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ASSESSMENT OF SELECTED TYPES OF THE STRUCTURAL ENGINEERED WOOD PRODUCTION FROM THE ENVIRONMENTAL POINT OF VIEW

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ABSTRACT

According to recent findings, the construction industry contributes to almost 40% of global CO_2 emissions. Life Cycle Assessment is one of the methods assessing the anthropogenic impact on the environment. This paper compares the production of selected types of structural wood-glued laminated timber (glulam), plywood and three-layer solid wood panel (SWP) in terms of their environmental impact. The results of this analysis are important especially for designers and architects, who can reduce the environmental footprint by choosing materials already in the design phase and thus be part of the building eco-design creation. This direction is becoming increasingly popular in the world and, in addition, it increases market competitiveness. The selected structural wood products were compared using the IMPACT 2002+ method and SimaPro 8.5.2 software was used for the assessment. Characterization and single score results were assessed. Glulam for indoor use achieved the lowest total environmental impact. On the other side, plywood for outdoor use was found the worst one of the assessed products. The two most affected impact category for all evaluated wood products was the impact on Human health and Ecosystem quality, respectively. Generally, plywood products present a considerable environmental burden, therefore it could be replaced by SWP. The study also showed the importance of production technology in the environmental context.

Key words: environmental impact, structural wood, eco-design, life cycle assessment, glulam, plywood, three-layer solid wood panel.

INTRODUCTION

Globally, the construction industry is showing an increase in emissions and energy consumption. In 2018, it was responsible for 36% of final energy consumption and 39% of CO_2 emissions, of which 11% came from the production of building materials and 28% of emissions were produced in connection with operational energy consumption (IEA 2019). Modern energy-efficient buildings limit the growth of energy consumption in both residential and non-residential buildings. Nevertheless, further actions to reduce energy performance still need to be carried out (Directive 2010/31/EU). Therefore, greenhouse gas emissions reduction steps should be one of the top environmental policy priorities for the construction sector.

Awareness of the need for greater use of renewable materials, that do not only reduce resource depletion but also address a range of other environmental issues is gradually increasing (SOTAYO *et al*. 2019). In the field of sustainable construction, structural engineered wood and wood-based building systems represent an irreplaceable position as they bond carbon and thus mitigate the climate change (PAROBEK *et al*. 2019, PALUŠ *et al*. 2020). Adoption of new regulations and the excellent physical, environmental and economic properties brought attractiveness of structural engineered wood products amongst architects, as well as slow replacement of mineral-based building materials use with sustainable ones (HILDEBRANDT *et al*. 2017). At present, massive wood constructions made of cross-laminated timber (CLT), glued laminated timber (glulam) and laminated veneer lumber (LVL) come to the fore as a substitute for concrete and steel (CRAWFORD, CADOREL 2017). Architects and designers often do not know the relationship between the choice of construction material and its impact on the environment. Assessment of alike impacts can bring new architectural practices and introduce environmental awareness in this area.

LCA – Life Cycle Assessment

LCA is a voluntary environmental management tool that systematically assesses the environmental aspects of products or services at all stages of their life cycle. It has a precisely defined structure (Fig. 1) and is standardized within the series of ISO 14040 standards (ISO 14040; ISO 14044).

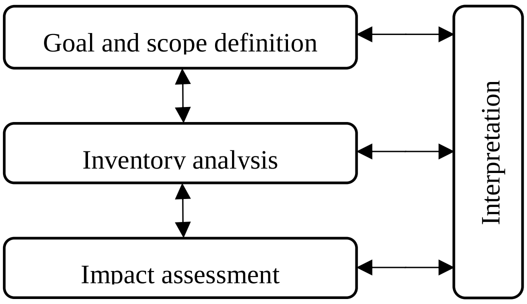

Fig. 1 LCA structure (ISO 14040).

The product life cycle is generally divided into stages (Table 1). It represents the cycle of materials and energy throughout individual life stages - from the acquisition of raw materials, production of construction materials, through the construction itself, the use of the building to its disposal and eventual recycling. The evaluation includes all material and energy inputs to the examined system and the corresponding output flows.

Tab. 1 Life cycle stages of buildings (EN 15804).

Product stage			Construction stage		Use stage							End of life stage				Benefits and loads beyond the system boundaries
Raw material supply	Transport to manufacturer	Manufacturing	Transport to site and on site	Construction process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction and demolition	Transport	Waste processing for reuse,	Waste disposal	Reuse Recovery Recycling potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

The results of LCA are used generally to support product decision-making activities, such as the identification of hotspots in product systems, product development, product comparison, green procurement and market requirements (HAHNEL *et al.* 2021; LIIKANEN *et al.* 2019). Moreover, LCA serves as a source of information for the development of eco-design by allowing comparison of different variants of considered product (PAJCHROWSKI *et al*. 2014). The results of the analysis can also be used to select appropriate product processing technologies and to introduce these technologies into the perspective of the product-related chain. LCA is increasingly used at the strategic level for business development, policy and education (UNEP/SETAC 2005).

Structural wood

Wood becomes one of the key building materials in the field of sustainable construction. New progressive wood-based materials are still being added to the market. Structural wood is a type of excellent quality wood (KRETSCHMANN 2013, DINWOODIE 2000). It meets the set technical requirements resulting from the valid technical standards (STN EN 1995, PORTEOUS KERMANI 2013). According to its technological composition, structural wood is divided into solid wood, modified wood and wood composites, that involves laminated structural wood, veneer-based structural wood, agglomerated structural wood and combined structural wood (Fig. 2). Composite represents wood-based product made by gluing wood material with a non-wood material. The individual types of structural wood also differ from each other by the production technology, which can be decisive in assessing the environmental impacts of construction materials. Energy consumption in the stage of material manufacturing, the need for thermal energy in drying operations and the amount and type of adhesive used are some of numerous factors in the environmental footprint assessment of structural wood.

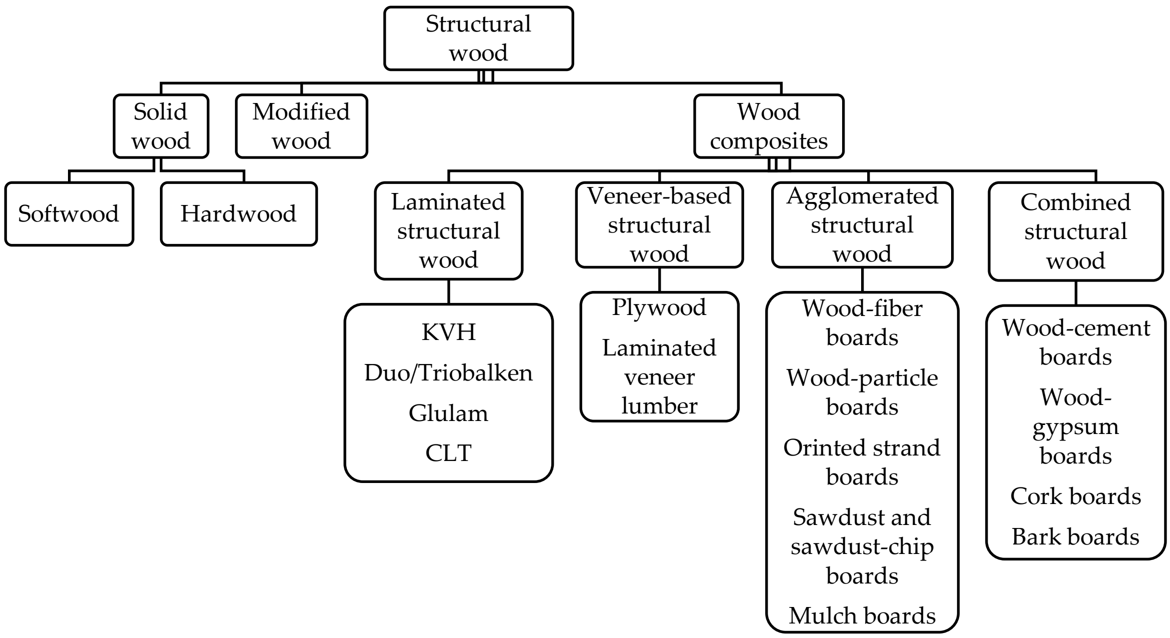

Fig. 2 Structural wood typology (STN EN 14080).

It is well known that wood has much lower negative impact on the environment compared to conventional construction materials. SAADE *et al*. (2020) compared wood frame buildings with their concrete variant and concluded that Global Warming Potential (GWP) for concrete building was higher than for the wood-based building in every aspect. At the same time, they claimed that the result of the LCA study is deeply dependent on the decisions made and scenarios created during the modeling of the life cycle of the investigated object.

Nowadays, CLT panels, LVL, glulam and fibreboards are becoming increasingly popular construction materials, recording annual demand growth rates of 2.5% to 15% (HILDEBRANDT *et al*. 2017). Moreover, KVH (Konstruktionvollholz), a finger-jointed solid timber; and Duo/Triobalken, a solid timber made of two to five planks glued together parallel to the fibres, can also be used for load-bearing wood structures. However, only data for structural engineered wood available in the ecoinvent database were included in this paper.

The study by POMMIER *et al*. (2016) evaluated 3 types of wood - hardwood, softwood and marine pine (*Pinus pinaster*) - using the ReCiPe Midpoint method (H). The latter had the lowest environmental impact values. The research also included the area of plywood production technology. The traditional plywood production process requires very thorough drying of the wood before gluing. Heat consumption in this process could be reduced by applying a new technology of gluing green wood and vacuum forming plywood (POMMIER *et al*. 2016, ENQUIST *et al*. 2014).

Glulam is one of the most popular construction materials globally. Its favorable environmental impact has also been confirmed by several studies. HASSAN AND JOHANSSON (2018) proved that glulam beams produce less CO_2 emissions than their steel variant. A similar conclusion was reached by SATHRE AND GUSTAVSSON (2009) when comparing wooden frames in construction with reinforced concrete materials. BRANDNER *et al*. (2016) found that central production of prefabricated products reduces costs compared to conventional construction techniques.

Generally, when assessing the environmental impacts of buildings, the manufacturing technology of construction materials is poorly described, leading to wider range of uncertainty of the base data. More and more studies show that the production of materials can have even greater impact on the environmental performance of buildings than the operation of them (MITTERPACH *et al*. 2018, CRAWFORD *et al*. 2017, DODOO *et al*. 2012, PETROVIC *et al*. 2019; HAFNER, SCHÄFER 2017). Therefore, it is important to know and select alternative construction methods that can help to reduce the environmental effects of production associated with the production of the material (CRAWFORD, CADOREL 2017).

Moreover, one of the most important features of glued wood-based materials is the type of glue used and its amount. Different types of adhesives have different environmental impacts (POMMIER *et al*. 2016). From the environmental point of view, particularly in terms of human health and toxicity, polyurethane-based adhesives prove to be the most suitable, as they do not emit VOCs (ENQUIST *et al*. 2014, POMMIER, ELBEZ 2006).

The aim of this study is to compare the production of five types of structural engineered wood used in wood-based constructions - glulam for outdoor and indoor use, three-layer solid wood panel and plywood for indoor and outdoor use – from the environmental point of view.

MATERIALS AND METHODS

The analysis was carried out using SimaPro 8.5.2 software and IMPACT 2002+ evaluation method was chosen (JOLLIET *et al.* 2003). This method provides characterization results as 15 midpoint impact categories whereas single score results are conjugated to 4 endpoint categories (Fig. 3). Characterization factors convert Life Cycle Inventory (LCI) result to the common unit of category indicator which creates impact categories as an outcome of physical, chemical and biological processes with the assessed system.

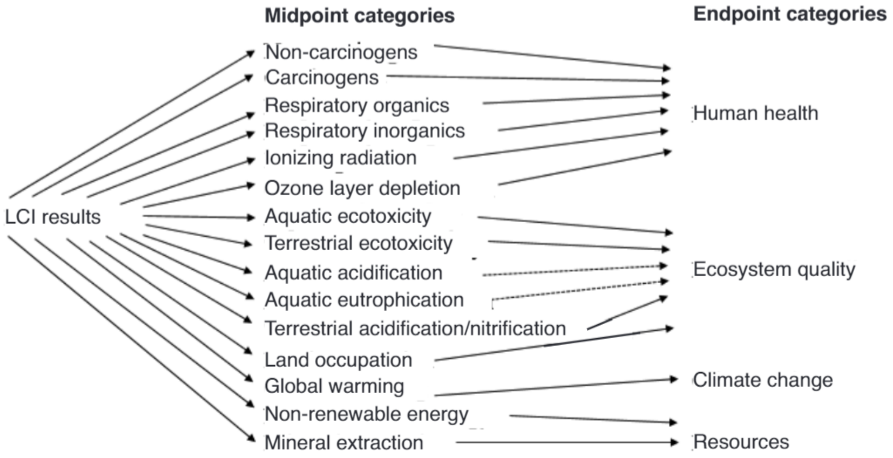

Fig. 3 Overall scheme of the IMPACT 2002+ framework (JOLLIET *et al.* 2003).

Single score is a weighting step within impact assessment which give weight to the different environmental impacts. Single scores are given in Pt units, representing one thousandth of the yearly environmental load of one average European inhabitant.

Background data of analyzed products were found in the ecoinvent v3.5 databases and are used by researchers to analyze and facilitate calculations of the environmental impacts of products and services (WERNET *et al*. 2016). The selected functional unit was 1 m^3 of the product. System boundaries from raw material acquisition to manufacture of the structural engineered wood were investigated („from cradle to gate“).

Inventory analysis

Glued laminated timber - Glulam

Glulam is a type of structural engineered wood produced by gluing lamellas to a length parallel to the direction of the fibers. It can be used as a beam, column or as a roof structure. A vast advantage is its high strength and ability to create an arch (STARK *et al*. 2002).

Tab. 2 Selected structural engineered wood.

Analysed wood product		Input raw material	Type of adhesive	Amount of adhesive (kg.m^{-3})
Glulam for indoor use		Softwood board, unplaned, dried - spruce	UF	11.36
Glulam for outdoor use			MF	11.36
Plywood for indoor use		Hardwood veneer - beech	UF	64.76
Plywood for outdoor use			MF	64.76
Three-layer solid wood panel		Softwood board, unplaned, dried - spruce	PVAC	7.32

In our study, glulam is made from unplaned, dried (u=20%) softwood board. Glulam for indoor and outdoor use differs from one another in the type of adhesive used – ure-formaldehyde (UF) and melamine-formaldehyde (MF), respectively. All types of selected structural wood are presented in Table 2.

Plywood

Plywood is one of the oldest wood-based composite materials. It consists of an odd number of layers of veneers laid perpendicular to the direction of the fibers. In construction, plywood is used in technically demanding formwork. Other applications include scaffolding work platforms, tiling, roofing elements, wood-based structures, facades and floors (STARK *et al.* 2002).

As with the previous product, the plywood is divided into indoor and outdoor use and the same types of adhesives are used in the production – UF and MF, respectively. However, PF is often used in construction plywood. The input material for the production of plywood is hardwood veneer.

Manufacturing of selected wood-based construction materials is similar but there is a difference in some processes. Wood processing begins with debarking of logs, which are then cut into either veneers or other sawmill products (in the production scheme glulam referred to as laths, boards and beams). In the case of glulam production (Fig. 4), the lumber is first joined to length and then the individual lamellas are glued to each other parallel to the direction of the fibers. In the production of plywood (Fig. 5), the veneers are laid and glued to each other perpendicular to the direction of the fibers. This is followed by cutting and surface treatment (BLASS *et al.* 1995).

Three-layer solid wood panel – SWP

The SWP is a special form of plywood with relatively thick layers - lamellas. The production of SWP is like the production of glulam. The lamellas are dried, planed, joined and glued into long slats and glued together into a block, which is cut into boards and eventually planed. The thermal energy for drying the slats is produced mainly by industrial residual wood (WERNER *et al.* 2007).

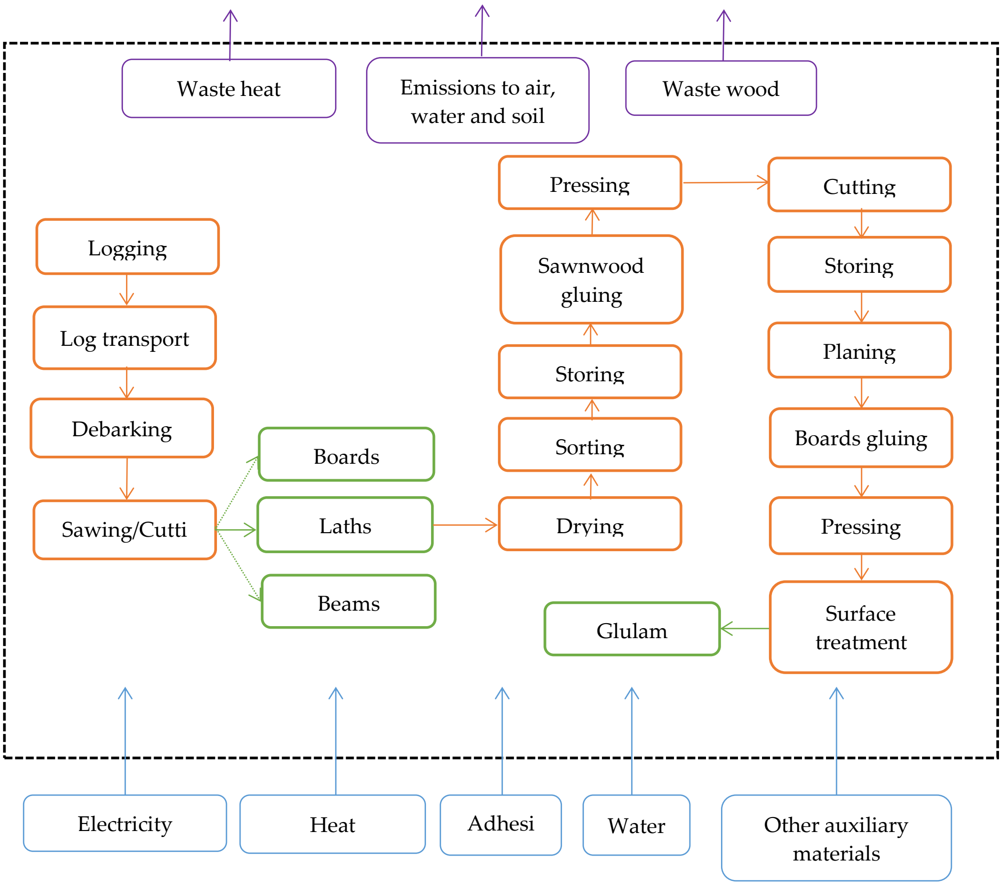

Fig. 4 Simplified glulam production scheme.

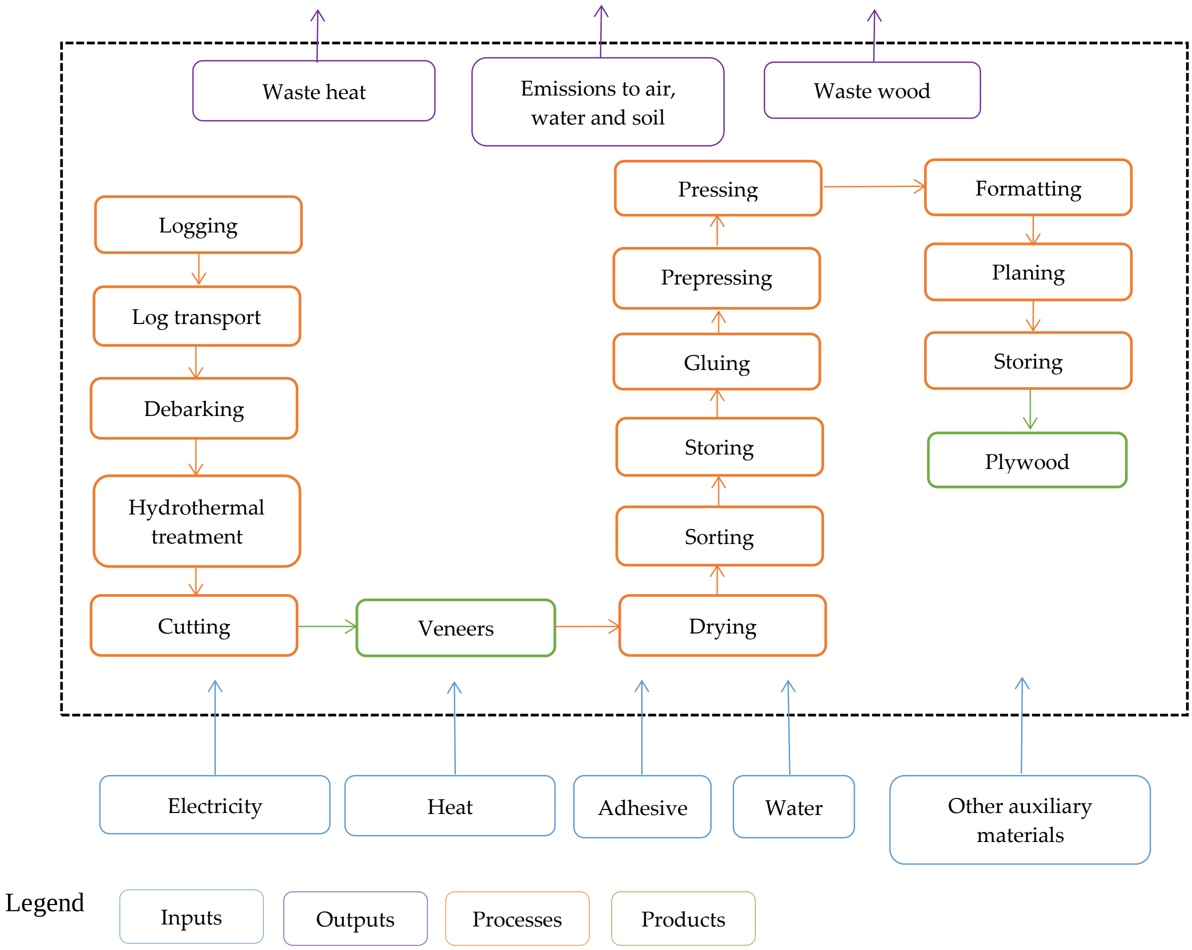

Fig. 5 Simplified plywood production scheme.

RESULTS

Prior to the analysis of selected types of structural wood, a preliminary analysis of the environmental impacts of the production and processing of wood types used (Table 2) and their variants was performed; planed softwood board and softwood veneer compared to unplaned softwood board and hardwood veneer, respectively.

Due to the analysis (Table 3, Fig. 6) planed board has significantly higher environmental impact than its unplaned variant. The most affected was the Ecosystem quality impact category, reaching its top in aquatic ecotoxicity values for all the analyzed wood types. Human health was hit the worst in Ionizing radiation impact category. Higher environmental impact of hardwood veneer against softwood veneer are bound to different chemical nature and physical characteristics of hardwood regarding more intense energy consumption in the manufacturing stage.

Tab. 3 Midpoint characterization of selected sawnwood.

Impact category	Category indicator	Softwood board, unplaned, dried (u=20%)	Softwood board, planed, dried (u=20%)	Hardwood veneer	Softwood veneer
Carcinogens	kg C_2H_3Cl eq	0.90	1.43	0.39	0.27
Non-carcinogens	kg C_2H_3Cl eq	1.03	2.66	0.37	0.27
Respiratory inorganics	kg $PM_{2.5}$ eq	0.11	0.23	0.03	0.02
Ionizing radiation	kBq C-14 eq	0.64	1.06	0.19	0.15
Ozone layer depletion	mg CFC-11 eq	9.28	11.11	3.99	3.23
Respiratory organics	g C_2H_4 eq	66.06	79.20	111.30	70.32
Aquatic ecotoxicity	t TEG water	4.23	13.71	1.63	1.28
Terrestrial ecotoxicity	t TEG soil	2.04	5.40	1.04	0.80
Terrestrial acid/nutri	kg SO_2 eq	2.10	3.27	0.65	0.53
Land occupation	m^2 org. arable	313.80	336.75	194.76	155.75
Aquatic acidification	kg SO_2 eq	0.40	0.64	0.12	0.09
Aquatic eutrophication	g PO_4 P-lim	10.88	21.11	3.16	2.36
Global warming	kg CO_2 eq	68.06	101.45	23.51	18.83
Non-renewable energy	GJ primary	1.03	1.48	0.37	0.29
Mineral extraction	MJ surplus	1.99	3.19	0.46	0.34

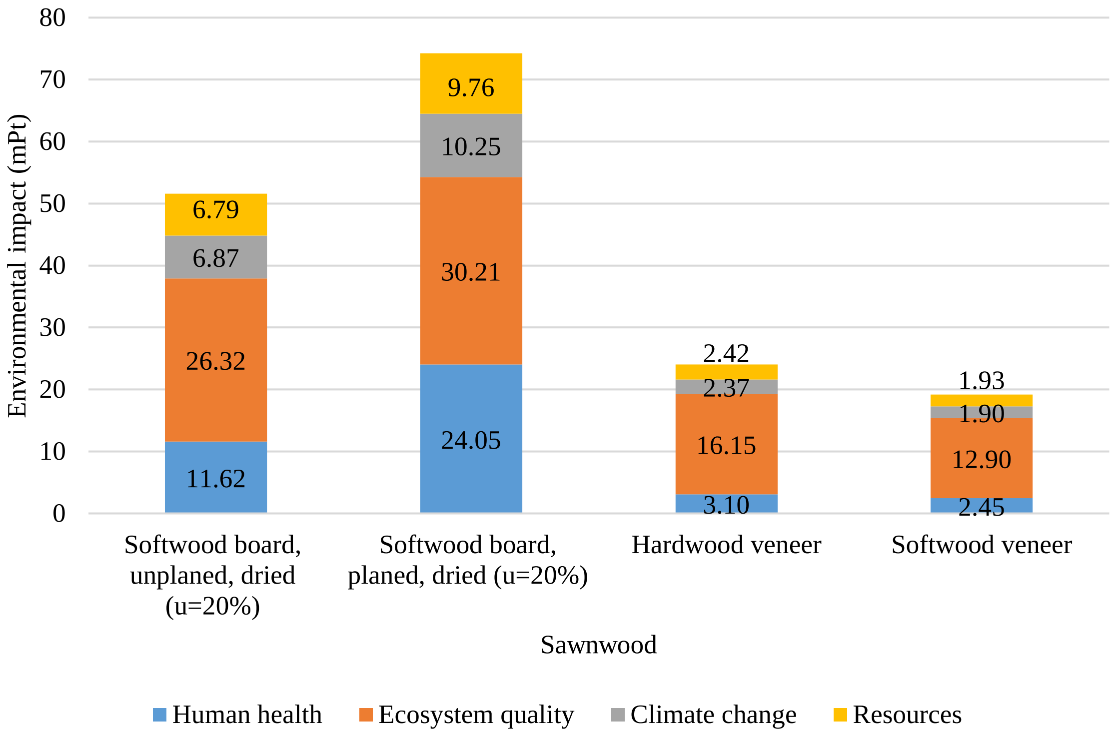

Fig. 6 Single score of selected sawnwood.

Following, a preliminary analysis of used adhesives was performed. It is clear from Table 4 and Fig. 7 that the most appropriate type of adhesive is polyvinyl acetate (PVAC). In this respect, the SWP should achieve the best environmental ratings. On the contrary, MF resin had the worst effect on the environment, and thus products for outdoor use should have worse environmental profile than products intended for indoor use. Ecosystem quality impact category was the least affected in all cases.

Tab. 4 Midpoint characterization of selected adhesives.

Impact category	Category indicator	MF	UF	PVAC
Carcinogens	g C_2H_3Cl eq	163.30	120.86	93.84
Non-carcinogens	g C_2H_3Cl eq	82.70	53.93	36.14
Respiratory inorganics	g $PM_{2.5}$ eq	5.66	3.11	2.55
Ionizing radiation	Bq C-14 eq	26.77	14.63	25.27
Ozone layer depletion	mg CFC-11 eq	0.65	0.42	0.31
Respiratory organics	g C_2H_4 eq	1.84	1.44	2.37
Aquatic ecotoxicity	kg TEG water	298.08	191.85	198.84
Terrestrial ecotoxicity	kg TEG soil	77.95	48.32	31.11
Terrestrial acid/nutri	g SO_2 eq	131.20	64.87	31.00
Land occupation	m^2 org.arable	0.04	0.03	0.02
Aquatic acidification	g SO_2 eq	27.73	14.65	9.71
Aquatic eutrophication	g PO_4 P-lim	0.95	0.59	0.70
Global warming	kg CO_2 eq	4.54	2.64	2.11
Non-renewable energy	MJ primary	89.81	59.87	66.13
Mineral extraction	MJ surplus	0.31	0.20	0.11

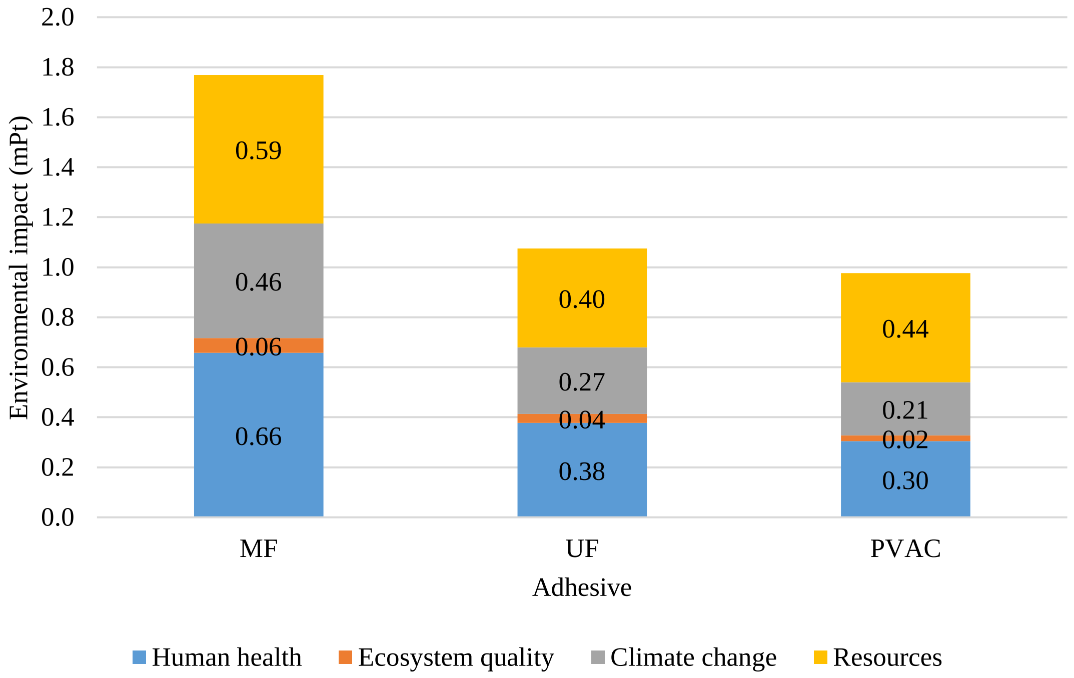

Fig. 7 Single score of selected adhesives.

Applying the previous results to compare selected types of structural engineered wood (Table 5, Fig. 8), it could be stated that:

- Plywood had the highest environmental impact, mainly due to the high consumption of glue. Another reason is the use of hardwood veneer.
- Products for outdoor use generally had higher values, due to the use of MF glue.
- Glulam for indoor use had the lowest environmental impacts at up to three endpoints – Human health, Climate change and Resources.
- Human health impact category was the most affected in all cases emerging from Ionizing radiation.
- Despite using PVAC as the best adhesive option the SWP board eventually reached the third place in the total environmental impact chart (Fig. 8).

Tab. 5 Midpoint characterization of selected structural engineered wood.

Impact category	Category indicator	Glulam, indoor use	Glulam, outdoor use	Plywood, indoor use	Plywood, outdoor use	SWP
Carcinogens	kg C_2H_3Cl eq	4.16	4.63	11.40	14.20	4.57
Non-carcinogens	kg C_2H_3Cl eq	10.70	11.00	25.00	26.90	9.16
Respiratory inorganics	kg PM2.5 eq	0.66	0.69	1.20	1.37	0.73
Ionizing radiation	kBq C-14 eq	3.99	4.13	8.74	9.53	4.52
Ozone layer depletion	mg CFC-11 eq	29.40	31.90	58.20	72.70	36.40
Respiratory organics	kg C_2H_4 eq	0.20	0.21	0.57	0.59	0.24
Aquatic ecotoxicity	t TEG water	69.80	70.60	171.00	178.00	50.50
Terrestrial ecotoxicity	t TEG soil	26.20	26.40	62.60	64.50	19.30
Terrestrial acid/nutri	kg SO_2 eq	8.16	8.88	14.10	18.40	9.46
Land occupation	m^2 org.arable	452.04	445.91	480.30	481.08	745.64
Aquatic acidification	kg SO_2 eq	1.58	1.72	2.71	3.56	1.99
Aquatic eutrophication	g PO_4 P-lim	70.61	74.50	159.73	182.64	76.11
Global warming	kg CO_2 eq	235.89	256.03	391.81	515.06	335.43
Non-renewable energy	GJ primary	4.02	4.33	8.10	9.79	5.33
Mineral extraction	MJ surplus	7.50	8.83	18.03	25.50	8.06

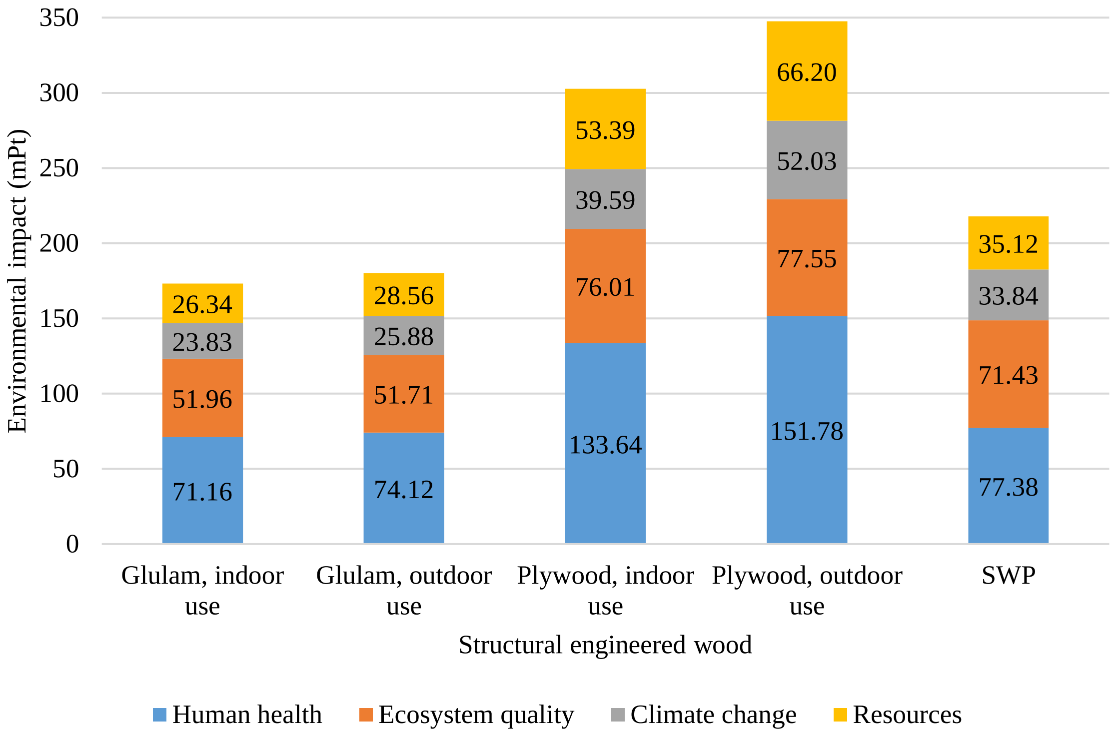

Fig. 8 Single score of selected structural engineered wood.

The results clearly showed that plywood production significantly burdens the environment, compared to other types of analyzed structural wood. This is mainly related to the manufacturing technology and the amount of glue consumed. In this case SWP could be considered environmentally more suitable variant compared to plywood. The two most affected impact category for all evaluated wood products was the impact on Human health and Ecosystem quality, respectively.

DISCUSSION

The production of SWP is similar to the production of glulam, so there are slight differences between them. Most of the negative environmental impacts of SWP come from the technology used, since the PVAC adhesive had the lowest environmental impact amongst used adhesives. Within all the assessed wood-based products glulam for indoor use achieved the lowest total environmental footprint, and thus appears to be the most suitable design variant.

Wood raw material choice also affects the environmental impact of the product. Diverse technology of processing and production of structural wood are related mainly to the different electricity consumption as was showed in the preliminary analysis of selected sawnwood (Table 3, Fig. 6). From this point of view, planed softwood boards were the worst assessed. The lowest environmental impact refers to softwood veneer, however, hardwood veneer is more common. However, production technology can have considerable effect on overall environmental assessment (POMMIER *et al*. 2016).

Structural engineered wood-based materials have not been compared in this way, thus this study is unique. The studies performed concerned either a comparison of different production technologies (ENQUIST *et al*. 2014, POMMIER, ELBEZ 2006), environmental impacts of wood-based and conventional buildings (HASSAN, JOHANSSON 2018, SATHRE, GUSTAVSSON 2009), or products containing wood-based materials as a part of the whole (GONZALEZ-GARCIA *et al*. 2012). Due to the different functional unit and different evaluation methods, it is not possible to compare these results in a relevant way. In general, the lesser adhesive used and the lesser energy and technologically demanding manufacture is, the better the engineered wood products perform from the environmental point of view.

The available data do not describe the production technology in detail, so some data may differ slightly from the actual ones. Errors in calculations may have occurred due to insufficient data, the use of estimated values from the available literature, different types of technology used and outdated data. The data for this study are typical for European countries.

The authors of the laminated board databases for outdoor and indoor use state that some data for glulam are derived from data for SWP. The type of plywood is unspecified. Emission data are limited. Transport is not included in the calculations (WERNER *et al*. 2007). Moreover, it is important to note, that none of selected wood products do not count with planing despite manufacturers do.

The results of the analysis should widen the knowledge of architects and people working in construction industry of the environmental context of the use of selected types of structural engineered wood-based materials.

CONCLUSIONS

LCA is a tool for quantifying the environmental performance of products, considering the entire life cycle, from the production of raw materials to the final disposal of products, including the recycling of materials (GOEDKOOP *et al*. 2013). The performed study deals with the comparison of selected types of structural engineered wood contained in the ecoinvent v3.5 database. SimaPro 8.5.2 software was used and the IMPACT 2002+ evaluation method was chosen for the analysis.

The aim of this paper was to analyze environmental impact of selected structural engineered wood and to deepen the knowledge of architects and people working in construction industry of the environmental context of the use of selected types of structural engineered wood-based materials.

The study proved considerable environmental burden of plywood production, mainly due to the high consumption of glue. Plywood achieved the highest environmental impact amongst the selected types of structural engineered wood. Generally, products for outdoor use showed higher values, due to the use of MF glue, which was the worst rated of the adhesives used. The SWP paradoxically had higher environmental impact than glulam, despite the use of PVAC glue. It follows that the resulting environmental impact of the SWP is significantly influenced by the manufacturing technology. The lowest values were reached by glulam for indoor use. Also, technical operations like planning and drying raise environmental burdens.

Several wood-based construction materials exist. However, world databases have this information only to a limited extent. This can be a problem when creating an LCA, as even a small detail in the form of newer technology can be decisive in the overall environmental assessment. If the studies are to be comparable with each other, the database needs to be extended to include new production processes and advanced products, considering the technology used, the geographical area, the electricity sources and many other related parameters. This is the only way to achieve the highest possible reliability of the environmental assessment and the lowest inaccuracy in subsequent calculations.

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