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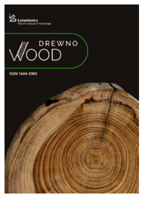

Modular Timber Structures As a Proposal to Reduce the Carbon Footprint in Civil Engineering

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Construction is responsible for a significant impact on environmental pollution; depending on the source, the value ranges from 35% to 40% of global carbon dioxide emissions. Due to increasing restrictions related to CO2 emissions, construction industries are obliged to reduce their impact on the environment. At each stage of the LCA (Life Cycle Analysis) of a building, solutions can be sought leading to the reduction of parameters. This paper focuses on the early stages, particularly the selection of construction materials and building technologies. The results of GWP analyses for a small modular building in two structural variants – steel and timber – and the amounts of building materials in buildings made using traditional and modular technology were compared. Analyses showed a significant reduction in the GWP value due to the use of timber construction.

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Introduction

The traditional construction method means making building elements on site from supplied building materials, some of which may be partially prefabricated. An alternative construction method is modular technology, in which the entire building is divided during the design process into parts (modules) of a size adapted to the transport capacity. The three-dimensional modules are made in a factory, under stable environmental conditions, and then transported to their destination and assembled on prepared foundations. On the construction site, module connections are made, as well as finishing works and installation connections.

Current literature about the LCA of wood elements focuses on challenges connected with transporting elements of considerable size from forests to factories (Perdomo, Schwarzbauer, Fürtner, 2021; Chen, Pierobon, Ganguly, 2019; Athre, González-García, 2014). This is a crucial factor in terms of creating global warming potential. However, wood is a renewable resource and offers clear ecological advantages, especially in comparison with more carbon-intensive materials like steel (Sečkár, Schwarz, Pochyb, Polgár, 2024). Transporting raw wood to factories, which might be in a significantly distant location, has an impact that depends heavily on the distance and the type of transport needed (Hemmati, Messadi, 2022). Even so, the initial phase of wood production, tree growth, is able to provide a negative GWP, which offsets or even exceeds the pollution produced during transport. This is in contrast to other materials where CO_2 is emitted during production.

There is also a lack of standardized data and methodologies for assessing the phases in LCA studies. Recent work (Bastein, 2021; Werner, Richter, 2007; Kogler,

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Beiglböck, Rauch, 2025; Kogler, Beiglböck, Rauch, 2024) addresses this gap in relation to the transportation phase by developing a more refined methodology for including transportation in the LCA of wood products. Scientists advocate for the creation of a global database on transport-related emissions in the forestry sector (Kogler, Beiglböck, Rauch, 2024).

The consistency of LCA results depends on reliable data provided by companies from the building materials and transportation sectors, and more data and improvements in its quality will be crucial to obtaining results that best reflect reality. In this case, mandatory standards and studies and analyses are needed to enable the real translation of data from manufacturers into the amount of CO_2 emitted in the case of different types of buildings, structures and materials (Pelyukh, Ilkiv, Kiyko, Soloviy, Chelepis, Lavnyy, 2025; Al-Sherrawi, Lyashenko, Edaan, Sotnik, 2018). In the work presented here, it was planned to design a modular wooden railway station building and then conduct a detailed LCA of stages A1–A3 and other stages, provided that data in EPD cards were available.

In the literature review, it is observed that studies focus on the early stages A1–A3, which include the production of building materials, their transportation, and installation. In contrast, our article encompasses the entire building life cycle, taking into account all LCA stages, with a particular emphasis on the use of modular construction, which enables the optimization of many aspects of a building's life cycle, including energy efficiency and waste minimization.

The literature discusses selected issues related to the analysis of the carbon footprint of wooden buildings, mainly concerning the production of wooden elements, but this analysis needs to be extended to include subsequent stages of the building's life. The existing discussion relates to forestry operations, and the use of wood as a sustainable renewable material is a key factor in the construction industry. The use of wood reduces the negative impact of the production of other materials such as steel. By optimizing production and delivery and improving processing efficiency, satisfactory economic as well as environmental results can be achieved. However, such analysis refers to the initial part of the building life cycle, including only the production and material delivery phases (Kogler, Schimpfhuber, Eichberger, Rauch, 2021; Schweier, Magagnotti, Labelle, Athanassiads, 2019; Kühmaier, Schweier, Sibiya, Marchi, Laschi, Grünberg, 2025). This article presents an estimate-based analysis of the impact of a selected construction technology on the global analysis of the building throughout its entire life cycle (Building Assessment Information – Cradle to Cradle).

Modular construction is advantageous, among other things, because of the short time of work needed on the target site compared with traditional technology, which is particularly important in the case of reconstruction or expansion of railway station buildings. Passenger service should be continuous, and the installation of modules takes only a few hours or days (depending on the size of the building), which minimizes the time for which the station needs to be closed. This article presents selected analyses that are part of the research conducted under the Europe's Rail FP4 Rail4Earth – Sustainable and Green Rail Systems project, in which railway station buildings with a reduced carbon footprint are designed.

Materials and methods

1. Environmental Product Declaration (EPD)

An EPD (Environmental Product Declaration) is a regulated and independently verified description of the environmental impact of products over their life cycle, determined by LCA for the following stages: A1–A3 product phase, A4–A5 construction phase, B1–B7 use phase, C1–C4 end of life phase, and D reuse, recovery or recycling. The creation of EPDs serves to present data in a universal and transparent way. Different standards are used as the basis for producing EPDs for different sectors. Construction, electrical, manufacturing, power delivery, and built environmental services have a few available standards (Sariola, Ilomaki, 2016; https://www.usgbc.org/credits/new-construction-core-and-shell-schools-new-construction-retail-new-construction-data-15?return=%2Fcredits%2FNew; https://www.epdhub.com/epd-basics; https://www.environdec.com/all-about-epds/create-your-epd). The first and most important for construction products is EN 15804:2019, which requires taking into account stages C1–C4 and D, regarding the final phase and benefits and burdens outside the system boundary, and not only phases A1–A3, which were mandatory previously (according to the 2014 standard). In turn, the PN-EN ISO 14025 standard contains rules and procedures for the development of type III environmental declarations, which are created voluntarily at the request of the manufacturer and are verified by independent accredited institutions; the EN 50693 standard defines the rules for product categorization (PCR), the process, and the requirements for life cycle assessment; ISO 21930 (Sustainability in buildings and civil engineering works) contains the main principles for EPDs for both products and services; ISO 14067 provides guidance and requirements for quantifying the greenhouse gas emissions of a product (Eurocode 5, EN 15804:2019, PN-EN ISO 14025, EN 50693, ISO 21930, ISO 14067). More and more legal standards are emerging to standardize the determination of GWP for buildings. However, the steps are still limited, up to an initial stage. Not all manufacturers create material sheets, which also affects the accuracy of such a result for a specific building.

To perform LCA analysis of a building, it is necessary to establish the quantities of individual building materials, which can be done on the basis of the drawings and descriptive documentation in the project. To facilitate the collection of quantitative data, it is possible to use a virtual model of the building (BIM, digital twin), from which one can obtain detailed statements of the quantities of materials used. LCA analysis is a complex task and often requires team collaboration. Analyses can be performed using programs from other manufacturers and are based on the imported IFC file, which should contain the necessary set of data. Transferring data simplifies the process, reduces costs, and provides the possibility of easy correction in the event of changes in the design (Shadra, Johansson, Lu, Schade, Olofsson, 2016; Obrecht, Potrč, Rock, Hoxha, Passer, 2020). The more complex the analysis process, the more advantageous it is to use automatic counting of the number of elements, which improves the reliability of the result, provided that the quality of the model is checked before data export. The need to calculate quantities manually increases the time needed and the risk of mistakes (Chen, Chen, Zhou, Huang, Sandanayake, Yap, 2024). LCA programs allow three ways of entering data: via the quantity list, with the help of plug-in tools, or as properties of parametric objects; entry can thus be done manually (least efficient and with the highest risk of information loss), semi-automatically with plug-ins, or automatically.

LCA involves many factors and variables. The largest proportion of data is required at stages A1–A3, where the quantities of all building materials used must be entered. This is also the most important from the point of view of the carbon footprint. It is difficult to change the materials already incorporated into the building, and their parameters affect the energy demand at the stage of long-term use of the building.

2. Building structure

Steel frame structures are most often used in industrial, warehouse, commercial or sports facilities. These structures consist mainly of beams and columns, which may be assembled entirely on site, or else certain parts (e.g. roof trusses) can be prefabricated and, after being transported to the construction site, mounted on prepared columns. Currently, modular construction is becoming popular and steel structures have a large share in this market. A factory produces three-dimensional structures (sized to accommodate wheeled transport) along with installations, insulation and finishing layers, and equipment. The finished elements are transported to the construction site and assembled on prepared foundations (Juraszek, Chybiński, 2020).

The advantage of steel is its high strength, ease of construction and low material consumption compared with masonry or reinforced concrete structures. Its disadvantages include its susceptibility to corrosion and the need for thorough protection against moisture, as well as the lack of resistance to high temperatures in the event of a fire (Rawska-Skotniczny, Kuchta, Tylek, 2018). Steel structures are highly durable, as illustrated by the example of the Eiffel Tower, built in 1889.

Wood has been used in construction for many centuries. Timber structure is particularly widely used in Scandinavia, the USA and Canada. The main use of wood in the structure of single-family houses in Poland is roof truss, both for new buildings and historic buildings, i.e. sacral buildings from different periods (the Church of St. James in Toruń from 1732, the cathedral in Opole from around 1880–1900, Norwegian medieval churches with a pole structure, built in 1242) which have retained their properties (Baran, 2013; Krawczyk, 2010; Szurowa, 1975; Witomski, 2008). The main factor contributing to the good condition of a wooden structure is the type of high-quality wood used (e.g. larch). In order to improve the durability of a wooden structure, it should be protected from moisture and pests to prevent degradation of the structure (Ważny, Kurpik, 2005; Witomski, 2015). It is also important to protect wood from fire.

Wood can be used in building structures in the form of a skeleton (columns and beams), but also as solid elements (full boards and walls). In addition to wood itself, laminated wood is also used, which permits larger spans of structural elements (Szumilas, 2006). Wooden construction is increasingly used not only in residential buildings, but also in public buildings and high-rise buildings because of the possibility of its protection and maintenance. Currently, the tallest skyscraper with a wooden structure is located in Norway in the city of Brumunddal. Mjøstårnet measures 85.4 metres and is made with cross-laminated wood (CLT) technology. Another example of a tall building is Treet in Bergen (14 floors), with a modular timber frame (Szewczyk, 2019; Al-Najjar, Dodoo, 2023).

An advantage of wood is its ecological properties. Given the construction industry's high percentage share in global CO_2 emissions, solutions to reduce this share are being sought (Stepien, Piotrowski, Munik, Balonis, Kwiatkowska, Krechowicz, 2022). Wood, as a natural material that absorbs CO_2 during growth, offers the opportunity to reduce the final emissions value, in contrast to steel, the production of which emits significant amounts of CO_2.

A modular frame structure was selected for analysis, thermally insulated according to the passive building standard and finished both inside and out, ready to be placed on concrete foundation footings. In order to compare different construction materials, the frame structure materials were chosen as steel and wood, while the remaining materials were left unchanged.

To compare information on the GWP (Global Warming Potential) index, the module of the free-standing toilet was analysed in the steel and wooden structure versions, taking into account phases A1–A3. EPD data from different manufacturers and from different European countries were collected. Elements related to HVAC (heating, ventilation, air conditioning) systems were omitted. The data were collected on the basis of a virtual model (BIM) of the project made in Archicad. Quantitative data were collected and manually entered into OneClick. The module is designed as a standalone module for small railway stations, but it can also be used for parking lots or sports facilities. The size of the module meets the needs of wheelchair users, and the external dimensions are adapted to the transport capacity. The external casing (walls, roof, floor and doors) is planned according to the passive building standard. The structure was designed in two frame variants: steel and wooden (Figure 1).

Tables 1–2 specify the quantities and cross-sections of elements of the two construction variants presented in Figure 1. The total volume of steel structure elements is approximately ten times smaller than that of the wooden structure.

For an adequate comparison of the amount of CO_2 emitted, cross-sections with similar load capacity utilization for individual elements were used. In both cases the average load capacity utilization for the entire structure is at a level of 60–61%. In the steel structure, square tube cross-sections are used, while in the wooden structure, square cross-sections are used, which affects the volume of material used. The weight of the installation was not taken into account, and so the load capacity reserve is assumed to be at a higher level. To determine the GWP of both design variants, data for structural elements were collected on the basis of EPDs. Depending on the manufacturer, the standard, and the time at which the material was tested, we obtain different

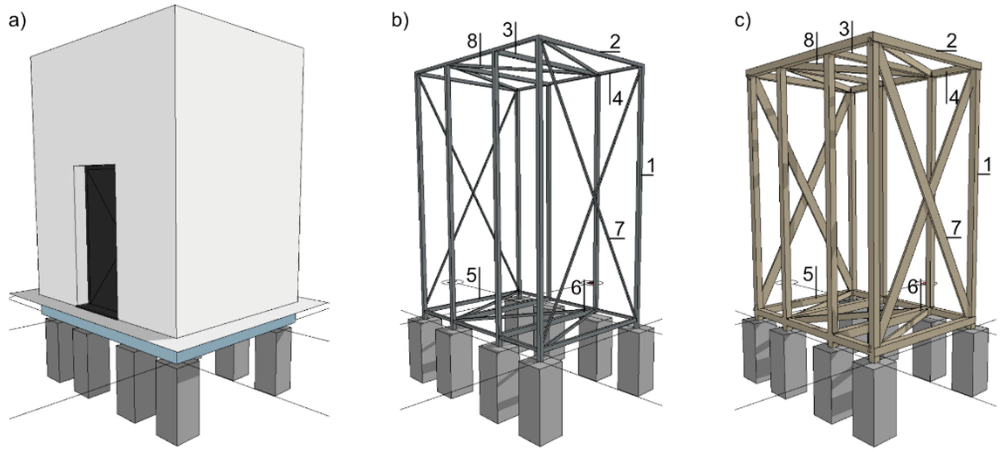

Fig. 1. Modular freestanding toilet building: a) architectural model, b) structural steel, c) structural wooden

Table 1. List of the number of steel structural elements

STEEL	Quantity	Cross-section			Length	Total volume
Item number	Pcs.	mm			m	m^3
1	8	60	60	5	4,20	0.01008
2	2	50	30	4	2,08	0.00049
3	2	60	40	5	2,08	0.00083
4	4	40	40	3	2,85	0.00140
5	2	60	40	5	2,08	0.00083
6	2	80	60	5	2,08	0.00120
7	8	25	40	3	4,31	0.00270
8	6	25	40	3	2,29	0.00150
-	-	-	-	-	Sum	0.019

Table 2. Summary of the number of wooden structural elements

WOOD Item number	Quantity Pcs.	Cross-section mm		Length m	Total volume m^3
1	8	100	100	4.20	0.042
2	2	100	100	2.08	0.021
3	2	80	80	2.08	0.013
4	4	100	100	2.85	0.029
5	2	110	110	2.08	0.025
6	2	130	130	2.08	0.035
7	8	30	160	4.306	0.0039
8	6	30	100	2.287	0.0021
-	-	-	-	Sum	0.170

information about the phases. In the 2012 standard, manufacturers were obliged to take into account only phases A1–A3, but with the introduction of the new version there are more phases required, which affects the amount of data obtained. Cards can be used to obtain information about the material itself, for example to enter the material parameters into programs that analyse the building in terms of thermal or carbon dioxide emissions, such as ArchiCAD. In order to obtain results that are closest to reality, using a given material, data should be taken from one source (one EPD). However, due to the lack of local market data, EPDs from several European countries were collected and compared to obtain average values.

3. The impact of construction technology on the life cycle analysis of a building

In the global life cycle analysis of a building, the construction stage (A4–A5) is considered. This study compared the following technologies:
- traditional, with all construction work performed on the construction site and multiple transports of building materials,
- modular – modules manufactured in a factory and a single transport to the construction site,

in order to determine which aspects have a positive and which a negative impact in the global analysis.

Based on the design documentation, a model of a virtual twin of the IDS-B type railway station building (built using traditional methods) and a model of the design of the station building with an analogous utility function in a modular version were made. The projects differ slightly in usable area:
- IDS-B: 72.53 m^2,
- modular: 63.50 m^2.

Based on the virtual twin, quantitative specifications were made of the building materials used. A comparative analysis was performed to compare the consumption of different material groups in both variants to determine which type of material has the greatest impact when switching from traditional to modular technology. Then, it was estimated how much the result of the entire LCA (Cradle-to-Cradle) analysis would change. Due to the lack of data on EPD cards for all materials, a detailed analysis is not possible at present.

Results and discussion

1. GWP parameter values

EPDs are available in online databases (the German Okobaudat or Danish EDPDanmark) and in programs for performing LCA, e.g. OneClick, which has a set of available databases (Rasmussen, Andersen, Wittche, Hansen, Birgisdottir, 2011; Almeidaa, Chavesb, Silvac, Carvalhoc, Caldasa, 2023). The number of cards available in the program varies depending on the country and type of production. Table 3 presents numbers of Polish product sheets, limited to structural steel and wooden elements.

The availability of EPDs on the Polish market is limited to only a few manufacturers, due to the lack of an obligation to provide data related to the life cycle of products in Poland. For structural steel and steel profiles, there are nine products among Polish manufacturers, of which only one manufacturer offers EPDs with full data. For other manufacturers, there are 55 results, of which as many as 44 are EPDs. In the absence of a card, OneClick offers only GWP data for phases A1–A3 determined on the basis of similar materials. For wood products, Polish manufacturers declare EPDs for plain wood in 13 cases, of which EPDs are

Table 3. Number of available EPDs for structural steel and timber elements [Data from OneClick]

	Generic data PL	EPD PL	Generic data rest	Epd rest
Steel	8	1	11	44
Plain wood	3	10	-	64
CLT, glulam, LVL	-	-		88

Table 4. GWP values for examples of steel and timber structural elements based on EPDs available in OneClick

Wood		Steel			
Country	**Phase A1-A3**	**Country**	**Phase A1-A3**		
-	**kgCO$_2$ekv/m^3**	**Group 1**	**kgCO$_2$ekv/t**	**kgCO$_2$ekv/kg**	**kgCO$_2$ekv/m^3**
Many countries	-713.01	Spain	567.26	0.567	4452.99
Ireland	-644.00	Czech Republic	589.00	0.589	4623.65
Norway	-672.00	Poland	811.00	0.811	6366.35
Denmark	-664.00	Luxembourg	842.00	0.842	6609.70
Czech Republic	-684.47	Italy	684.00	0.684	5369.40
Average	**-675.50**	Average	698.65	0.699	**5484.42**
		Group 2	-	-	-
		Germany	327.00	0.327	2566.95
		Sweden	121.00	0.121	949.85
		Average	224.00	0.224	**1758.40**

available for 10. There are also 64 cards from other countries available. For CLT, glulam and LVL, there is no local provider offering data, in which case comparable data from other countries must be used, as the database contains 88 products with EPDs.

Considering steel, concrete and wood construction, only wood has a negative carbon footprint. Based on data collected from Europe, North America and Australia by Rasmussen, the GWP parameter for wood and various types of glulam (CLT, Glulam, LVL) in stages A1–A3 is negative. Based on the review of EPD data for the analysed construction materials (wood and steel), sample data on the GWP parameter are provided in Table 4.

Table 4 presents data from sample EPDs for structural timber and structural steel. A difference in the cards that creates problems is the different declared unit to which the GWP values refer: square metres, cubic metres, tons or kilograms (these being the most common variants). In the case of complete data on the density of the material or the thickness of the component, the user is able to convert the units of the necessary parameters in order to compare it with another material or enter it into a program that imposes the unit. However, if any of the parameters is omitted, one needs to look for data on related materials or use general data, e.g. density for steel. Through various approximations and generalizations, the result moves further from the actual value. With different units and conversions, there is a probability of error, which could be avoided by standardizing the units used in the EPD. To compare CO_2 emissions for wood and steel, the parameter was recalculated in the same unit, assuming the same steel density for each case. Even without data on the quantities used in a building, it can be seen that steel is a much more polluting material. No harmful chemicals are emitted during wood production; on the contrary, during growth, the tree absorbs pollutants, enabling a negative result for the A1 phase (extraction and processing of raw materials, processing of secondary materials, i.e. recycling processes), and as a result for the entire A1–A3 stage. Steel has been divided into two groups, due to the significant discrepancy in data. They illustrate the scale of the potential of reduction emissions, which may be at an average level of almost 5500 kgCO$_2$/m^3 or 1750 kgCO2/m^3. The density of steel is assumed to be 7850 kg/m^3, which is the density most commonly reported in EPDs. The dimensions were taken from the cards of each element for steel components and converted from tons to m^3.

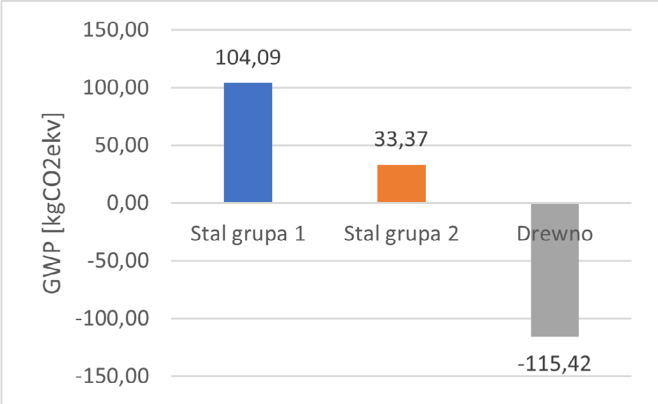

Fig. 2. Comparison of GWP values for a toilet module with a steel structure (in two variants) and a wooden structure in the A1–A3 phase

All selected material sheets are counted as low-carbon in the OneClick program. For comparison, high-emission steel has a GWP value of 21450 $kgCO_2ekv/m^3$ on average [OneClick]. The average value in the unit $kgCO_2ekv/m^3$ for the considered materials was used for the analysis.

The GWP calculation for the structure was performed according to the following formula:

$$GWP_k = V \cdot GWP_m \tag{1}$$

where: V is the volume of material;
GWP_m is the global warming potential of the material;
GWP_k is the global warming potential of construction.

The graph (Figure 2) shows the CO_2 emissions for each variant. Due to the positive result already obtained in the A1 phase, the steel structure obtains a result of over 100 $kgCO_2ekv$ with a small toilet module, but by using the manufacturers' best proposals in terms of emissivity, it becomes possible to reduce this value by about 70%, to a result of 33.37 $kgCO_2ekv$. The result for a wooden structure is the most advantageous because it does not emit carbon dioxide, which is the main goal for achieving zero emissions in construction.

2. Impact of construction technology on LCA

The different stages of LCA were analysed to determine how the choice of construction technology affects the different stages of design and construction. A comparison was made between traditional on-site construction and modular construction. The results of the analyses are presented in Tables 5–8, separately for phases A (building materials and construction), B (building use) and C (demolition). The results enable an assessment of whether the construction method affects the design process. Additionally, it is indicated whether the decisions made during the design will have a positive (+) or negative (–) impact on the life cycle assessment of the building.

The production of building materials is independent of the construction technology. In both cases, building materials produced using recycled raw material may be used. For both modular and traditional buildings, the material used should be taken into account. The structure must meet the strength conditions, and checking these is inextricably linked to the material used. A designer who wishes to take into account the CO_2 emitted by the solution used (phase A1) will have to use EPD data, which, as already mentioned, is lacking on the Polish market. This creates a problem and a need to estimate the GWP value for both cases: traditional and modular construction. The solution may be to use cards provided by foreign manufacturers. The transport of materials to the manufacturer (A2) is independent of the designer and design, but the closer the production site, the lower the carbon footprint. Also, the building materials production process (A3) is independent, related only to the manufacturer and the technology it uses. In the case of transport to the construction site (A4), a single transport of finished modules and their assembly by crane lasting several hours or several days should be compared with multiple transport of individual construction materials by vehicles, mostly underloaded, and daily transport of employees. This translates into a lower overall cost of transporting materials, due to the making of fewer trips. The disadvantage is the need to apply for permission to transport oversized elements, which also increases the price. Before deciding on the size of the segments, it is necessary to analyse the type of access roads to the destination, especially in terms of the radius of bends and the width of passages. With modular technology, erecting the building (A5) is much faster than with traditional technology. Most of the work with the preparation of the modules takes place in the factory; on the construction site it remains to assemble them and secure the contacts. This makes

Table 5. Impact of construction technology on design in relation to the production and construction phase of A1-A5

Phase	Impact of design		What is included?
	Traditional	**Modular**	
Product phase			
A1, extraction and processing of raw materials, secondary material processing (recycling processes)	YES	YES	supply of materials, products and energy, processing of waste until the waste is lost
A2, transport to the manufacturer	NO	NO	distance, type of transport, as above
A3 – production	NO	NO	as above
Construction phase			
A4 – transport to the construction site	NO -	YES +	distance to construction site, type of transport
A5 – building building	NO -	YES +	energy and materials needed on the construction site

Table 6. Impact of construction technology on design in relation to the use phase – structural and material solutions B1-B7

Phase	Impact of design		What is included?
	Traditional	**Modular**	
Phase of use, construction and material solutions			
B1 – use or application of the embedded device	YES	YES	including the delivery and transport of all materials, articles and the associated energy and water consumption, as well as the treatment of waste, until the end of the waste status or the removal of the final remaining permanence from this part of the use phase; the information modules also include all impacts and aspects related to losses during this part of the use phase (e.g. production, transport, waste treatment and disposal of lost goods and materials)
B2 – maintenance B3 – repair B4 – replacement B5 – renovation	YES	YES	
Phase of use, operation of the building			
B6 – energy consumption in the use phase	YES	YES	renewable energy generation systems, nonrenewable
B7 – water consumption in the use phase	YES	YES	wear and tear during use

it possible to reduce the number of workers and the time spent on the construction site and the resulting difficulties. Additionally, the factory can use renewable sources to produce electricity.

During the use phase, which includes, among others, maintenance, repair, replacement and renovation, the difference between buildings made with traditional technology and modular technology lies in the way these activities are performed. The advantage of traditional technology is the proximity of factories and the availability of materials, while module factories do not occur at comparable densities. The phase of use and

Table 7. Impact of construction technology on design in relation to the C1-C4 end-of-life phase

Phase	Impact of design		What is included?
	Traditional	Modular	
End-of-life phase			
C1 – demolition, demolition	NO -	YES +	energy and materials needed for demolition
C2 – transport to the waste treatment site	NO +	NO -	distance and type of transport
C3 – treatment of waste for re-use, recovery and/or recycling	NO -	YES +	energy and materials
C4 – removal	NO -	NO -	emission and waste transport

Table 8. Impact of construction technology on design in relation to gains and losses outside system D boundaries

Phase	Design Impact		What is included?
	Traditional	Modular	
Gains and losses beyond the system boundaries			
D	NO -	YES +	potential for reuse, recovery/recycling, expressed as impact losses and gains in the

functioning of the building is not affected by the type of construction technology used, but it is necessary to take into account the level of energy and water consumption in order to design appropriate installations. Due to the lack of obligation to provide data on the use phase and the difficulties in testing, few manufacturers include them in the EPD. After 50 years of use of the building, it will be possible to determine these parameters. In the case of modular wooden construction in Poland, the production services of such facilities are provided for 30–40 years.

Modular technology means designing modules that have a load-bearing capacity not only after assembly, but also during transport, so that after the building has been used, they can be transported back to the factory. In the end-of-life phase of a building with modular technology, it is possible to reuse the modules. They can be used as an element of a new part of the building or as a replaceable element in the event of damage to another module. With traditional technology, we do not recover materials with their original properties, but they can be used as processed, e.g. recycling aggregate for concrete; despite all this, only a small amount of building materials is recycled. The transport of waste requires more logistic preparation for modules, due to their size. In the case of traditional construction waste, transportation is simpler while we have shorter distances.

When designing a modular building, the principles of "design for disassembly" (DfD) are applied. This means that the reuse of modules, parts or materials is assumed from the very beginning, which allows the life cycle of the building to be continued, not closed.

The results of the comparative analysis of the quantities of individual types of construction materials performed for the entire station building are presented in Table 9. The IDS-B type building was built using the traditional method with a reinforced concrete structure, while the modular variant has a steel structure. The analysis was conducted to estimate the impact of the type of construction and construction technology on the LCA result.

An 88% increase in the number of steel profiles in a modular structure is offset by an 86% reduction in reinforcement steel. It is significant that the amounts of concrete and masonry are reduced by 84% and 100%, respectively. The reduction in the amount of thermal insulation materials is caused by the separation of the roof structure from the modules, which makes it possible to shape the slope only through the shape of the

Table 9. Comparison of the number of material groups of IDS-B and modular buildings

-	Quantity change in the modular variant compared to IDS-B	
	Increase [%]	**Decrease [%]**
steel profiles [kg]	88	-
Concrete [m^3]	-	84
concrete reinforcement [kg]	-	86
wall [m^3]	-	100
thermal insulation materials [m^2]	-	22
waterproofing materials [m^2]	5	-
Finishing materials [m^2]	52	-
joinery, glass facades [m^2]	-	72

supporting structure, and not the polystyrene slope layer in a building with traditional technology. This change is due to the architectural shape of the analysed example, so it is not taken into account in the technology comparison. A slight increase in waterproofing materials (5%) was also omitted from the analysis. A 52% increase in the amount of finishing materials is observed in a modular building. This change is caused by the technology used. Each partition between the advancing modules is doubled and must be protected from the outside against weather conditions due to the small expansion joint clearance allowing independent assembly/disassembly of the modules. The 72% reduction in the size of the glass façade is due to the use of modular building technology and is mainly due to the height of the modules, limited transport capacity, and a slight reduction in usable space (by 12%).

If the steel structure were to be replaced with a wooden one, even assuming that its volume is 10 times larger, the global result of the LCA would be more favourable, due to the negative value of the GWP parameter for wood.

Conclusions

Due to the significant opportunities to reduce the carbon footprint that occur in the initial phase of building construction (A1–A3), it is necessary to use a material that will allow the achievement of a low result for kgCO_2ekv. The carbon footprint of materials is primarily determined by emissions from extraction, transportation, and production processes. For (low-carbon) wood as a natural material, the global warming potential is significantly lower than for steel, even a more advantageous variant. In this case, staying with the leading material, namely steel, still offers the possibility of very low emissions, reduced by almost 70%. Wood, by virtue of its ability to sequester carbon, has a GWP that is 4.5 times lower than the alternative steel variant. This is due to the lack of pollutants emitted during mining, because trees absorb unfavourable compounds during growth. It is worth noting that, compared to high-emission steel, use of the alternative option allows one to reduce kgCO_2ekv significantly (fourfold).

Replacement of concrete reinforcement steel in a traditional structure with steel structure profiles in modular technology does not significantly change the GWP value. A beneficial reduction in the value of this parameter can be achieved by using a wooden modular structure, for which the GWP parameter is lower. Due to the increase in the quantity of finishing materials in modular technology, it is necessary to pay attention to their GWP value when choosing specific solutions. The use of a modular design limits the external dimensions of the transported components and can reduce the amount of materials used.

The combination of a modular solution that reduces the external dimensions of transported components also has the potential to minimize material usage, and choosing a timber structure results in a building with a very low carbon footprint. However, it is important to recognize that the full potential of materials like wood is still in the early stages of development. Steel structures have enjoyed a much longer history and have been favoured in the case of high-rise and industrial buildings. As noted, this trend is beginning to change, as there are examples of the use of wood as the main material for high-rise buildings. As awareness of climate change grows and construction standards become more stringent, new solutions are needed. Modular buildings with a wooden structure may be the answer.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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