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Environmental performances of different timber structures for pitched roofs

Sebastian George Maxineasa [a, *], Ioana-Sorina Entuc [a], Nicolae Taranu [a, b], Ion Florenta [a], Alexandru Secu [a]

[a] "Gheorghe Asachi" Technical University of Iasi, Faculty of Civil Engineering and Building Services, Department of Civil and Industrial Engineering, 1, Prof. Dr. docent Dimitrie Mangeron Blvd., Iasi, 700050, Romania
[b] Academy of Romanian Scientists, Splaiul Independentei nr. 54, Sector 5, 050094, Bucharest, Romania

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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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* Corresponding author.
E-mail address: sebastian.maxineasa@tuiasi.ro (S.G. Maxineasa).

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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

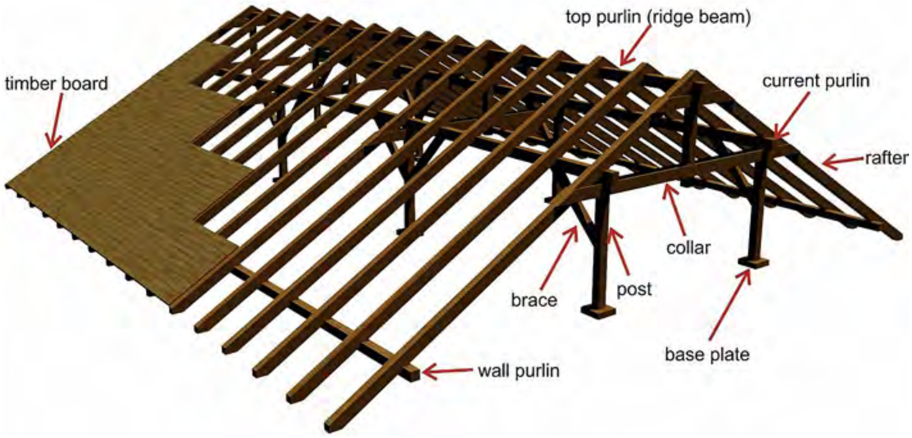

Fig. 1. Case study no. 1 (trestle frame roof structure).

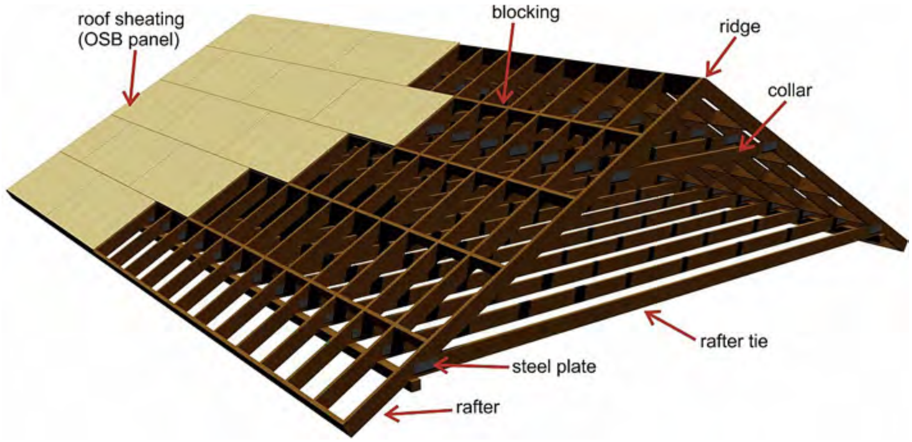

Fig. 2. Case study no. 2 (roof structure with collars).

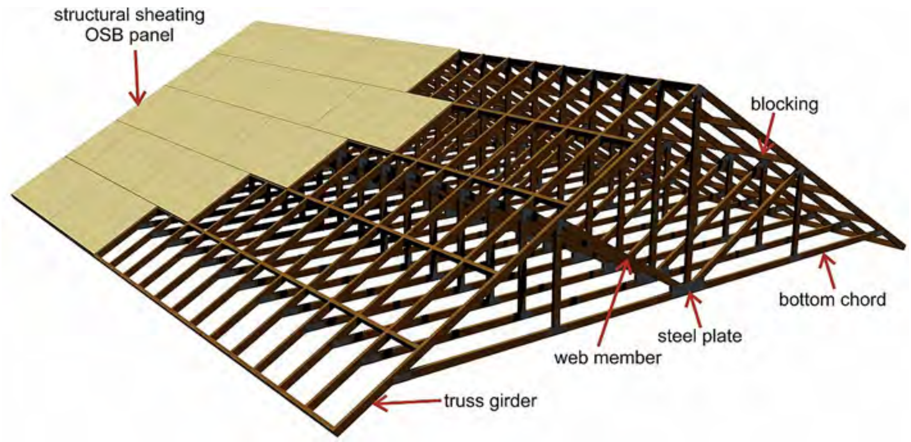

Fig. 3. Case study no. 3 (trusses roof system).

impact over the natural environment of a product specific to the construction sector.

3. Assessing the environmental impact of the construction products over the pre-operation stage

In order to evaluate the cradle-to-cradle environmental performances of the considered structures, the impact resulted from the pre-operation stage of the products was first analysed. Thus, at this point in the study, the A1, A2, A3, A4, and A5 life cycle modules detailed in Table 1 were considered.

3.1. Environmental impact in case study no. 1

The first case study assesses the environmental performances of the classical trestle frame roof system. The amount of component

Table 2
Distances considered for the transportation phase.

Material	Distance [km]	From → To	Case study
Sawn timber	150	manufacturing unit → construction site	1, 2, 3
Oriented Strand Board (OSB) panels	150	manufacturing unit → construction site	2, 3
Steel staple pins	10	manufacturing unit → construction site	1
Steel screws	10	manufacturing unit → construction site	1, 2, 3
Steel plates	10	manufacturing unit → construction site	2, 3
Paint system	10	manufacturing unit → construction site	1, 2, 3
Scrap steel	10	construction site → recycling unit	1, 2, 3
Wood products (post-operation stage)	50	construction site → waste incinerator unit	1, 2, 3

Table 3
Considered impact categories.

Impact category	Parameter	Methodology	Unit
Acidification	Accumulated exceedance (AE)/Acidification potential	Accumulate exceedance model/ILCD 2011	mole of H^+ eq.
Global Warming (Climate Change) – excluding the biogenic carbon	Radiative forcing Global warming potential (GWP)	IPCC	kg CO_2-eq.
Global Warming (Climate Change) – including the biogenic carbon	Radiative forcing Global warming potential (GWP)	IPCC	kg CO_2-eq.
Ecotoxicity for aquatic freshwater	Ecotoxicity potential	USEtox	CTUe
Aquatic Eutrophication, freshwater	Potentially Disappeared Fraction of species (PDF)	ReCiPe	kg P eq.
Aquatic Eutrophication, marine	Expression of the degree to which the emitted nutrients reaches the marine end compartment	ReCiPe	kg N eq.
Terrestrial Eutrophication	Accumulated exceedance (AE)	Accumulate exceedance model/ILCD 2011	mole of N eq.
Human Toxicity, cancer effects	Human toxicity potential, cancer effects (HTPc)	USEtox	CTUh
Human Toxicity, non-cancer effects	Human toxicity potential, non-cancer effects (HTPnc)	USEtox	CTUh
Ionizing radiation, human health	Ionizing Radiation Potential (IRP)	ReCiPe	kBq U-235
Ozone Depletion	Depletion potential of the stratospheric ozone layer/Ozone depletion potential (ODP)	ReCiPe	kg CFC-11 eq.
Particulate matter/Respiratory inorganics	Intake fraction for fine particles/Particulate matter potential	RiskPoll	kg PM 2,5 eq.
Photochemical ozone formation, human health	Photochemical ozone creation potential (POCP)/Maximum incremental reactivity (MIR)	ReCiPe	kg NMVOC
Resource depletion, water	Freshwater scarcity/Biotic resource depletion potential	Swiss Ecoscarcity	m^3 eq.
Resource depletion, mineral, fossils and renewables	Scarcity of mineral resources/Abiotic resource depletion	CML2002	kg Sb-eq.

materials considered for conducting the cradle-to-gate analysis are presented in Table 4.

The environmental performances of the assessed construction product are presented in Table 5. By analysing the resulted values, it can be observed that the sawn timber elements and the painting system have the most important contribution in establishing the impact of the trestle frame roof system. The amount of wood products considered in the study has the biggest negative impact in the case of nine environmental parameters, while the volume of protective paint has the most significant effect in six categories. The resulted values show that the sawn timber elements have an important positive impact in the case of the Global Warming, including the biogenic carbon environmental parameter.

3.2. Environmental impact in case study no. 2

The second case study evaluates the impact over the natural environment of the roof structure with collars presented in Fig. 2. The quantities used for assembling the considered construction product are presented in Table 6.

Table 4
Amount of component materials used in Case study no. 1.

Component material	Quantity [kg]
Sawn timber	2155.60
Steel staple pins	28.26
Steel screws	2.40
Paint	348,11

Table 7 presents the impact over the natural environment of the analysed roof structure with collars. The results show that the overall negative effects for the considered categories are mainly influenced by the production of the solid timber elements, a stage that is responsible for a maximum impact in 10 environmental parameters. Other materials that are responsible for a significant amount of environmental burdens are the painting system (with 2 peak values), OSB panels, and steel screws and plates (each phase with one maximum value). The wood elements have a positive effect only within the Climate Change, including the biogenic carbon impact category.

3.3. Environmental impact in case study no. 3

The last considered case study in the cradle-to-gate part of the analysis consists of the evaluation and interpretation of the environmental impact of a trussed rafter roof system. The quantities of component materials are presented in Table 8.

Table 9 shows the values resulted after conducting the analysis, describing, by using the considered impact categories, the negative effects over the Earth's ecosystem of the last assessed construction product. It can be observed that the timber elements have the highest impact in six parameters. At the same time, the steel plates used in the assembly have the most important influence over the

Table 5
Cradle-to-Gate impact in case study no. 1.

Impact category	Life cycle stages					
	Sawn timber	Steel screw	Steel staple pins	Paint system	Diesel	Transport
Acidification [mole of H^+ eq.]	4.5526	0.0273	0.1845	1.87	0.0511	0.0171
Global Warming (Climate Change) – excluding the biogenic carbon [kg CO_2-eq.]	665.2252	7.6262	61.7412	899.5891	7.5926	41.0747
Global Warming (Climate Change) – including the biogenic carbon [kg CO_2-eq.]	-2776.9087	7.6452	61.0372	903.7371	4.9349	43.2077
Ecotoxicity for aquatic freshwater [CTUe]	63.3814	1.1855	5.0626	112.7940	8.3964	1.10E-06
Aquatic Eutrophication, freshwater [kg P eq.]	0.0028	2.16E-05	9.03E-06	0.0067	0.0003	0
Aquatic Eutrophication, marine [kg N eq]	0.3555	0.0004	0.0006	0.1058	0.0059	0.0083
Terrestrial Eutrophication [mole of N eq.]	19.3452	0.0564	0.3287	5.0991	0.1200	0.0952
Human Toxicity, cancer effects [CTUh]	2.57E-06	3.56E-08	4.88E-08	4.84E-06	3.33E-07	5.12E-12
Human Toxicity, non-cancer effects [CTUh]	3.75E-05	1.54E-06	5.70E-06	3.44E-05	4.48E-06	1.30E-12
Ionizing radiation, human health [kBq U-235]	133.3873	0.2405	0.0567	41.6167	0.2066	0
Ozone Depletion [kg CFC-11 eq.]	2.21E-07	1.86E-10	2.88E-07	5.15E-08	3.42E-10	0
Particulate matter/Respiratory inorganics [kg PM 2,5 eq.]	3.3638	0.0043	0.0104	0.0937	0.002	0.0004
Photochemical ozone formation, human health [kg NMVOC]	5.0511	0.0176	0.1125	1.5710	0.0296	0.0068
Resource depletion, water [m³ eq.]	4.2228	0.0225	-0.0188	4.2078	0.0235	0
Resource depletion, mineral, fossils and renewables [kg Sb-eq.]	0.0012	0.0015	0.0002	0.0024	1.98E-05	0

Table 6
Amount of component materials used in Case study no. 2.

Component material	Quantity [kg]
Sawn timber	2658
OSB panels	196.70
Steel screws	23.55
Steel plates	313.22
Paint	237,09

total effects in five categories, the paint system presents three peak values, while the screws have the most significant impact over the last considered environmental parameter. Also, as in the previously assessed case studies, the timber elements have an important role in reducing the carbon footprint of the analysed roof structure, provided the biogenic carbon is taken into account.

3.4. Comparing the pre-operation environmental impact of the assessed roof structures

In the present section, the authors have compared the environmental impact of the pre-operation stage of the analysed roof structures. It can be observed that the trusses roof system assessed in the last case study has the highest impact over the natural environment (Fig. 4). This structure is responsible for the largest volume of negative effects in the case of 11 impact categories, the most important difference between the impact of this structure and the other two being registered in the case of the ODP parameter. Within the same impact category, we can see that the roof structure analysed in the first case study has the lowest environmental effect. If we consider the GWP-including the biogenic carbon parameter, the roof structure with collars assessed in the second case study presents the most important positive effect over the climate change phenomena. At the same time, this structure has the largest impact in the case of the IRP parameter. The first roof system is responsible for the most important volume of negative effects in the case of the Aquatic Eutrophication and Water Resource Depletion categories. Considering the values resulted in this section, it can be stated that from a cradle-to-gate point of view, the trusses roof system has the highest ecological impact, while the trestle frame roof structure is the most environmentally friendly solution, having the lowest impact in 11 categories.

4. Assessing the environmental impact of the construction products over the operation stage

This part of the analysis takes into consideration the maintenance activities, which consist in applying a new protective paint system to the solid timber elements every five years. The life span of the assessed roof structures is considered to be 50 years, therefore the maintenance operations mentioned above will be undertaken nine times. The amount of materials used for assessing the environmental impact of the maintenance phase is presented in Table 10 (quantities used every five years). The same transport distance for the paint system presented in Table 2 is considered.

The environmental impact resulted from the operation phase of the assessed roof structures is presented in Fig. 5 and Table 11. It can

Table 7
Cradle-to-Gate impact in case study no. 2.

Impact category	Life cycle stages						
	Sawn timber	OSB panels	Steel screw	Steel plates	Paint system	Diesel	Transport
Acidification [mole of H^+ eq.]	5.6136	0.2736	0.2675	2.2450	1.2736	0.0678	0.022658
Global Warming (Climate Change) – excluding the biogenic carbon [kg CO_2-eq.]	820.2675	147.5742	74.8317	774.7256	612.6902	10.0718	54.48667
Global Warming (Climate Change) – including the biogenic carbon [kg CO_2-eq.]	-3424.1155	-271.7079	75.0189	769.8701	615.5153	6.5463	57.31617
Ecotoxicity for aquatic freshwater [CTUe]	78.1535	3.0375	11.6326	17.3435	76.8215	11.1381	1.46E-06
Aquatic Eutrophication, freshwater [kg P eq.]	0.0035	0.0002	0.0002	0.0002	0.0045	0.0004	0
Aquatic Eutrophication, marine [kg N eq]	0.4384	0.0017	0.0037	0.0110	0.0720	0.0078	0.011007
Terrestrial Eutrophication [mole of N eq.]	23.8539	1.1042	0.5538	4.3016	3.4729	0.1591	0.126328
Human Toxicity, cancer effects [CTUh]	3.17E-06	1.00E-07	3.49E-07	4.08E-07	3.30E-06	4.42E-07	6.79E-12
Human Toxicity, non-cancer effects [CTUh]	4.63E-05	1.08E-06	1.51E-05	3.19E-05	2.34E-05	5.94E-06	1.72E-12
Ionizing radiation, human health [kBq U-235]	164.4756	0.3934	2.3596	0.5669	28.3442	0.2741	0
Ozone Depletion [kg CFC-11 eq.]	2.73E-07	4.35E-06	1.83E-09	2.85E-06	3.51E-08	4.54E-10	0
Particulate matter/Respiratory inorganics [kg PM 2,5 eq.]	4.1478	0.0093	0.0419	0.1221	0.0638	0.0027	0.000479
Photochemical ozone formation, human health [kg NMVOC]	6.2284	0.3115	0.1725	1.5932	1.0699	0.0392	0.008992
Resource depletion, water [m^3 eq.]	5.2070	-0.0700	0.2208	-0.0716	2.8659	0.0312	0
Resource depletion, mineral, fossils and renewables [kg Sb-eq.]	0.0015	0.0003	0.0145	0.0016	0.0017	2.63E-05	0

Table 8
Amount of component materials used in Case study no. 3.

Component material	Quantity [kg]
Sawn timber	2619
OSB panels	196.70
Steel screws	20.41
Steel plates	792.10
Paint	247.59

be observed that the most significant values have been registered in the case of the maintenance works over the life span of the trestle frame roof structure analysed in the first case study (Fig. 5). For all considered parameters, the environmental impact of the first analysed product is approximately 50% larger than the negative ecological effect resulted in the second case study and 40% larger than that resulted in the third (Table 11). Therefore, it can be stated that during the operation phase, the trestle frame roof system has the most significant impact, while the roof structure with collars analysed in the second case study is responsible for the lowest level of negative environmental effects.

5. End of life assessment (post-operation environmental impact)

The last step of the present LCA study consists in evaluating and interpreting the impact over the natural environment of the analysed roof structures after the operation stage of their life cycle, by assessing the modules C1, C3, and D. The structures' demolition has been considered to be done by hand, no mechanical processes being used in this stage, in order to take into account a high volume of recovered materials in the post operation analysis.

The considered end of life scenario for the timber elements is based on the premise that nowadays the post-operation phase from the life cycle of wood products consists of using the post-consumer elements as a source of bioenergy (Dodoo et al., 2014; Estrada et al., 2012; Hafner et al., 2014). Therefore, the post-operation stage timber products are used as fuel for obtaining energy in a municipal waste incineration unit. Regarding the case of the steel products, it has been considered that the resulted steel scrap is used in the manufacturing processes of a new volume of steel. The recovery percentage of the materials used to build the analysed roof structure was 90% in the case of the timber elements, and 80% in the case of the steel elements (see Table 12).

Fig. 6 and Table 13 display the resulted values describing the environmental performances of the analysed roof structure in the considered end-of-life scenarios. It can be noticed that the trestle frame roof has a negative environmental effect (positive value) only in one impact category, Ozone Depletion. The other two analysed structures exert a negative impact in the case of the ODP parameter as well, but these structures also have a significant level of environmental burdens in the case of other three parameters (Fig. 6). Analysing all resulted effects, we can see that in the seven environmental impact categories within which the last assessed structure has a favourable impact, there have also been registered the highest negative numerical values compared to the ones resulted in the same parameters for the other two structures (Table 13). However, the first structure has the most important overall positive environmental impact due to the larger number of categories where the structure has registered negative numerical

Table 9
Cradle-to-Gate impact in case study no. 3.

Impact category	Life cycle stages						
	Sawn timber	OSB panels	Steel screw	Steel plates	Paint system	Diesel	Transport
Acidification [mole of H^+ eq.]	5.5313	0.2736	0.2318	5.6772	1.3300	0.06769	0.0226
Global Warming (Climate Change) – excluding the biogenic carbon [kg CO_2-eq.]	808.2320	147.5742	64.8542	1959.1984	639.8243	10.04891	54.3627
Global Warming (Climate Change) – including the biogenic carbon [kg CO_2-eq.]	-3373.8745	-271.7079	65.0164	1946.9195	642.7746	6.5314	57.1857
Ecotoxicity for aquatic freshwater [CTUe]	77.0068	3.0375	10.0816	43.8598	80.2237	11.11271	1.46E-06
Aquatic Eutrophication, freshwater [kg P eq.]	0.0034	0.0002	0.0002	0.0006	0.0047	0.000398	0
Aquatic Eutrophication, marine [kg N eq]	0.432	0.0017	0.0032	0.0279	0.0752	0.007786	0.011
Terrestrial Eutrophication [mole of N eq.]	23.5039	1.1042	0.4799	10.8782	3.6267	0.158786	0.126
Human Toxicity, cancer effects [CTUh]	3.13E-06	1.00E-07	3.03E-07	1.03E-06	3.44E-06	4.41E-07	6.78E-12
Human Toxicity, non-cancer effects [CTUh]	4.56E-05	1.08E-06	1.31E-05	8.06E-05	2.45E-05	5.93E-06	1.72E-12
Ionizing radiation, human health [kBq U-235]	162.0623	0.3934	2.0450	1.4337	29.5995	0.273456	0
Ozone Depletion [kg CFC-11 eq.]	2.69E-07	4.35E-06	1.58E-09	7.22E-06	3.66E-08	4.53E-10	0
Particulate matter/Respiratory inorganics [kg PM 2,5 eq.]	4.0869	0.0093	0.0363	0.3089	0.0666	0.002708	0.0005
Photochemical ozone formation, human health [kg NMVOC]	6.137	0.3115	0.1495	4.0291	1.1173	0.039116	0.0090
Resource depletion, water [m^3 eq.]	5.1306	-0.0700	0.1914	-0.1811	2.9928	0.031082	0
Resource depletion, mineral, fossils and renewables [kg Sb-eq.]	0.0015	0.0003	0.0126	0.0040	0.0017	2.62E-05	0

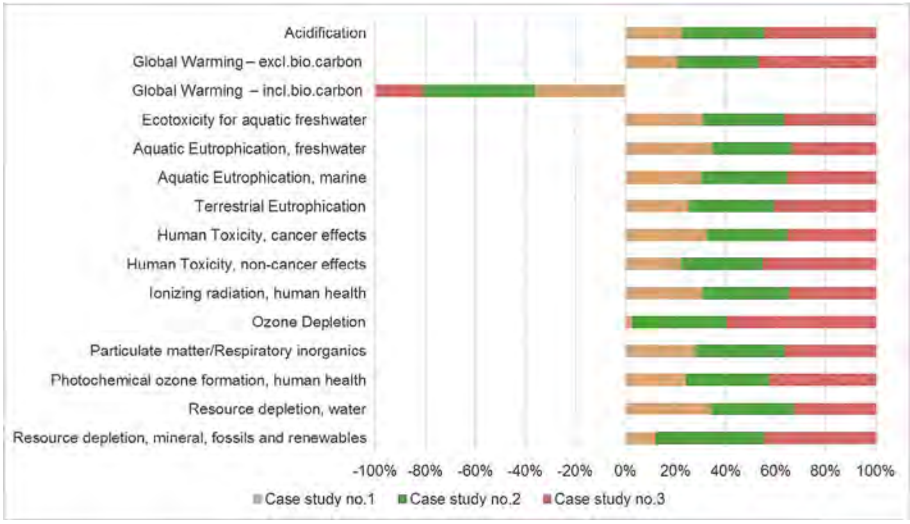

Fig. 4. Comparing the pre-operation phase impact.

Table 10
The amount of paint used for one maintenance stage.

Case study	Quantity [kg]
1	243.68
2	165.96
3	173.31

values (which can be translated into a more important positive influence over the natural environment). Also, in the case of the only parameter where the trestle frame roof system has a negative impact, i.e. ODP, the resulted value is much lower compared to the effects over the stratospheric ozone layer of the other two analysed structures.

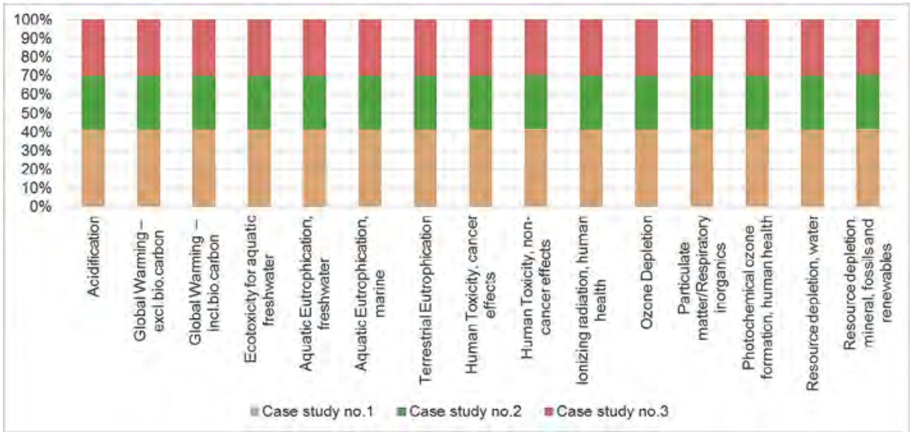

Fig. 5. Comparing the operation phase impact.

Table 11
Environmental performances of the operation phase (impact of all the maintenance stages).

Impact category	Case studies		
	1	2	3
Acidification [mole of H^+ eq.]	11.7859	8.0269	8.3823
Global Warming (Climate Change) – excluding the biogenic carbon [kg CO_2-eq.]	5670.7436	3862.1003	4033.1442
Global Warming (Climate Change) – including the biogenic carbon [kg CO_2-eq.]	5696.8416	3879.8745	4051.7056
Ecotoxicity for aquatic freshwater [CTUe]	711.1741	484.3502	505.8010
Aquatic Eutrophication, freshwater [kg P eq.]	0.0420	0.0286	0.0299
Aquatic Eutrophication, marine [kg N eq]	0.6674	0.4545	0.4747
Terrestrial Eutrophication [mole of N eq.]	32.1393	21.8887	22.8581
Human Toxicity, cancer effects [CTUh]	3.054E-05	2.08E-05	2.172E-05
Human Toxicity, non-cancer effects [CTUh]	2.17E-04	1.48E-04	1.54E-04
Ionizing radiation, human health [kBq U-235]	262.2022	178.5747	186.4834
Ozone Depletion [kg CFC-11 eq.]	3.246E-07	2.211E-07	2.309E-07
Particulate matter/Respiratory inorganics [kg PM 2,5 eq.]	0.5902	0.4020	0.4198
Photochemical ozone formation, human health [kg NMVOC]	9.8996	6.7422	7.0408
Resource depletion, water [m^3 eq.]	26.5112	18.0556	18.8553
Resource depletion, mineral, fossils and renewables [kg Sb-eq.]	0.0154	0.0105	0.0109

Table 12
Amount of materials used in the end-of-life scenario.

Material	Quantity [kg]		
	Case study no. 1	Case study no. 2	Case study no. 3
Timber	1940.04	2392.20	2357.10
OSB panels	–	177.03	177.03
Steel scrap	24.53	269.42	650.01

6. Discussion

The objective of the present paper is to determine and compare, by using the LCA methodology, the environmental impact of three different types of timber roof structures by using the cradle-to-cradle type of study, thus determining the solution possessing the minimum negative effects over the Earth's ecosystem considering the entire life cycle of the products. The study was carried out in four stages: in the first three, the impact of the product during the pre-operation, operation, and post-operation phases has been evaluated and interpreted, while the last stage of the study is dedicated to comparing the overall impact.

By this point in the study, it has been established that the trestle frame structure analysed in the first case study is the most environmentally friendly solution in the pre- and post-operation stages of the life cycle, while the second assessed structure, the roof structure with collars, has the lowest impact in the operation stage. Analysing Fig. 7, which shows the total life cycle environmental impact of the structures under analysis, leads to the understanding of the importance of considering all life cycle modules in determining the environmental performances of a product specific to the construction sector.

Taking into account the total life cycle impact, it can be stated that the trestle frame roof represents the solution with the most negative environmental impact, this type of structure having the highest values in the case of nine parameters considered in the analysis (Table 14). The structure evaluated in the third case study has likewise obtained maximum values in four impact categories. The most suitable solution, with respect to the environmental dimension of sustainability, is represented by the structure assessed in case study number two. The roof structure with collars has the lowest level of ecological effects in the case of 12 impact categories, being at the same time the only structure that has a negative carbon footprint in the case of the GWP-including biogenic carbon parameter. In comparison, the structures analysed in the first and last case studies have a minimum impact in only three categories, two in the case of the trestle frame structure and one in the case of the trusses roof system.

7. Conclusions

Considering that the construction sector has a tremendous role in the efforts towards achieving sustainable development at the global scale, seeing as it is an industry with a significant impact over the Earth's ecosystem, the authors consider that knowing and understanding the environmental effects of building materials represents an important step in the design process of a structure. Taking into account that forests have a critical function in sustaining life, by using wood as a construction material, the natural environment can be substantially influenced in a negative manner. This aspect stood as the primary reason in conducting the presented LCA studies, with the goal of determining the timber roof system with the lowest load over the natural environment by considering a cradle-to-cradle approach.

The performed analyses illustrate that by way of the cradle-to-gate approach, the roof structure with collars has the most advantageous benefit regarding the amount of CO_2 equivalent, this construction system exerting the most significant negative carbon footprint in the case of GWP, including the biogenic carbon parameter; the resulted value is approximately 1.25 and 2.35 times larger than the one resulted in the first and respectively, in the last case study. If we take into account all the considered environmental parameters, we can conclude that the trestle frame roof system is the most environmentally friendly option due to the fact that the ecological influence of this structure is lower than that of the other two considered roof solutions for 11 indicators. In the case of these parameters, the highest difference has been registered for ODP, where the impact in case study no. 1 is approximately 21 times lower than the one resulted in the last case study, while the lowest ecological difference was marked between the first two case studies for the Ecotoxicity for aquatic freshwater indicator, where the impact resulted for the trestle frame roof structure represents approximately 96% of the one exerted by the roof structure with collars.

The assessment regarding the impact over the operation stage of

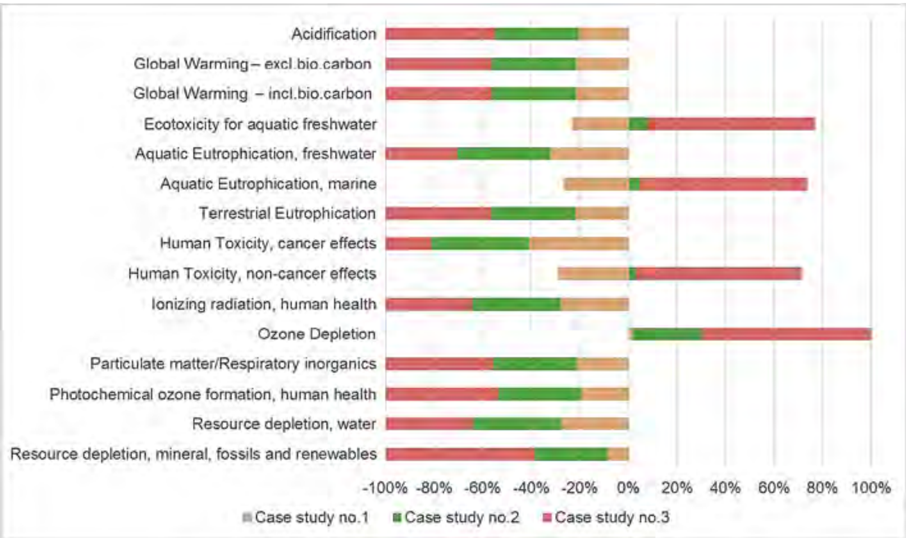

Fig. 6. Comparing the end-of- life phase impact.

Table 13
Environmental performances of the end-of-life phase.

Impact category	Case studies		
	1	2	3
Acidification [mole of H^+ eq.]	-2.3959	-3.9355	-5.1948
Global Warming (Climate Change) – excluding the biogenic carbon [kg CO_2-eq.]	-1322.2901	-2084.1298	-2638.1804
Global Warming (Climate Change) – including the biogenic carbon [kg CO_2-eq.]	-1324.2456	-2085.1913	-2636.8126
Ecotoxicity for aquatic freshwater [CTUe]	-15.5427	5.1680	46.1873
Aquatic Eutrophication, freshwater [kg P eq.]	-0.0011	-0.0013	-0.0010
Aquatic Eutrophication, marine [kg N eq]	-0.0290	0.0053	0.0748
Terrestrial Eutrophication [mole of N eq.]	-5.5623	-8.7021	-10.9286
Human Toxicity, cancer effects [CTUh]	-4.75E-07	-4.67E-07	-2.16E-07
Human Toxicity, non-cancer effects [CTUh]	-1.04E-05	1.06E-06	2.46E-05
Ionizing radiation, human health [kBq U-235]	-247.1893	-320.0267	-311.8541
Ozone Depletion [kg CFC-11 eq.]	7.70E-07	1.25E-05	3.09E-05
Particulate matter/Respiratory inorganics [kg PM 2,5 eq.]	-0.1177	-0.1864	-0.2372
Photochemical ozone formation, human health [kg NMVOC]	-1.6143	-2.7530	-3.7641
Resource depletion, water [m^3 eq.]	-6.4327	-8.3697	-8.2236
Resource depletion, mineral, fossils and renewables [kg Sb-eq.]	-0.0029	-0.0104	-0.0209

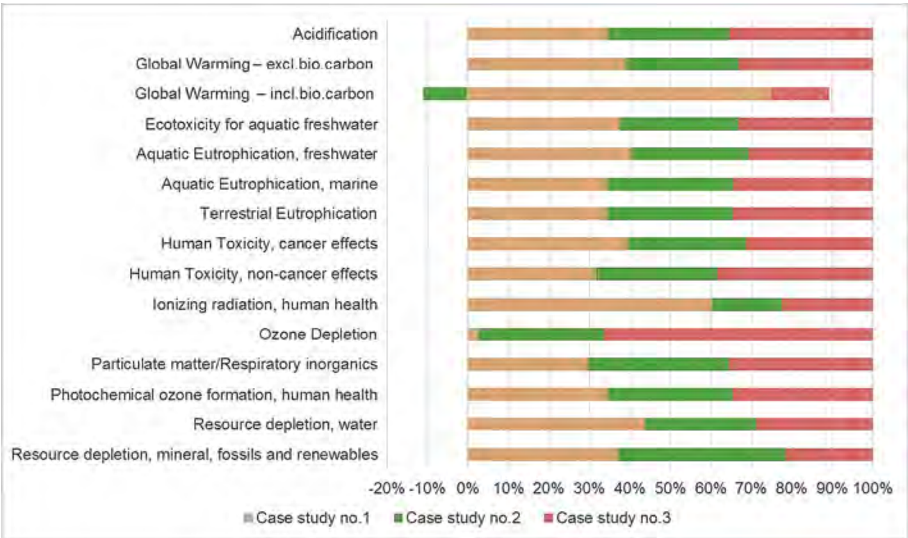

Fig. 7. Comparing the entire life cycle impact.

Table 14
Environmental impact over the entire life cycle.

Impact category	Case studies		
	1	2	3
Acidification [mole of H^+ eq.]	16.0926	13.8551	16.3218
Global Warming (Climate Change) – excluding the biogenic carbon [kg CO_2-eq.]	6031.3025	4272.6181	5079.0583
Global Warming (Climate Change) – including the biogenic carbon [kg CO_2-eq.]	2616.2495	-376.8734	487.7381
Ecotoxicity for aquatic freshwater [CTUe]	886.4513	687.6448	777.3103
Aquatic Eutrophication, freshwater [kg P eq.]	0.0507	0.0364	0.0385
Aquatic Eutrophication, marine [kg N eq]	1.1148	1.0055	1.1082
Terrestrial Eutrophication [mole of N eq.]	51.6217	46.7585	51.8073
Human Toxicity, cancer effects [CTUh]	3.79E-05	2.81E-05	2.99E-05
Human Toxicity, non-cancer effects [CTUh]	2.90E-04	2.73E-04	3.50E-04
Ionizing radiation, human health [kBq U-235]	190.5207	54.9618	70.4365
Ozone Depletion [kg CFC-11 eq.]	1.66E-06	2.02E-05	4.30E-05
Particulate matter/Respiratory inorganics [kg PM 2,5 eq.]	3.9471	4.6037	4.6938
Photochemical ozone formation, human health [kg NMVOC]	15.0739	13.4130	15.0693
Resource depletion, water [m^3 eq.]	28.5363	17.8691	18.7263
Resource depletion, mineral, fossils and renewables [kg Sb-eq.]	0.0178	0.0198	0.0103

the products has revealed that the trestle frame roof system from the first case study has an impact between 40% and 50% higher than the one resulted for case studies no. 2 and 3, within all considered environmental indicators. The end-of-life scenarios have demonstrated that the structure analysed in the first case study has a negative influence only in one impact category, while the other two roof systems have adverse effects in four environmental parameters. Therefore, for the post-operation phase, the trestle frame structure can be considered the best choice with respect to the natural environment.

The study argues that even if the trestle frame roof structure can be considered the best option when taking into account only the pre- and post-operation phases, by analysing the total life cycle impact, it can be concluded that this roof structure is the one with the most significant negative impact over the natural environment. The conducted evaluations clearly reveal that the roof structure with collars assed in the second case study represents the most environmentally friendly solution over the entire life cycle. The resulted values also show that the last evaluated roof structure can be considered as a second option, seeing as it has a maximum impact in less environmental parameters compared with the first analysed system. In conclusion, the study at hand underscores the importance of considering the entire life cycle of a product, while also demonstrating that the overall impact of the construction sector over the natural environment can be reduced by using different building solutions (in this case, by using the roof structure with collars).

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