each structure were computed. All the processes before the construction phase were also considered. Ecoinvent data were used for each material except concrete; the data concerning concrete were modified using more refined Italian data collected by detailed environmental product declarations. Structural steel is composed of 37% recycled steel (from energy-optimizing furnaces) and

63% new steel (from basic oxygen furnaces) according to the Ecoinvent data. Coatings to prevent steel corrosion and wood treatments were also included. Table 3 lists the amount of materials and processes, as well as the data sources.

For each life-cycle phase of the three buildings, the results are shown in terms of midpoint and endpoint categories. For each category, impact values are divided by the maximum value achieved among the three buildings and are plotted in percentage, to effectively illustrate the building environmental performance comparison.

Figure 7 shows that the steel and wood structures had the greatest environmental impact in the E&P phase. A wooden structure made the highest contribution to ecosystem quality, while a steel version had the greatest impact on human health, climate change, and resources. It was also found that the steel material was responsible for the highest impact of a steel structure, while glued laminated timber was responsible for the greatest impact of a wooden structure on ecosystem quality.

### Pre-use phase—construction phase

The construction phase includes the transportation of materials from plants to construction sites and all the processes



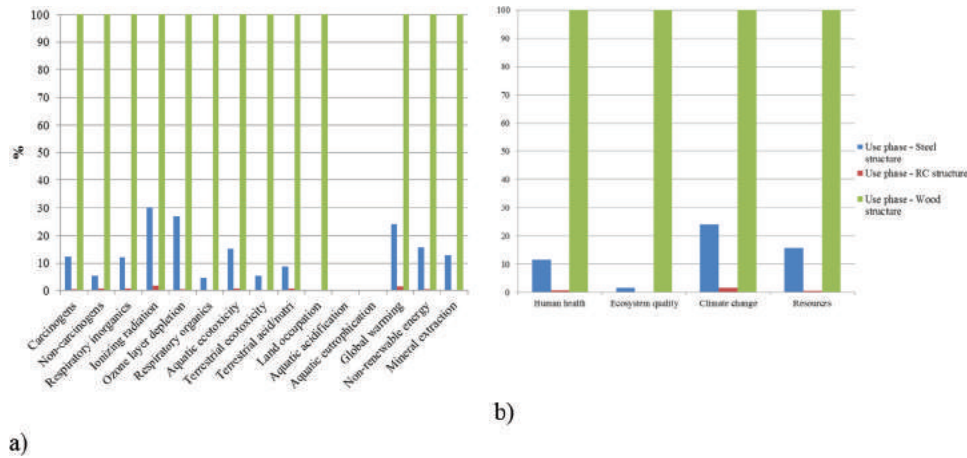


Fig. 9—Environmental impact for use phase: (a) environmental impact for each midpoint category; and (b) environmental impact for each endpoint category.

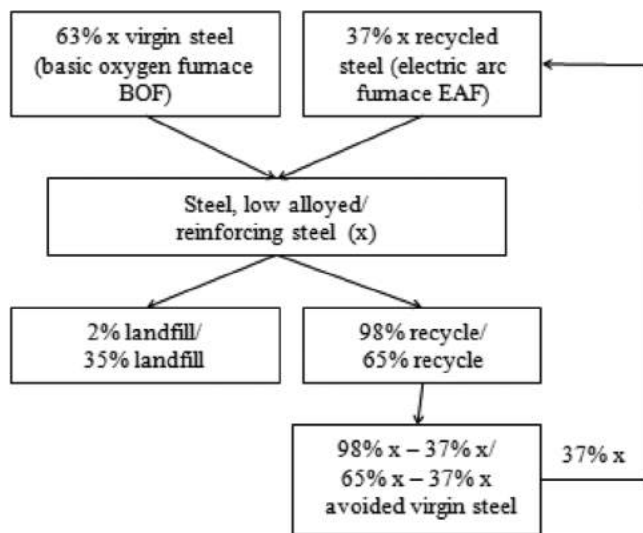


Fig. 10—Open loop with closed-loop recycling procedure for steel.

needed to build the structural systems. It was assumed that the concrete and reinforcing steel plants were 30 km (18.64 miles) from the construction site when considering the transportation phase.<sup>30</sup> The Riva production plant in Patrica (FR) was chosen (87.5 km [54.37 miles] from Rome) for the steel elements and the Rubner Holzbau production plant in Calitri (AV) (249 km [154.72 miles] from Rome) for the wooden elements.

Figure 8 shows that a wooden structure causes the most damage to human health. Such buildings also affect ecosystem quality, the climate, and resources, mainly due to the transportation phase.

### Use phase

In the use phase, only ordinary maintenance is considered because the study's focus is 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 was assumed. The steel elements of the steel structure were assumed to be subjected to zinc<sup>31</sup> and a powder coating during production to prevent envi-

Table 4—Waste scenario

Materials	Recycling, %	Incinerator, %	Landfill, %	Reference
Concrete/inert materials	65	0	35	ISPRA
Steel	98	0	2	Arcelor-Mittal <sup>35</sup>
Reinforcing steel	65	0	35	Arcelor-Mittal <sup>35</sup>
Glued laminated timber	16	4	80	TRADA <sup>37</sup>

ronmental corrosion. Consequently, according to UNI EN ISO 14713,<sup>31</sup> given the typical consumption of this kind of coating,<sup>32,33</sup> it was assumed that only limited maintenance would be required and, consequently, powder coating on just 20% of the total metallic surface was 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 were therefore assumed.

Figure 9 shows that RC and steel structures require less maintenance than wood versions. The ordinary maintenance of glulam structures had the greatest impact due to the need to frequently apply preservatives. Nevertheless, there were fewer impacts due to the use phase than the other phases.

### End-of-life phase (EoL phase)

The EoL phase includes structure demolition and material disposal. Mechanical, conventional demolition was chosen for each structure, and was assumed to be carried out by one excavator with a hydraulic hammer (for foundation demolition) and jaw (for structure demolition and inert crushing), one wheel loader, and 28 m<sup>3</sup> (988.81 ft<sup>3</sup>) lorries to remove demolition waste from the site. The RC structure demolition would need three 28 m<sup>3</sup> (988.81 ft<sup>3</sup>) lorries carrying inert waste for 17 journeys and one such lorry carrying steel waste for one journey. The demolition of the steel structure would

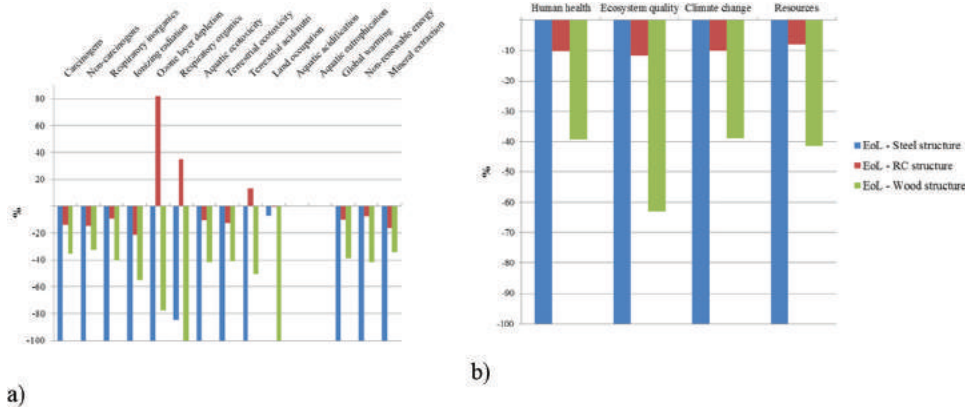


Fig. 11—Environmental impact for end-of-life phase: (a) environmental impact for each midpoint category; and (b) environmental impact for each endpoint category.

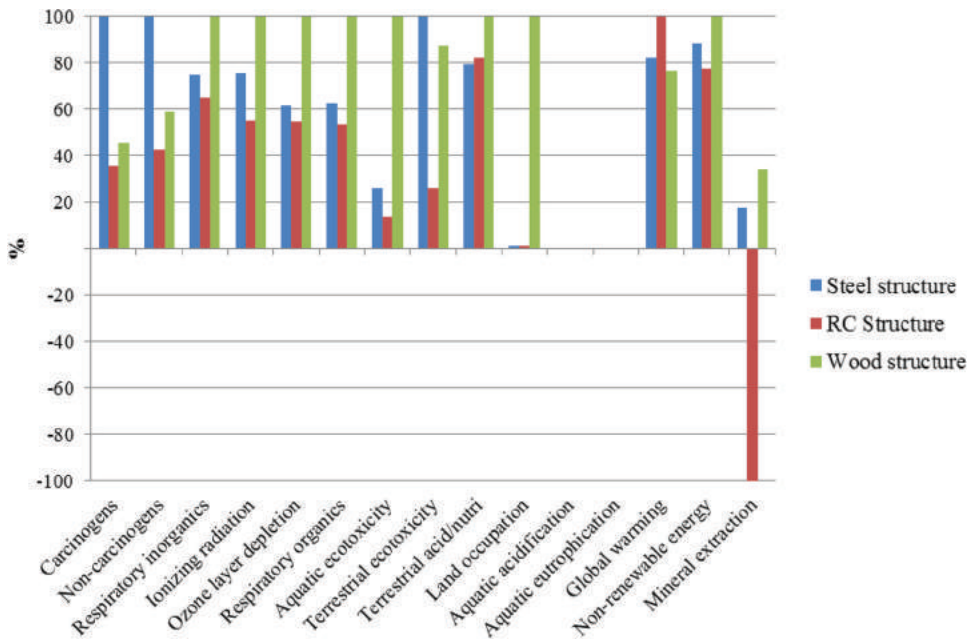


Fig. 12—Environmental impact for each midpoint category according to IMPACT2002+ method.

require two lorries carrying inert waste for six journeys and two carrying steel waste for six journeys. Finally, demolition of the wood structure would need one lorry carrying inert waste for three journeys, one carrying steel waste for one journey, and two carrying wood waste for seven journeys.

After demolition, it was 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 (18.64 miles) away. The separated materials were sent for recycling, landfill, and/or to an incinerator according to national or European reference amounts. The recycled materials were computed in SimaPro as an avoided product. According to ANPAR<sup>34</sup> 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,<sup>35</sup> 65% of reinforcing steel is recycled and 35% is sent to landfill. Given that reinforcing steel is composed of 37% recycled steel, 28% (that is, 65% minus 37%) of steel leaves the system boundary and is modeled

as avoided new steel (from basic oxygen furnaces).<sup>36</sup> Also according to ArcelorMittal,<sup>35</sup> 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% (that is, 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,<sup>37</sup> 16% of glued laminated timber is recycled, 4% is sent to an incinerator, and 80% for landfill. Table 4 lists the waste scenarios for building materials, while Fig. 10 shows the recycling procedure for steel just described.

In terms of demolition, transportation, and material disposal, Fig. 11 shows that steel structure has the lowest impact on human health, ecosystem quality, climate change, and resource use. The demolition and transportation phases make little contribution to overall EoL. The main parameter influencing the results is the recycling steel percentage, which is higher than the percentage of the other materials.

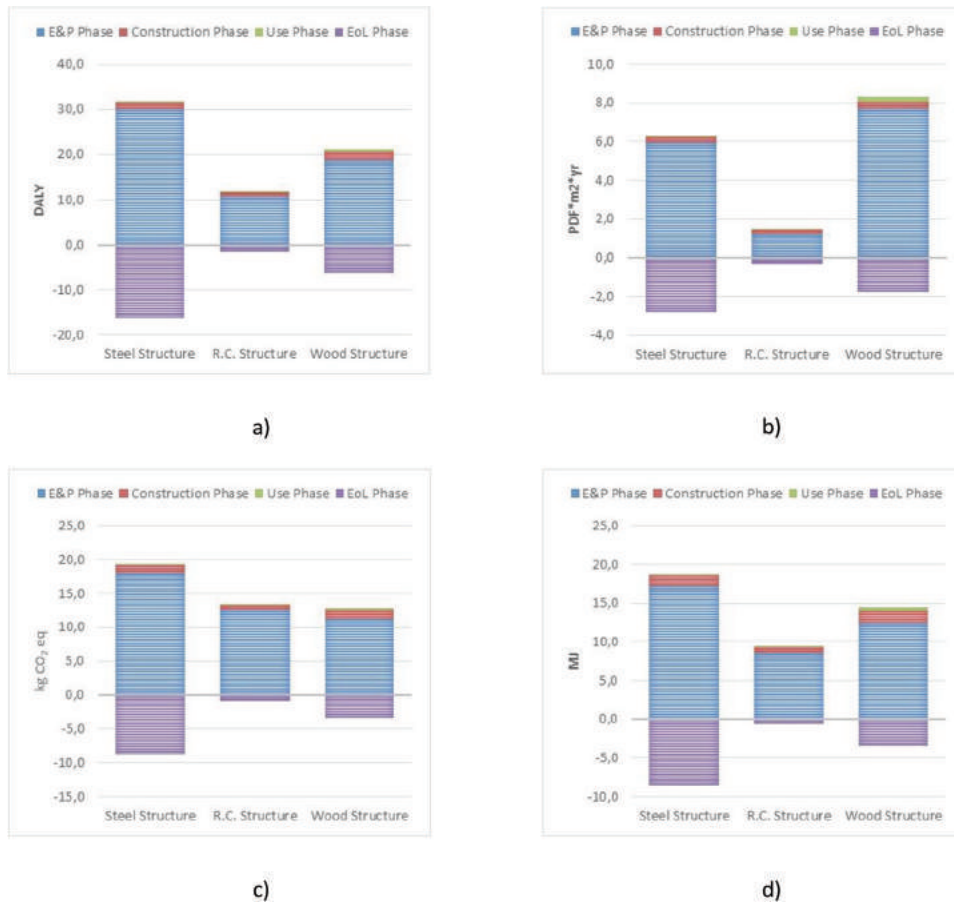
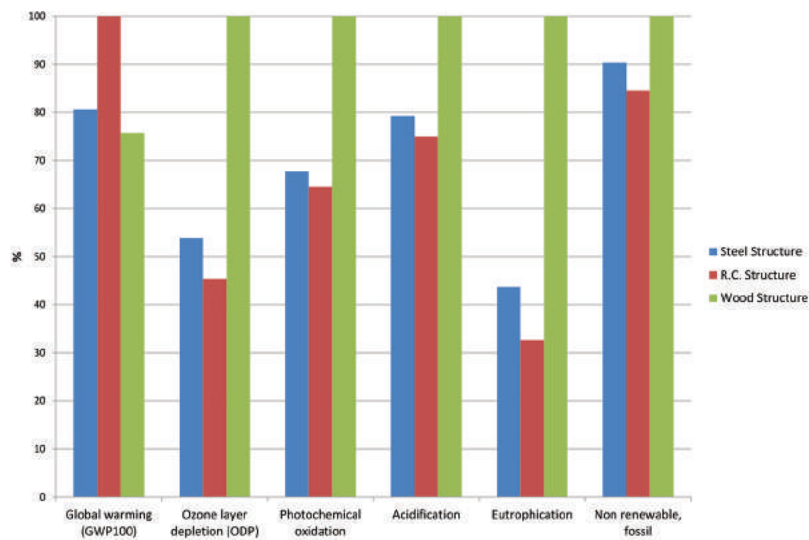


Fig. 13—Environmental impact for each structural life-cycle phase considering each endpoint category according to IMPACT2002+ method: (a) human health; (b) ecosystem quality; (c) climate change; and (d) resources.



Impact category	Unit	Steel structure	RC structure	Wood structure
Global warming (GWP100)	kg CO <sub>2</sub> eq	1,06E+05	1,31E+05	9,94E+04
Ozone layer depletion (ODP)	kg CFC-11 eq	1,02E-02	8,59E-03	1,89E-02
Photochemical oxidation	kg C <sub>2</sub> H <sub>4</sub> eq	1,07E+02	1,02E+02	1,58E+02
Acidification	kg SO <sub>2</sub> eq	3,48E+02	3,29E+02	4,39E+02
Eutrophication	kg PO <sup>4-</sup> eq	1,66E+02	1,24E+02	3,79E+02
Non renewable, fossil	MJ eq	1,51E+06	1,41E+06	1,67E+06

Fig. 14—Environmental impact according to EPD method.

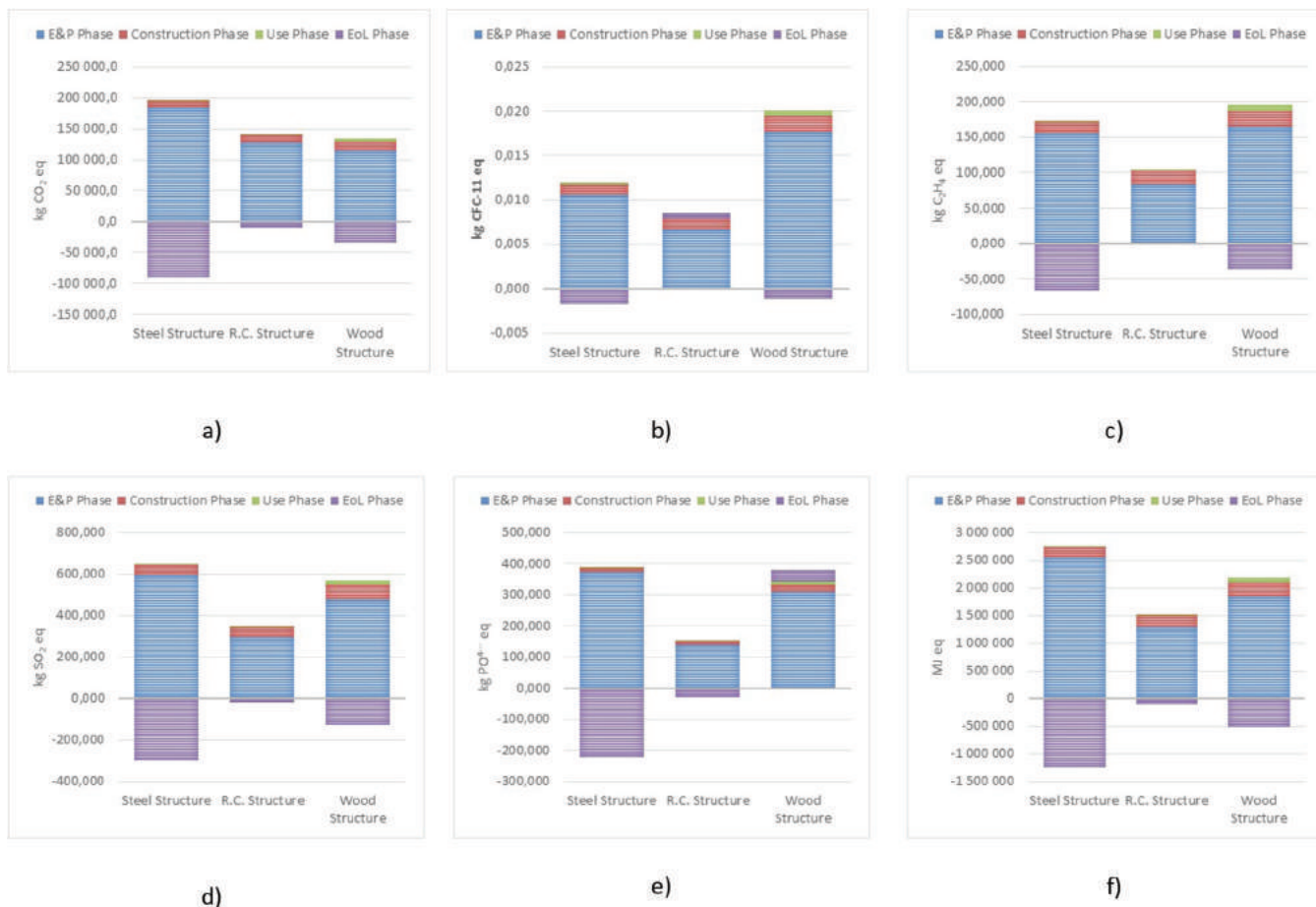


Fig. 15—Environmental impact for each structural life-cycle phase according to EPD method: (a) global warming (GWP); (b) ozone layer depletion (ODP); (c) photochemical oxidation (POPC); (d) acidification (AP); (e) eutrophication (EP); and (f) non-renewable, fossil.

### Global impact assessment

Figure 12 reports the aggregated results of the LCA analysis over all the phases in terms of the mid-point categories of the IMPACT 2002+ method. Figure 13 shows the environmental impact for each damage category when considering all the life-cycle stages of the buildings. It can be demonstrated that 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, and the greatest impact on climate change is caused by RC structures. Finally, RC structures have the least impact on each damage category, except climate change.

To further elaborate on these results and provide a sensitivity analysis of the study, data on the environmental impact according to the EPD method<sup>29</sup> have been also computed and reported in Fig. 14. In particular, the EPD method requires elaboration on some of the midpoint categories of the IMPACT 2002+ method. In detail, the EPD method reports the results in terms of: 1) global warming; 2) ozone layer depletion; 3) photochemical oxidation (equivalent to respiratory organics); 4) acidification; 5) eutrophication; and 6) non-renewable, fossil (equivalent to non-renewable energy). Figure 14, as already evidenced in Fig. 12, shows that the RC structure has the most impact on global warming, followed by steel (80%) and then wood (75%). For all the

other categories, a wood structure is responsible for the greatest impact, always followed by steel and RC structures.

Figure 15 shows the environmental impact according to the EPD method, taking into consideration 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 to 50% of the extraction and production of materials phase.

### SUMMARY AND CONCLUSIONS

This paper has dealt with a methodological approach to effectively perform a comparative environmental sustainability assessment of building structures. The assessment is conducted using an LCA-based analysis. The environmental impacts of different building material options, related to the structural system of a residential building, were quantified. Three alternative structural material options were investigated: RC, steel, and wood. Each option was designed to fulfill predefined structural, functional, and architectural requirements. The following conclusions can be drawn:

- Given the state of the art on LCA of buildings available in literature, the innovative features of the proposed

approach regard the external constraints on the minimum design performances that building options are required to satisfy.

- The environmental results revealed that, within this methodological framework, the RC option is an environmentally worthy building solution.
- When considering the four damage categories of IMPACT2002+, the RC structure has the highest impact for climate change (15 to 20% higher than the impact due to steel and wood), but the lowest for the other damage categories throughout the entire life-cycle of the building.
- According to the EPD results, the RC structure has the highest impact for only one of six categories; it has the lowest impact for all the other categories. On the other side, the steel structure is able to provide the widest benefit related to recycling.
- There is no apparent straightforward indication on the best environmental performance among the proposed structural options when all the damage categories are considered within the “extended” system boundary of the LCA (including a set of performance requirements). Indeed, the results have revealed that there is no option that produces the best LCA-based environmental performance in all impact categories. As a consequence, a rigorous environmental analysis based on the proposed methodology can influence and orientate the decision-making process when it comes to defining the most sustainable design alternative with respect to one of the selected environmental categories.

As a final remark, it is important to point out that, besides the sustainability assessment methodology, the obtained environmental results are strictly dependent on the case study considered. Moreover, the environmental outcomes depend also on the databases that users and practitioners are able to gather. In example, future studies could run similar comparisons using a database that include data about cements with low carbon footprint. Similarly, future advances could also include the enrichment of the proposed framework with energy performance indicators in the use-phase.

## AUTHOR BIOS

**Maria Chiara Caruso** is a Research Fellow at the University of Naples Federico II, Naples, Italy. Her research interests include environmental assessment in construction industry, building sustainability, and life-cycle assessment.

**Costantino Menna** is an Assistant Professor at the University of Naples Federico II. His research interests include the development and integration of materials and techniques for sustainable constructions, and sustainability assessment in construction industry.

**Domenico Asprone** is an Assistant Professor at the University of Naples Federico II. His research interests include sustainability-oriented technologies for civil structures, city resilience against extreme events, seismic risk, and natural hazard insurance systems.

**Andrea Protà** is an Associate Professor at the University of Naples Federico II. His research interests include seismic behavior and strengthening of reinforced concrete and masonry structures, sustainable structures, and materials.

**Gaetano Manfredi** is Full Professor at the University of Naples Federico II. His research interests include seismic engineering, and application of advanced and sustainable materials for structures.

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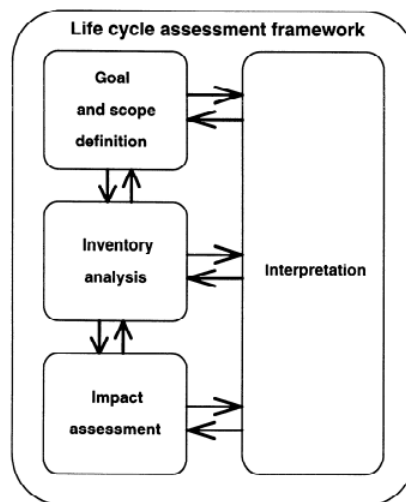
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## APPENDIX

For the environmental assessment of products, the life-cycle assessment (LCA) technique can be used following the scheme described in Figure A1 (ISO 14040 [9]). In the “Goal and Scope Definition” phase, system boundary and functional unit (FU) are set. The life-cycle Inventory analysis (LCI analysis) is the inventory of input/output data with regard to the system being studied. The life-cycle Impact Assessment (LCIA), meanwhile, provides additional information to help assess a product system’s LCI results so as to better understand their environmental significance. Impact assessments can be performed using different methodologies. Life-cycle interpretation is the final phase of the LCA procedure, where the results of an LCI or an LCIA are summarized and discussed in accordance with the goal and scope definition.



*Figure A1: LCA structure according to ISO 14040*

For building systems, different environmental standards regulate the life-cycle assessment procedure. EN 15978 [17] provides information about the system boundary in the construction industry. Figure A2 shows the modular approach of EN 15978. Life-cycle stages of building systems are classified into four modules: (1) module A, representing the pre-use phase (product

stage and construction process, including transport); (2) module B, representing the use phase and including seven possible stages; (3) module C, representing the end of life phase and including all possible scenarios; and (4) module D, representing supplementary information beyond the building life-cycle and including benefits and loads beyond the system boundary. The use of module D is consistent with a cradle-to-cradle approach.

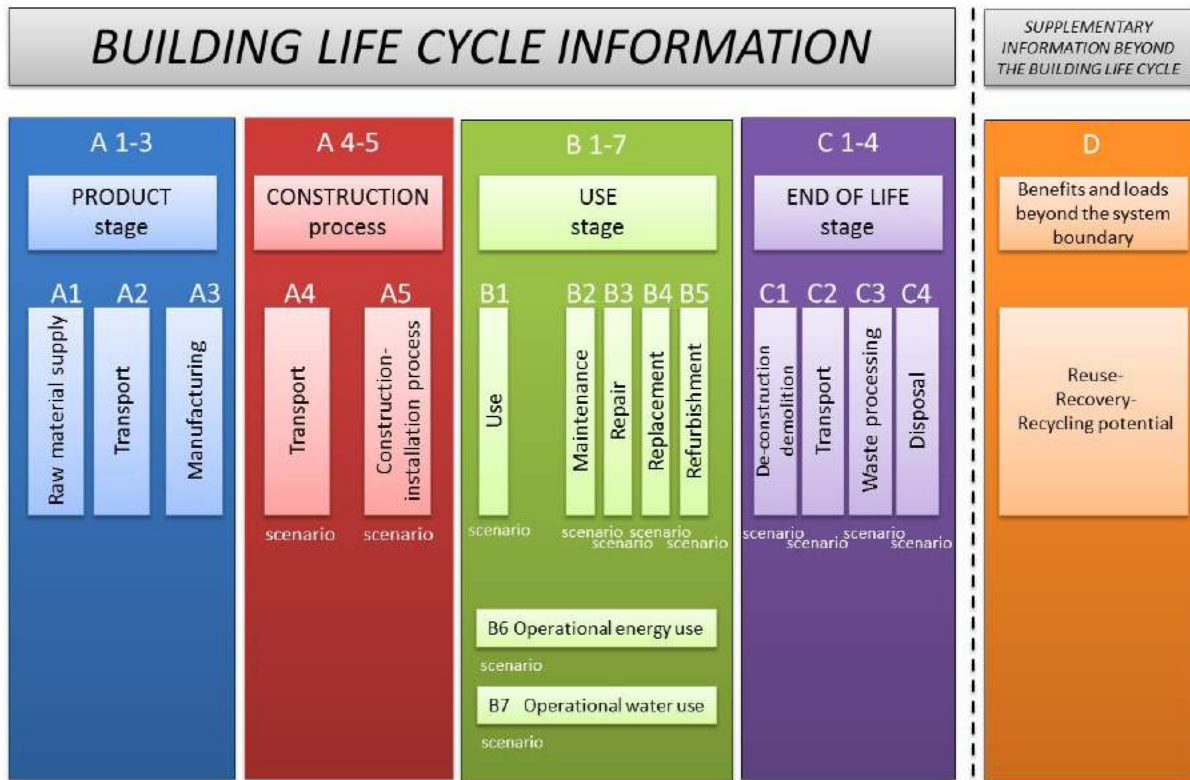


Figure A2: Definition of the life-cycle stages and system boundary according to EN 15978

For the impact assessment phase of the LCA analysis, two methodologies are utilized. The basis of the mentioned methodologies are described below.

### IMPACT2002+

As reported in [28], the life cycle impact assessment methodology IMPACT 2002+ proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle

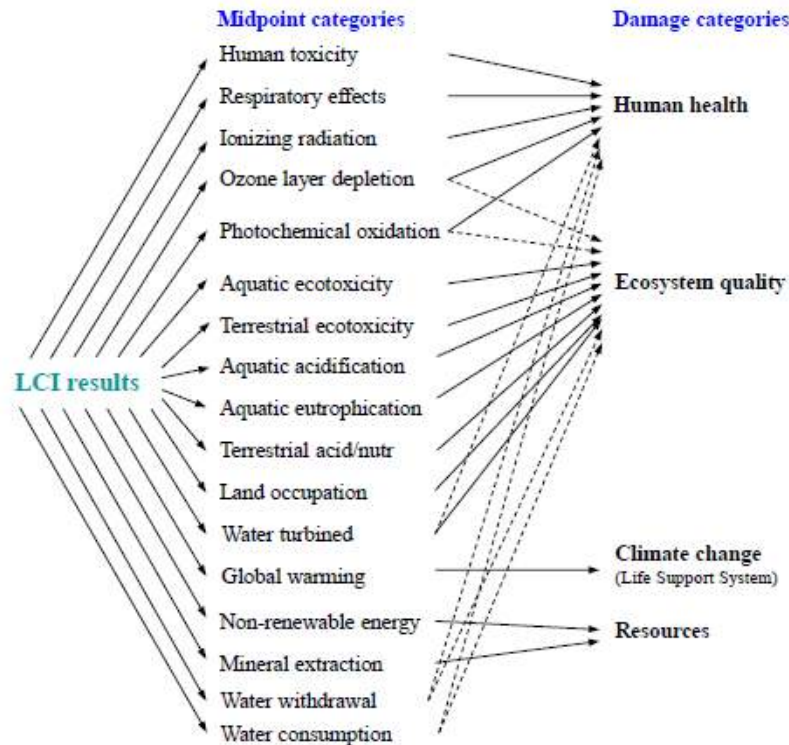


inventory results via several midpoint categories to several damage categories. IMPACT 2002+ considers several midpoint categories which are expressed in reference units of a given substance and are quantified starting from preexisting impact assessment methods (see Table B1). Midpoint categories are then combined to define four damage categories: human health, ecosystem quality, climate change, and resources (Figure B1). These four damage categories are expressed in DALY,  $\text{PDF} \cdot \text{m}^2 \cdot \text{y}$ ,  $\text{kg CO}_2\text{-eq}$ , and MJ, respectively.

<b>Midpoint category</b>	<b>Reference unit</b>	<b>Impact source</b>
Human toxicity (carcinogens + non-carcinogens)	kg Chloroethylene into air-eq	IMPACT 2002 model (IMPact Assessment of Chemical Toxics) Pennington et al. 2005, 2006
Respiratory (inorganics)	kg $\text{PM}_{2.5}$ into air - eq	Eco-indicator 99 (Goedkoop and Spriensma 2000)
Ionizing radiations	Bq Carbon-14 into air - eq	Eco-indicator 99 (Goedkoop and Spriensma 2000)
Ozone layer depletion	kg CFC-11 into air - eq	Eco-indicator 99 (Goedkoop and Spriensma 2000)
Photochemical oxidation (= Respiratory (organics) for human health)	kg Ethylene into air - eq	Eco-indicator 99 (Goedkoop and Spriensma 2000)
Aquatic ecotoxicity	kg Triethylene glycol into water - eq	IMPACT 2002 model (Pennington et al. 2005, 2006)
Terrestrial ecotoxicity	kg Triethylene glycol into soil - eq	IMPACT 2002 model (Pennington et al. 2005, 2006)
Terrestrial acidification/nutrification	kg $\text{SO}_2$ into air - eq	Eco-indicator 99 (Goedkoop and Spriensma 2000)
Aquatic acidification	kg $\text{SO}_2$ into air - eq	CML (Guinée et al. 2002)
Aquatic eutrophication	kg $\text{PO}_4^{3-}$ into water - eq	CML (Guinée et al. 2002)
Land occupation	$\text{m}^2$ Organic arable land - eq · year	Eco-indicator 99 (Goedkoop and Spriensma 2000)
Water turbined	inventory in $\text{m}^3$	-
Global warming	kg $\text{CO}_2$ into air - eq	IPCC list (IPCC 2001, and IPCC 2007 for $\text{CH}_4$ , $\text{N}_2\text{O}$ and $\text{CO}$ )

Non-renewable energy	MJ or kg Crude oil - eq (860 kg/m3)	Eco-indicator 99 (Goedkoop and Spriensma 2000)
Mineral extraction	MJ or kg Iron - eq (in ore)	Eco-indicator 99 Goedkoop and Spriensma (2000)
Water withdrawal	inventory in m <sup>3</sup>	-
Water consumption	inventory in m <sup>3</sup>	-

**Table B1: Reference units and corresponding source of each midpoint category - IMPACT2002+ IA Method**



*Figure B1: Overall scheme of the IMPACT 2002+ linking LCI results via the midpoint categories to damage categories. Water turbined, water withdrawal and water consumption are not included in the midpoint outputs [28]*

Environmental Impact loads are firstly characterized according to the methods reported in Table B1; then, they are normalized with reference to mean European values representative of a certain period of time, either at midpoint or at damage level. Normalization allows the different categories to be plotted on the same graph, making the interpretation of results easier and contextualizing the

results. Normalization is performed by dividing the impact values by the corresponding normalization factor.

## EPD

EPD Impact Assessment (EPD) method is used for the creation of Environmental Product Declarations, as published on the website of Swedish Environmental Management Council (SMEC) <http://www.environdec.com/>. Environmental Product Declarations are Type III environmental declarations, standardized by ISO 14025 [38]. This procedure aims to support organizations and companies to achieve the EPD certification of their products. EPD method provides environmental information of products, by quantifying the following environmental impacts: global warming potential for the time horizon 100 years (GWP100); ozone depletion potentials (ODP) for the time horizon 20 years; Photochemical Oxidation; Acidification Potential (AP); Eutrophication Potential (EP); Non-renewable, fossil. Environmental impacts are expressed in units of measure referred to a certain substance and are quantified starting from preexisting impact assessment methods or scientific approaches (see Table B2), according to EPD reports [29][39].

<b>Impact</b>	<b>Unit of measure</b>	<b>Impact source</b>
Global Warming Potential	kg CO <sub>2</sub> - eq	IPCC (Intergovernmental Panel on Climatic Change), Climate Change 2001: the Scientific Basis. Cambridge University Press, Cambridge UK.
Ozone layer depletion	kg CFC-11 into air - eq	Solomon & Albritton, 1992, in Nordic Guidelines on Life-Cycle Assessment, Nord 1995:20, Nordic council of Ministers, Copenhagen
Photochemical oxidation	kg Ethylene into air - eq	POCP (Jenkin & Hayman, 1999; Derwent et al. 1998; high NO <sub>x</sub> ); baseline (CML, 1999)
Acidification Potential	kg SO <sub>2</sub> - eq	(CML, 1999); (Huijbregts, 1999; average Europe total, A&B)

Eutrophication Potential	kg PO <sub>4</sub> <sup>3-</sup>	(CML, 1999); (Heijungs et al. 1992)
Non-renewable, fossil	MJ - eq	Not specified

**Table B2: Unit of Measure and corresponding source of each environmental impact – EPD2008 IA Method**