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ENVIRONMENTAL PERFORMANCES OF LONG-SPAN BEAMS

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Abstract

In the last decades, the effects of the climate change phenomena and the consumption rates of raw materials have led to an increasing awareness regarding the need of implementing the sustainable development concept at the global scale. The activities we complete each day have a direct negative influence over the current situation of the natural ecosystems, and therefore it is highly important to understand and reduce at the same time our global environmental footprint. One of the most significant economic activities that has at the same time a major influence over human wellbeing and a tremendous impact over the environment is represented by the construction sector. Considering the level of pollutants emitted into the air, water and soil that are related to the built environment, it can be stated that this sector represents a critical factor in achieving global sustainability. Therefore, it is essential that civil engineering specialists clearly understand the negative ecological effect of the materials and structural elements that are currently being used, in order to promote solutions with a low level of environmental influence. Taking under account the above, the authors aim at comparing the influence over the natural environment of a long-span beam made from different structural materials, in order to clearly determine the solution that implies a low level of negative environmental impact. In order to achieve this objective, the Gabi software was used and the Life Cycle Assessment has been considered. The resulted values attained by taking under study the cradle-to-cradle approach justify considering the linear element made by using glued laminated timber as a solution that can be successfully used in achieving the sustainability goals in the built environment.

Keywords: built environment, cradle-to-cradle, Life Cycle Assessment, pollutants, sustainable development

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1. Introduction

It is common knowledge that fulfilling the primary aspects of the sustainability concept, especially the one regarding the environment, represents the most important undertaking that modern society will face in this century. The climatological anomalies registered in the last decades around the world have led to an increasing public awareness regarding the negative way in which the climate change phenomena can significantly alter the present way of life. Another important issue is reflected by the fact that the present generations will have a highly important negative impact over the chance of development of future generations if the actual level of environmental burdens does not significantly decrease. Thus, different solutions and actions should be undertaken in order to reduce the negative load over the environment resulted from human daily activities. At the level of the general public, it must be fully understood that it is necessary to drastically reduce the volume of emissions and also to significantly optimize the present alarming natural resources consumption rates.

Taking into account the high volume of ecological burdens resulted from the activities specific to the built environment, the construction sector is considered to be one of the most pollutant economic

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activities (Agusti-Juan et al., 2017; Brejnrod et., 2017; Di Maria et al., 2018; Hafliger et al., 2017; Hossain and Poon, 2018; Ingrao et al., 2014; Maxineasa et al., 2015; Maxineasa and Taranu, 2018; Maxineasa et al., 2018; Ortiz et al., 2009; Simion et al., 2013; Vacek et al., 2017; Zhao et al., 2017). Worldwide, the construction sector consumes between 40 and 60% of the total volume of natural resources used yearly, thus being the most important consumer (Di Maria et al., 2018; Ingrao et al., 2014; Maxineasa et al., 2015; Maxineasa and Taranu 2018; Miller and Ip, 2013; Ortiz et al., 2009). This sector also produces approximately 25% of the total global waste and more than 40% of the greenhouse gases emitted worldwide, being responsible at the same time for the consumption of more than 40% of the total primary energy and over 15% of the global freshwater resources (Ding, 2014; Hoxha et al., 2017; Maxineasa and Taranu, 2018; Mokhlesian and Holmen, 2012; Pacheco-Torgal, 2014; Palacios-Munoz, 2018; Simion et al., 2013). Another important aspect that clearly shows the importance of the construction sector in the global environmental policies is reflected by the fact that out of the total volume of materials that are consumed worldwide, almost 50% are construction materials (Blankendaal et al., 2014; Maxineasa and Taranu 2018; Miller and Ip, 2013; Pacheco-Torgal and Labrincha, 2013; Pacheco-Torgal, 2014).

Analyzing the above, it is justified to state that the built environment represents one of key factors in the overall efforts of achieving global sustainability. Therefore, we should develop, apply and promote different solutions with the goal of significantly improving the ecological performances of the built environment. In order to achieve this goal, it is necessary to apply a life cycle type of thinking so as to resolve all the challenges that are specific to the built environment. Even if from the life cycle of a construction, the pre-operation phase only accounts only for between 8 and 20% of the total environmental impact, and at first glance it appears that this stage should not be treated as a key one, the production and consumption of building materials should be regarded as highly important processes that can significantly reduce the total level of environmental burdens of a building (Hays and Coke, 2009; Huberman and Pearlmutter, 2008; Maxineasa et al., 2018; Ortiz et al., 2010).

Thus, in the designing phase, civil engineering specialists should bear in mind, besides designing the most suitable structural system, the ecological effects of the considered elements and materials. Thus, the adopted solutions regarding the structural elements and materials should also be supported by a full understanding of the ecological performances of all the structural and non-structural members over the entire life cycle of the building. A very interesting challenge related to both structural and environmental consideration is represented by industrial buildings with large spans that usually imply the use of structural components with large cross sections, and the consumption of high amounts of construction materials. Taking into account the rapid industrial development of the last decades, one that is believed to continue into the future, the number of new industrial buildings will significantly increase. Therefore, by taking into consideration different solutions for reducing the pre-operation ecological negative impact of these buildings, the negative environmental influence of the construction industry can be notably reduced. Keeping in mind the above, the present papers aims at determining what construction material should be used for a new prefabricated long-span beam. For achieving this goal, the authors used the GaBi ts software in order to employ the Life Cycle Assessment (LCA) methodology by taking under observation the cradle-to-cradle approach.

2. LCA case studies

LCA is defined by the international standards ISO 14040:2006 and ISO 14044:2006 as a “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 2006a,b). By using this methodology, the environmental negative effects resulted from the life cycle of a product or a service can be significantly reduced by understanding the main causes and by applying different solutions to overcome them.

As stated before, the cradle-to-cradle approach has been considered for evaluating and comparing the environmental performances of the analyzed products that are specific to the construction sector. Table 1 presents the modules from the life cycle of the analyzed products that have been taken under analysis. These modules have been established according to the European standards EN 15978:2011 and EN 15804+A1:2013 (EN 2011, 2013). The LCA studies have been completed by taking under observation a life span of the products of 50 years. The functional unit considered in the present research is a horizontal linear element with a length of 19 m that can be used for the structural system of an industrial building with long spans. In order to take into account the influence of the transportation phases, a Euro 6 diesel truck has been considered. The transportation distances of the prefabricated analysed linear elements from the manufacturing unit to the construction site was considered to be 30 km. This assumption was made in order to reduce the influence over the final results of a variable number that will change from one construction site to another.

The following case studies have been considered:

- case study no.1: a 19 m span, pre-stressed reinforced concrete beam (Fig. 1a);
- case study no.2: a 19 m span, steel beam (Fig. 1b);
- case study no.3: a 19 m span, glued laminated timber (glulam) beam (Fig. 1c).

Table 1. Life cycle phases considered in the analysis

Life cycle phase	*Life cycle module*
Extraction of raw materials	A1
Processing of raw materials and manufacturing the construction materials	A3
Manufacturing and installation of the analysed linear elements	A5
Use of the linear elements	B1
Maintenance	B2
De-construction/demolition	C1
Waste processing	C3
Recycling of the materials	D
Transportation phases	A2, A4, C2

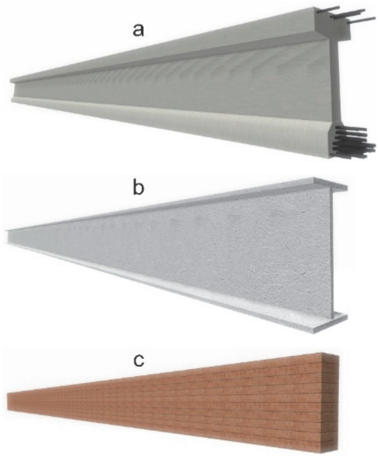

Fig. 1. Analyzed case studies: a. case study no.1; b. case study no. 2; c. case study no. 3

Table 2 contains the impact categories and environmental parameters that have been considered in order to describe the environmental impact of the analysed construction products. These parameters were selected by taking under observation the recommendation of the European Commission - Joint Research Centre (2011) and the specifications from the European Norm 15804:2012+A1:2013 (EN, 2013).

As Table 2 shows, in order to assess the carbon footprint of the analysed construction elements, the environmental impact categories Global Warming – excluding the biogenic carbon, and Global Warming – including the biogenic carbon have been considered. This decision was made in order to have a better understanding on the negative ecological effects resulted from the operations needed for constructing the linear structural elements that are under evaluation. It is well known that the consideration of biogenic carbon in analyzing the amount of CO_2 emitted into the atmosphere during the manufacturing of a timber element represents a sensitive issue due to the fact that trees consume a significant amount of carbon dioxide before they are harvested, and therefore the carbon footprint of the manufactured timber product can be considered negative (Fouquet et al., 2015; Head et al., 2019; Wiloso et al., 2016). Therefore, in order to have a complete view over the influence of biogenic carbon over the overall carbon footprint of the linear construction element made from glued laminated timber analyzed in the last case study, the authors decided to use both Global Warming environmental impact categories.

3. Assessing the environmental performances of the considered products

3.1. Evaluating the environmental performances over the pre-operation phase

The first part of the study pertains to the cradle-to-gate environmental impact of the considered construction products. In order to complete this stage of the analysis the A1, A2, A3, A4, and A5 life cycle modules are considered. As stated before, the environmental performances of a long-span beams made of 3 different materials will be assessed and compared. Therefore, in order to achieve the goal of the study the following structural materials have been considered: C60/75 concrete, S355 structural steel, and GL 36 glue laminated timber. The assessment was completed by considering the amount of component materials that are shown in Table 3. In order to perform an LCA study with a lower level of uncertainties, for case study number 1, the analysis also considered information regarding energy consumption during the mixing of concrete stage.

Table 4 and Fig. 2 present the values describing, from a cradle-to-gate approach, the negative ecologic effects of the assessed construction elements over the pre-operation stage. In the case of the Global Warming –excluding the biogenic carbon environmental impact category, the pre-stressed reinforced concrete beam has the highest negative influence followed by that of the steel and the glulam beams.

Table 2. Impact categories used for assessing the environmental impact

Impact category	*Parameter*	*Methodology*	*Units*
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.
Human Toxicity, cancer effects	Human toxicity potential, cancer effects (HTPc)	USETox	CTUh
Ozone Depletion	Depletion potential of the stratospheric ozone layer/Ozone depletion potential (ODP)	ReCiPe	kg CFC-11 eq.

Table 3. Component materials considered in the pre-operation environmental impact assessment

Material	*Quantity [kg]*	*Case study*
Water	805.95	1
Cement	2985	
Coarse aggregate	6567	
Fine aggregate	4179	
Superplasticizer	83.58	
Steel strands and rebars	235.79	
"I" steel profile	2318	2
Coating system	7.90	
Glulam	2258	3
Paint	13.5	

As presented in Table 4, the amount of CO_2 emissions during the manufacturing of the linear structural element completed by using timber products has a significantly lower value than the ones resulted in the case of the concrete and steel products. At the same time, it can be observed that in all the analyzed case studies, the component materials have the highest impact over the global warming phenomena when the biogenic carbon is excluded.

By analyzing Fig. 2, it visible that for the Global warming - including the biogenic carbon impact category, the pre-stressed reinforced concrete beam has the highest negative ecologic influence, followed closely by the steel beam. The resulted values show that due to the use of timber products in the manufacturing processes, the glulam beam has a negative carbon footprint, and therefore a positive influence over the global warming phenomena. For this linear timber element, only the transportation phase and the use of the painting system have a negative influence over the amount of CO_2 emitted into the atmosphere over the pre-operation stage (Table 4). As in the case of the previously analyzed environmental parameter, the final values showing the carbon footprint of the assessed construction elements are mainly influenced by the type and amount of the component materials that are used in the production stage. For the third considered environmental parameter, the resulted values are in contrast with the ones describing the influence of the elements over the global warming phenomena. The element that exerts the most important volume of negative effects over human health is represented by the one that is manufactured by using structural steel.

The results presented in Table 4 and Fig. 2 show that the use of the pre-stressed reinforced concrete beam and of the glulam beam implies a level of human toxicity that represents approximately 51% and 40% of the one registered in case study number 2. For the last considered environmental impact category, that is describing the negative effects of the considered construction elements over the stratospheric ozone layer, the cradle-to-gate LCA analysis shows that the linear element from case study number 1 has the highest impact. The glulam beam and the steel linear construction product have a negative environmental influence that is approximately 90% and 98% lower than the one registered in the case of the pre-stressed reinforced concrete element.

3.2. Evaluating the environmental performances over the usage phase

The goal of the second part of the environmental impact assessment study is to determine the negative ecological influence of the considered products over the operation phase, by taking into account a series of maintenance works. The authors considered that every 10 years, each of the three analyzed beams are subjected to the following repairing activities: in the case study number 1, on the surface of the pre-stressed reinforced concrete beam is applied a layer of mortar, and in the case studies number 2 and 3 the coating and painting system is renewed. The life span of the assessed construction products is considered to be 50 years, therefore the maintenance works mentioned above will be completed four times.

Table 4. Cradle-to-gate environmental impact

Life cycle stages		*Impact categories*			
		Global Warming (Climate Change), excluding the biogenic carbon [kg CO_2-eq.]	*Global Warming (Climate Change), including the biogenic carbon [kg CO_2-eq.]*	*Human Toxicity, cancer effects [CTUh]*	*Ozone Depletion [kg CFC-11 eq.]*
Case study no. 1	Component materials	2965.25	2961.08	4.41E-6	2.76E-6
	Mixing	42.11	42.14	3.78E-8	1.13E-8
	Transport	23.11	22.86	1.58E-7	1.62E-10
Case study no. 2	Component materials	2520.33	2510.73	8.86E-6	5.33E-8
	Coating	15.71	16.53	4.34E-8	2.41E-9
	Transport	3.63	3.59	2.48E-8	2.55E-11
Case study no. 3	Component materials	834.31	-2862.41	3.32E-6	2.63E-7
	Paint	34.89	35.05	1.88E-7	2.00E-9
	Transport	4.08	4.03	2.79E-8	2.86E-11

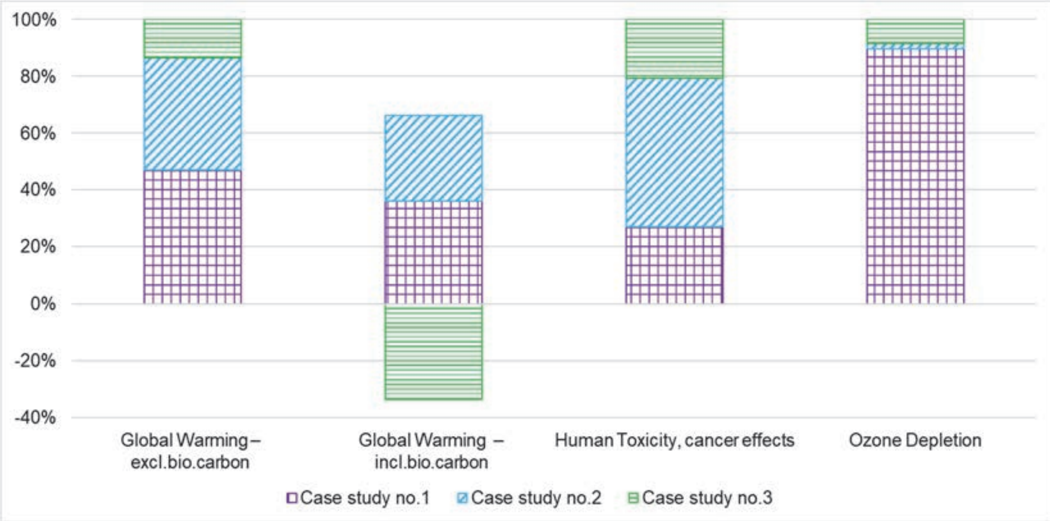

Fig. 2. Comparing the cradle-to-gate environmental impact

Table 5 presents the quantities of the materials that are used every 10 years, and that have been used in order to describe the effects over the natural environment during the operation stage of the analyzed products. As in the case of the pre-operation phase, in order to take into consideration the transportation phase, a Euro 6 diesel truck has been used, and the transportation distance of the repairing materials from the manufacturer to the construction site was considered to be 30 km.

Table 5. Amounts of materials used during one maintenance process (every 10 years)

Material	*Quantity [kg]*	*Case study*
Mortar	7.65	1
Coating system	3,95	2
Paint	11.25	3

Fig. 3 and Table 6 show the values that describe the environmental impact resulted during the maintenance works over the entire life span of the considered linear construction elements. By analyzing the results, it can be observed that in all the analyzed impact categories, the reparation works completed for the glulam beam assessed in case study number 3 have the highest level of negative ecological effects, followed by the ones resulted in the case of the pre-stressed reinforced concrete and steel beams.

The values achieved during the assessment demonstrate that the differences between the linear construction element that is manufactured by using timber elements and the other two studied products are highly significant. This is mainly due to the fact that during the maintenance works performed for the product from the last case study, the amount of paint consumed is significantly higher than the quantities of materials used in the case studies number 1 and 2. Another important aspect that can be noticed after performing the second phase of the cradle-to-cradle LCA study is that in all analyzed case studies, for all the considered environmental impact parameters, the materials used for completing the maintenance operations have the most important influence over the total negative influence over the natural environment.

3.3. Determining the post-operation environmental impact

In the last part of the life cycle assessment study, the environmental benefits of the considered linear construction products have been determined by taking under observation different end of life scenarios. In case study number 1, it has been considered that the prestressed reinforced concrete element is dismounted and crushed on the construction site in order to recover almost 100% of the component materials (i.e. steel strands, reinforcement bars, and crushed concrete). During the study, it has been assumed that all of the recovered steel reinforcement and steel strands are going to be used as recycled materials in order to produce new steel based products, and that from the recovered crushed concrete, 50% is going to be used as crushed aggregate in new concrete mixture and the other half is going to be disposed as waste.

The end of life scenario used in case study number 2 considers that the steel beam is fully recovered and recycled as waste material used for manufacturing new steel materials. In the last case study, the post-operation phase from the life cycle of the assessed product has been modelled by considering that the element is 100% recovered from the structure and recycled as a source for obtaining bioenergy in a municipal incineration unit. The amount of materials that have been used in the last part of the LCA study are presented in Table 7.

In order to take into consideration the transportation phase of the waste materials from the construction site to the recycling unit, a Euro 6 diesel truck and a transport distance of 45 km have been considered.

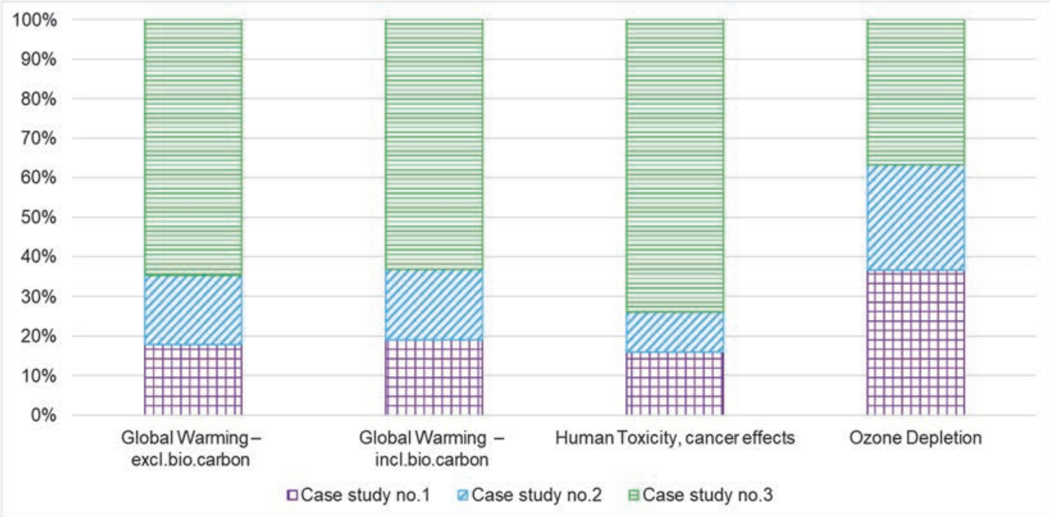

Fig. 3. Comparing the maintenance operations environmental impact during the entire life span of the elements

Table 6. Environmental impact of the maintenance works during the entire life span of the elements

Life cycle stages		*Impact categories*			
		Global Warming (Climate Change), excluding the biogenic carbon [kg CO_2-eq.]	*Global Warming (Climate Change), including the biogenic carbon [kg CO_2-eq.]*	*Human Toxicity, cancer effects [CTUh]*	*Ozone Depletion [kg CFC-11 eq.]*
Case study no. 1	Repairing mortar	32.07	35.15	1.34E-7	6.68E-9
	Transport	0.14	0.13	9.35E-10	9.60E-13
Case study no. 2	Coating	31.40	33.06	8.67E-8	4.82E-9
	Transport	0.07	0.07	4.83E-10	4.96E-13
Case study no. 3	Paint	116.29	116.83	6.26E-7	6.66E-9
	Transport	0.20	0.20	1.38E-9	1.41E-12

Table 7. Amounts of materials considered in the post-operation phase

Material	*Quantity [kg]*	*Case study*
Crushed concrete	7268.47	1
Steel strands and reinforcement bars	235.79	1
Steel element	2318	2
Glulam element	2258	3

By analyzing the resulted values presented in Fig. 4 and Table 8, it can be observed that for the environmental impact parameters Global Warming excluding and including the biogenic carbon, the linear construction element made entirely by using steel, assessed in the second case study, has the highest negative value of carbon footprint and therefore the most important positive ecological effect. At the same time, out of all three analyzed building products, the steel beam has the highest negative influence in the case of the Human toxicity, cancer effects, and Ozone depletion impact categories.

As in the case of the steel element, the pre-stressed reinforced concrete beam has a negative carbon footprint for both environmental parameters that are describing this ecological issue, but compared with the element analyzed in the second case study, for these two categories, the product assessed in case study number 1 has a 10 times lower environmental benefit.

Also, by analyzing the values from Table 8 and Fig. 4, it can be stated that for the post-operation phase from the life cycle of the analyzed products, the beam made of glulam considered in the last case study represents the most environmentally friendly solution due to the fact that for all four impact categories, the resulted values are negative, meaning that the use of this type of element has an important positive ecological influence.

4. Comparing the environmental impact of the analyzed products over the entire life cycle

In order to have a better understanding of the overall environmental impact or benefit of the assessed construction products, in the last part of the study, the values that have been presented and discussed until this point are going to be compared from a cradle-to-cradle perspective. Therefore, the results describing the ecological impact of the three analyzed construction products over the pre-operation, operation and post-operation life cycle phases are going to be considered with the goal of having a complete overview regarding the best solution that can be used with respect to the natural environment. The total environmental impact resulted in the three considered case studies is presented in Table 9 and Fig. 5. It can be observed that the pre-stressed reinforced concrete beam has a negative influence in all the impact categories that have been considered in the study. At the same time, the steel linear construction element has a negative carbon footprint in both Global warming parameters, but compared with the other two studied products in the case of the Human toxicity, cancer effects, and Ozone depletion impact categories, the element from the second case study has a massive negative environmental influence. Also, by analyzing Table 8 and Fig. 5, it can be observed that the only construction element that has negative values for all impact categories is the one in case study number 3. Therefore, it is justified to argue that the glulam beam represents the only solution that has a positive influence on the natural environment over the entire life cycle.

5. Conclusions

The alarming rates of raw materials consumption and the current extreme effects of the climate change phenomena are effectively increasing the level of awareness regarding the tremendous negative effect of human daily activities over the natural environment, endangering the chance to development of future generations.

Therefore, all industrial sectors are implementing various solutions in order to minimize the present environmental issue with the goal of implementing the sustainable development goals. One significant economic activity that is also considered to be the most important factor in achieving global sustainability is the construction sector.

Table 8. Environmental impact of the end of life phase

Case studies	*Impact categories*			
	Global Warming (Climate Change), excluding the biogenic carbon [kg CO_2-eq.]	*Global Warming (Climate Change), including the biogenic carbon [kg CO_2-eq.]*	*Human Toxicity, cancer effects [CTUh]*	*Ozone Depletion [kg CFC-11 eq.]*
Case study no. 1	-357.23	-355.74	1.60E-7	1.14E-5
Case study no. 2	-3514.12	-3499.57	1.49E-6	1.12E-4
Case study no. 3	-1507.23	-1509.56	-6.51E-7	-4.84E-7

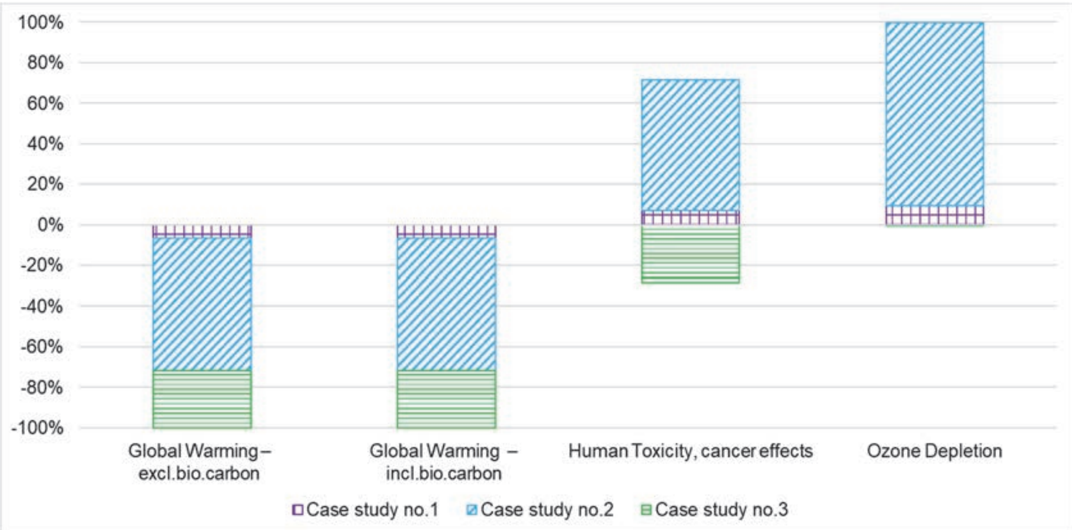

Fig. 4. Comparing the end of life environmental impact

Table 9. Environmental impact of the entire life cycle of the analyzed products

Case studies	*Impact categories*			
	Global Warming (Climate Change), excluding the biogenic carbon [kg CO_2-eq.]	*Global Warming (Climate Change), including the biogenic carbon [kg CO_2-eq.]*	*Human Toxicity, cancer effects [CTUh]*	*Ozone Depletion [kg CFC-11 eq.]*
Case study no. 1	2705.45	2705.62	4.90E-6	1.42E-5
Case study no. 2	-942.98	-935.59	1.05E-5	1.12E-4
Case study no. 3	-517.46	-4215.86	-3.51E-6	-2.10E-7

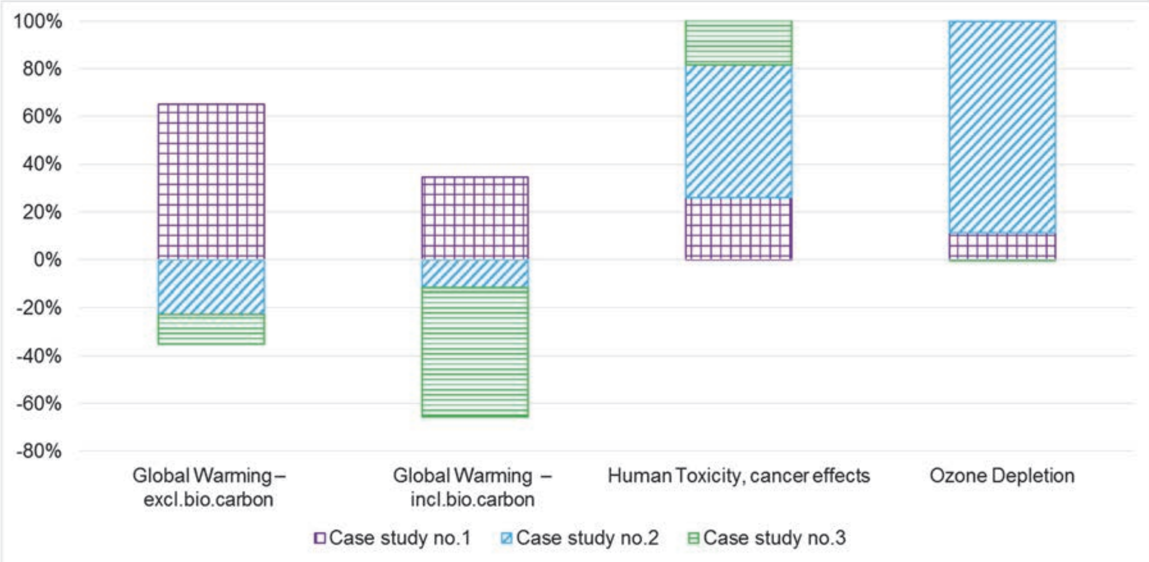

Fig. 5. Comparing the end of life environmental impact

Thus, in order to minimize the environmental footprint of the built environment, it is necessary to fully understand the ecological effects of the materials and of the structural elements that are used for resolving different civil engineering problems.

Considering the above, during the present study the authors have attempted to fully describe the environmental performances of new prefabricated long-span beams manufactured by using three different structural materials. In order to achieve the goal of the study, it was considered that the linear element was constructed by using pre-stressed reinforced concrete (case study number 1), structural steel (case study number 2), and glued laminated timber (case study number 3). The performed Life Cycle Assessment study has been undertaken by using the cradle-to-cradle approach with the objective of describing in an objective manner the environmental influence over the entire life cycle of the considered construction products.

By analyzing the resulted values, it is justified to say that the element considered in the last case study, the glulam beam, represents the solution that presents the most import level of environmental benefit, being the only product that shows negative values for all considered impact parameters. The differences between this element and the other two are highly significant, especially in the case of the Global warming, including biogenic carbon, Human toxicity, cancer effects, and Ozone depletion environmental categories. Another solution that can be considered environmentally friendly is represented by the steel beam, due to the fact that it has a positive effect in the case of the Global warming, excluding and including biogenic carbon parameters. At the same time, the element studied in case study number 2 has the most important negative effect over human health and the ozone layer.

The pre-stressed reinforced concrete analyzed in the first case study is the structural solution that exerts the most important negative environmental impact. Therefore, by taking into account the environmental performances of all three solutions considered under the study, the glulam beam is the most suitable.

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