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Environmental performances of different timber structures for pitched roofs

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ABSTRACT

The construction industry is one of the most important actors in the global sustainability act, seeing as it is responsible for a significant negative load over the natural environment. In the journey towards minimising these damaging effects, the first key step is understanding the environmental performances of the materials used in this sector. Taking into account that forests have a crucial role in sustaining life, analysing the environmental impact of wood as a construction material represents a necessary task for civil engineers. The present paper aims at evaluating and comparing the environmental performances of three timber structures for pitched roofs: the trestle frame roof structure, the roof structure with collars, and the trussed rafter roof structure. The environmental burdens have been determined by using the cradle-to-cradle Life Cycle Assessment methodology and the GaBi ts software. Upon analysing the results, the authors have concluded that the roof structure with collars has the lowest impact over the Earth's ecosystem. The study also shows that even if the trestle frame is the leading environmentally friendly solution over the pre- and post-operation phases, this structural system is responsible for the highest unfavourable effects over its entire life cycle. The authors argue that by using the roof structure with collars, the damaging load of the construction sector over the natural environment is one step closer to being minimised.

1. Introduction

Considering and fulfilling the dimensions of sustainability represent the most important challenge for humankind at the beginning of the 21st century. The climate change phenomena registered in the last decades have led to a growing public awareness regarding the critical situation that current generations have to confront. Conjointly, the current rates of natural resources consumption are considered to be unsustainable, jeopardizing the Earth's capability of fulfilling our basic needs in the future. Therefore, in order to minimize the negative effects of our daily activities over the Earth's ecosystem, and to offer an equitable chance at development for the next generations, society as a whole must drastically reduce the volume of raw materials used and the amount of emissions to the natural environment, and at the same time increase the number of applications/technical solutions which make use of renewable resources.

Taking into account the amount of raw materials and energy consumed in the construction sector, and the volume of greenhouse gases emitted from the various processes that are specific to the built environment, this industry justifiably represents a key factor in satisfying the primary aspects of global sustainable development (Agusti-Juan et al., 2017; Brejnrod et al., 2017; Ding, 2014; Lu et al., 2017; Margarido, 2015; Maxineasa et al., 2015; Pacheco-Torres et al., 2017; Sathre and Gonzalez-Garcia, 2014; Sinha et al., 2016; Vacek et al., 2017; Yao, 2013; Zhao et al., 2017). An important phase from the life cycle of a structure that has a significant impact over the total environmental footprint of the construction industry is represented by the manufacturing of building materials (Hafliger et al., 2017). At the global scale, it is estimated that compared with other industries, the construction sector is the most substantial consumer of natural resources, a significant volume of which is being used before the operation

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stages of the built structures (Estrada et al., 2012). Of the total environmental footprint of a construction, only 8%–20% results from the materials' production stage (the pre-operation phase of a structure), thus, it can be considered that the negative effects of building materials do not represent the industry's biggest ecological problem (Hays and Cocke, 2009; Huberman and Pearlmutter, 2008; Ortiz et al., 2009, 2010). Nevertheless, if we take into consideration the fact that in the near future the environmental impact of the operating stage of a building is expected to significantly decrease due to the development of new carbon neutral operations systems (Estrada et al., 2012), the choice of materials should be regarded as an important element in reducing the effects of the built environment over the natural one.

Wood is one of the first construction materials, being used by different ancient civilisations in order to build various structures (Isopescu and Astanei, 2012). Nowadays, timber is mostly used as a structural material for buildings and short-span bridges (Kim and Harries, 2010). The distinctive properties of this traditional material, like high strength-to-weight ratio and good thermal insulating properties, as well as its wide availability around the world have turned wood into one of the most valuable natural resources (Asif, 2010).

Forests are known to hold a critical role in ensuring and improving life conditions, being the Earth's most powerful tool for sequestering a significant volume of carbon dioxide (CO_2), while at the same time releasing an important amount of oxygen (O_2) into the atmosphere (Asif, 2010; DeStefano, 2009; Estrada et al., 2012; Gold and Rubik, 2009; Miller and Ip, 2013). A well administered forest has the ability to deliver approximately 490 g of O_2 for every 670 g of sequestered CO_2 (DeStefano, 2009; Estrada et al., 2012). As such, timber can be considered a carbon negative material (Caniato et al., 2017; Estrada et al., 2012). However, it must be mentioned that the amount of captured CO_2 will be released back into the atmosphere at the end of the life of the tree or the used timber product through the decomposing process or by burning the wood mass in order to obtain energy (Estrada et al., 2012; Fouquet et al., 2015; Vogtlander et al., 2014).

In the last decades, the forestry and logging industries have had to tackle the problem of uncontrolled and illegal deforestation. Thus, decision makers around the world have developed and implemented a series of measures with the goal of developing a sustainable system of using wood and therefore to protect and enhance the existing forested areas. For example, in the European Union, after considering such solutions, the forested areas have increased by approximately 2% between 2000 and 2010. The trend was noticed in 2015 as well (Eurostat, 2011, 2016), while in Canada and the United States of America, these areas are the same size as they were 100 years ago (Estrada et al., 2012; Ward, 2010).

Considering that a significant amount of wood products is used in specific civil engineering applications, the construction sector assumes an important role in protecting the existing forested areas through a well-managed consumption of timber products, and therefore, decreasing the environmental pressure over the Earth's ecosystem. In view of the above, the present paper aims at evaluating the ecological implications derived from utilising timber elements in the construction sector through assessing and comparing the environmental footprint of three different roof structure types by using the Life Cycle Assessment (LCA) methodology.

2. LCA case studies

In order to achieve the objective of the investigation, the methodology presented in the international standards ISO 14040:2006 and ISO 14044:2006 has been used. These norms define LCA as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" that can be used for "identifying opportunities to improve the environmental performance of products at various points in their life cycle; informing decision-makers in industry, government or non-government organization; the selection of relevant indicators of environmental performance, including measurement techniques and marketing" (ISO, 2006a, b).

Depending on the period of the life cycle under analysis, there are different types of LCA studies that can be used to determine the environmental impact of a product or service (Tundrea et al., 2014). The analysis aims at assessing the environmental impact of the roof structures resulted from the total life span of the products by using the cradle-to-cradle LCA type of study. Table 1 displays the life cycle stages considered in the assessed case studies. The life span of the roof structures has been considered to be 50 years and the considered life cycle modules have been established according to the European standards EN 15978:2011 and EN 15804+A1:2013 (EN, 2011, 2013).

The following case studies have been analysed:

- **Case study no. 1**—trestle frame roof system presented in Fig. 1;
- **Case study no. 2**—roof structure with collars presented in Fig. 2;
- **Case study no. 3**—trussed rafter roof system presented in Fig. 3.

The functional unit of the present study is a roof structure that is designed for a single-family residential building with a length of 12 m and a width of 9 m. Detailed descriptions and structural analyses of the evaluated roof elements are presented in Entuc et al. (2016).

For the transportation stages of the LCA studies, a Euro 6 diesel truck with 3.3 tons payload capacity was considered. The transport distances are presented in Table 2.

In order to have a clearer understanding of the environmental results, the quantities of wood processed to manufacture the following construction elements were included in the sawn timber component material category:

- case study no. 1 (see Fig. 1): timber board, top purlin, current purlin, collar, brace, post, base plate, rafter, and wall purlin;
- case study no. 2 (see Fig. 2): rafter tie, ridge, rafter, blocking, and collar;
- case study no. 3 (see Fig. 3): truss girders, blocking, web member, and bottom chord.

The environmental performances of the considered elements have been quantified by using the impact categories presented in Table 3. These environmental parameters have been recommended by the European Commission – Joint Research Centre (2011), and the index of indicators provided by EN (2013), for assessing the

Table 1
Considered life cycle phases.

Life cycle phase	Life cycle module	Life cycle stage
Extraction of raw materials/harvesting the mature trees	A1	Pre-operation
Processing of raw materials and manufacturing the construction materials	A3	
Construction of the analysed roof structures	A5	
Use of the considered roof structures	B1	Operation
Maintenance of the roof structures	B2	
De-construction/demolition	C1	Post-operation/ end of life
Waste processing	C3	
Recycling of the materials	D	
Transportation phases	A2, A4, C2	Considered in all stages