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Research paper

Environmental life cycle assessment (LCA) of model massive timber and concrete buildings. Implementation of cross-laminated timber (CLT) in an educational facility at the Forest Botanical Garden "Marszewo" in Gdynia

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Abstract: During the second decade of the 21st century, the effects of climate change became particularly noticeable, as population growth and aggressive urbanisation degraded the natural environment. In modern construction industry, the concepts of sustainable development and life cycle assessment (LCA) are important, covering the investment process from design and construction to operation and potential demolition. Wood, a natural raw material present in architecture for centuries, unites the ecological, economic and social principles of sustainable design. Thanks to innovative processing techniques such as cross-laminated timber (CLT) technology, wood can meet the challenges of modernity. Given the growing consumer interest in pro-environmental attitudes and the tightening of regulations within the European Union, the main emphasis will likely be on choosing environmentally friendly materials with a low carbon footprint, favourable energy balance, and ultimately, recovery or reuse potential. Based on this hypothesis, the paper presents a comparative LCA analysis of CLT and concrete technology for the implementation in an educational building at the Forest Botanical Garden "Marszewo" in Gdynia.

Keywords: CLT, life cycle assessment, sustainability, wood architecture

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1. Introduction

Historically, timber has been linked to construction above all by its local availability-proximity to the forest economy and craftsmen. The gradual decline in its popularity can be traced to two major contributors. The first is the widespread technological progress and the emergence of new building materials. Technological development also means the development of infrastructure and, therefore, the possibility of importing material without having to resort only to what is available locally. Finally, (it is) the rapid development of the construction sector, which offers many economically and practically advantageous solutions. The second contributory factor is the perception that timber is a weather-sensitive raw material, attracting vermin, insects, fungi, etc. The problem with wood pests in historic substance as well as in new buildings, e.g. made of logs, is still prevalent these days, although some solutions are available to eradicate or prevent the occurrence of insects or fungi. At the same time, a number of initiatives have been taken to replace chemical methods of wood protection with natural products of plant origin, such as essential oils, tannins and extracts [1,2]. One concern that has always been associated with wood is its flammability. Indeed, wooden buildings of the past often suffered from fires, and even today this is the case with historic buildings. In this respect, scientific progress has also made it possible to identify methods that protect wooden structures. In general, modern fire protection methods are highly effective at producing flame-retardant materials [3]. However, the foregoing concerns have impacted greatly on the lack of public interest in choosing wood as a building material. Other materials seemed to be safer and – which is worth emphasising again – easily available and cost-effective at the same time. A more up-to-date approach to timber construction can be considered the timber frame technology (mostly popular mostly in North America), where the structure is made up of wooden pillars with thermal insulation infill, clad on both sides in planks or wood-based panels. The advantage of this technology was the unquestionable ease of assembly and economy of construction [4]. Adaptation of the technology was also possible in European conditions, however, taking Poland as an example, it has not been widely embraced and is deemed suitable for temporary houses, and also due to span limitations, it is not at all attractive for public utility facilities. End users have raised concerns about the structure's durability over time and in harsher climatic conditions. They have also pointed out that timber does not make up a large percentage of the space-dividing elements, which reduces the benefits of the psycho-physical experience of raw materials. This paves the way for further exploration of wood innovations [5].

The current state of the environment, climate change and increasing urbanisation have forced people to reflect on how societies function and how the construction sector operates, paying closer attention to eco-friendly values. [6]. Above all, (it is) the dominance of materials such as concrete, steel, aluminium, which worsen the natural conditions significantly and emit an increasing amount of exhaust fumes, (that) has become problematic. The present-day progress in the field of building structures is a turn towards timber construction as an alternative to energy-consuming materials. As a result, both the scientific and industrial communities have set their sights on the innovation factor, seeking new technologies based on wood as a natural and environmentally neutral raw material, which offers excellent thermal and acoustic performance but eliminates its weaknesses [7,8].

The most up-to-date innovation in the contemporary approach to timber construction should be considered the technology of solid wood as cross laminated timber (CLT), which allows it to be an alternative to current more energy-intensive materials, while maintaining favourable technical performance. CLT panel is made of softwood strips (the most common are spruce and larch) stacked one on top of the other, which are joined using high-strength, formaldehyde-free adhesives to form large-format building components. Solid wood products are environmentally friendly and ensure dual climate protection. Sustainably cultivated wood, as a raw material, is one of the most important natural reservoirs of CO_2. Trees depend on a climate- damaging gas to grow. They extract it from the atmosphere through photosynthesis and it remains stored in solid wood products for decades [9]. Wood as a construction material replaces many conventional materials, the production of which releases huge volumes of CO_2 from fossil fuels. On average, using one cubic metre of wood as a substitute for other building materials reduces CO_2 emissions by 1.1 tonnes. Thus, the use of the raw material slows the build-up of CO_2 in the atmosphere and verifiably mitigates the greenhouse effect [10]. Prefabricated CLT panels, are a renewable and ecological material, taking into account the raw material, but also considering the sustainable way of harvesting and production with 'zero waste' principle. Once the raw material has been harvested, the company almost completely recycles the logs into sawn timber, solid wood panels, etc. Wood waste such as bark, offcuts, chips, sawdust and shavings, are processed into compacted biofuels, green electricity or pressed pallet blocks [11, 12].

Wooden interiors are associated with warmth and cosiness, which has a positive impact on people's mental and physical health. In combination with the unique properties of the wood substance as a heat and moisture store (where it is warmer in winter and feels cooler in summer), the warm perceptions of wood surfaces ensure a well-balanced living climate and ultimately the well-being of the occupants. In the production process of CLT panels, natural wood is used without additional building chemicals. Cheap materials as well as furniture are capable of releasing undesirable substances that can cause allergies and other illnesses. Solid wood is an utterly uncontaminated building material and also strengthens the immune system and invigorates the nervous system [13]. Wood is an ideal material for biophilic design, which involves drawing inspiration from nature and making use of its resources. The raw material is therefore attractive by allowing contact with nature, which is made using all the senses. The presence of wood in interior design is notable for its ability to enhance the senses, offering a combination of visual appeal and tactile experience [14, 15].

CLT technology offers a material that is an alternative to conventional construction products such as steel or concrete, and can replace both structural and partition wall infill materials, ceramic bricks, concrete blocks, plasterboards etc. Thanks to the transverse construction of the longitudinal and transverse lamellas, expansion and contraction of the timber in the plane of the panel is limited to a negligible minimum. At the same time, this increases the structural load bearing capacity and dimensional stability in the plane of the panel. The timber is distinguished by its very high static performance, has good compressive strength, meaning that it can withstand significant pressure without deforming. Steel generally has a higher tensile strength than timber. However, timber can offer a comparable level of compressive strength, and it is less dense than steel and concrete. Wood is therefore a lightweight building material with excellent technical properties. Despite its light weight, timber provides high tensile and compressive resistance and, when used correctly, is weatherproof [16]. An unquestionable advantage of CLT buildings is that they retain their durability and stability over a long period of time. In contrast to timber frame structures, solid wood buildings are more robust. Unlike wooden log buildings, owing to the method of gluing the layers together, the wood does not react violently to temperature changes and, with maintenance, remains visually attractive for a long time. Cross- gluing gives the panel better strength parameters, but also fire resistance (where the flame will only burn the top layer over a longer period of time while the core of the structure will remain intact), which increases the safety of the building [17–19]. Due to the fact that each project is treated individually there are no typical panel thicknesses and sizes, each issue is an element of coordination between architectural and structural designers based on the manufacturer's approved calculation program. However, it can be noted that solid timber structures have an attractive ratio of gross and net residential area compared to conventional methods. Hence, CLT technology enables smaller cross-sections of elements to be achieved, saving space, as well as fewer structural elements, allowing a variety of shapes and forms [20]. The prefabrication process uses exactly as much raw material as needed, so the use of solid wood structural solutions reduces waste at the end of a building's life cycle and generally increases resource efficiency in line with the principle that today's material choice is tomorrow's waste avoidance [21].

CLT panels ensure very good thermal but also acoustic performance. When it comes to achieving good interior acoustics, attention must also be paid to the details of the wood joints and the surface texture. According to available studies, the density and stiffness of solid wood panels significantly reduces airborne and impact noise. Perforated panels can reduce reverberation and sound reflections caused by unfinished wood surfaces [22, 23].

One disadvantage of CLT panels is their potential to delaminate. While elements consisting of several layers of wood joined by glue improve the performance of the whole element, they also give rise to one of the basic disadvantages of multilayer structures. Publications addressing this issue are available in the literature, but there are many of them. This may be due to the anisotropy of wood and the difficulty of testing such elements in laboratories or modelling them numerically. Available studies analyse shear strength in three- and four-point bending and two-lap shear tests, using numerical and laboratory methods [24–26]. Research on glulam has mainly focused on flexural and shear strengths, or modelling approaches to estimate flexural strength and failure mechanisms. As the technology becomes more popular and investment increases, it is necessary to consider the reactivity of the product, taking lateral properties into account to determine the component specification [27]. During the preparation of the study, previous papers related to similar topics were taken into account – addressed both the importance of material selection in environmentally sensitive design and the scope of envelope type choice in relation to energy costs at each stage of the building life cycle. [29, 30]

2. Methodology of research

The research methodology involves comparing the sustainability of CLT and conventional concrete technologies. Ecological, economic and social considerations are taken into account, as well as the associated life cycle assessment (LCA). The study focused on the construction of an educational building at the Forest Botanical Garden “Marszewo” in Gdynia — the first public building in Poland constructed entirely above ground using CLT technology (Fig. 1).

The design of the building was selected through an architectural competition. The award-winning work by the Gierbienis + Poklewski studio was recognised for its inspiring land development concept, which comprised a composition of dispersed homestead buildings, and for its solid design referencing the archetype of the barn, while favouring innovative solutions.

Designed in 2016 and completed in 2023, the building is distinguished by the use of CLT technology and larch facade finished using the Japanese Shou Sugi Ban technique, which involves charring the wood’s surface with fire. This process creates a black layer that gives the wood unique properties. It effectively protects the wood from pests and makes it resistant to weather, moisture and even fire. The blackened aesthetic is also highly regarded. The building was made up of two blocks arranged in the style of a barn, connected by a glass link.

Fig. 1. Educational building at the Forest Botanical Garden Marszewo, photos: Fotomohito, 2023

The starting point for the LCA was to identify the attributes of two construction materials: solid wood using CLT and glue-lam technology and reinforced concrete. Both materials were analysed in terms of their physical properties and how they were obtained, produced and processed, as well as their energy intensity. Ultimately, the analysis covered their availability and rationality of use, as well as their psychophysical perception and impact on user comfort.

The authors indicate that the comparison is between CLT and concrete construction. The foundation slab, thermal insulation, façade finishes and glazing solutions remain identical in both cases. This enables the research to focus primarily on transforming the approach to constructing modern buildings by considering the environmental impact and societal implications of the chosen material. In an LCA, the choice of raw material is crucial, and timber is a significant alternative to the energy-intensive materials used in concrete or steel structures.

The comparison includes standard interior wall finishes resulting from structural and partition technologies. This is because it directly relates to solid wood technology, where each wall is taken into account in structural calculations and its parameters adjusted. In the case of concrete, partition walls are not structural elements. This technology is not intended for partition walls, which are not thin. In a CLT design, therefore, all the walls are made of wood, whereas in a concrete variant, the partition walls are made using masonry technology with aerated concrete blocks. Timber walls require no finishing, whereas for the analysis, concrete walls were assumed to be plastered and painted.

2.1. Ecological assessment

LCA explicitly addresses the choice of materials as a key design decision that affects the design, use, and environmental impact of implementation. From an ecological view, this choice is important, taking into account not only the pro-environmental potential of the raw material itself, but also factors related to the supply chain: its sourcing, production and transportation, and thus its embodied carbon footprint. As presented in Table 1, the stages encompass all activities related to the production, transportation and use of construction materials.

Table 1. The different stages of the construction LCA, source adapted from BS EN 15978:2011 Sustainability of construction works. Assessment of environmental performance of buildings [31]

<table>
<tr><th colspan="2">Embodied carbon</th><th colspan="2">Use-phase carbon footprint</th><th>External factors</th></tr>
<tr><th>Product stage</th><th>Construction stage</th><th>Use stage</th><th>End of life stage</th><th>beyond life cycle</th></tr>
<tr><td rowspan="2">A1
Raw material supply</td><td rowspan="2">A4
Transport to construction</td><td>B1 Use</td><td rowspan="3">C1
Deconstruction & demolition</td><td rowspan="3">D1
Benefits and loads</td></tr>
<tr><td>B2 Maintenance</td></tr>
<tr><td rowspan="2">A2
Transport to manufacturing</td><td rowspan="2">A5 Installation / assembly</td><td>B3 Repair</td></tr>
<tr><td>B4 Replacement</td><td>C2 Transport</td><td rowspan="4">D2
Reuse-recovery-recycling-potential</td></tr>
<tr><td rowspan="3">A3
Manufacturing of products</td><td rowspan="3"></td><td>B5 Refurbishment</td><td rowspan="2">C3 Waste Processing</td></tr>
<tr><td>B6 Energy use</td></tr>
<tr><td>B7 Water use</td><td>C4 Disposal</td></tr>
</table>

In the case of a material such as solid wood, the production stage (A1-A3 with reference to Table 1) plays an important role in reducing CO_2 emissions. This is due not only to the negative environmental impact of the raw material itself, but also to the sustainable economic and management policies of companies that produce CLT solutions. Wood is sourced from special commercial forests in close proximity to processing factories to minimise residues and waste.

In contrast, the process of obtaining and producing concrete solutions is energy-intensive and leaves a carbon footprint. The raw slats used are sourced from sustainably forestry and are either PEFC or FSC® C119602 certified.

The construction stage (A4, A5) refers to the carbon footprint associated with transporting materials to the construction site and erecting the structure. Depending on the distance, type of material and project needs, there are different ways to transport. The most common method is transportation concrete by rotary bin truck. Concrete plants are relatively easy to access in Poland, which makes it possible to assume short transportation times to the construction site. The situation is different with solid wood, which is not currently produced domestically and must be imported from abroad. This means that there is a greater distance to transport the materials to the construction site. However, woodworking companies nowadays carry out their production processes in a sustainable manner. A supply chain can also be available to track and assess the environmental impact of purchasing components.

For the analysis of the phases involved in transporting the CLT product from KLH Massivholz to the construction site, it was assumed that the distance to the construction site would be up to 1,170 km. On average, a truck transporting wood (a 76-tonne timber transport kit) uses about 57 litres of fuel per 100 km. Two transports were required for implementation. For the concrete variant, one local concrete plant was chosen. Production companies in the local area were considered, with a maximum distance of 20 km assumed. The combustion of a concrete mixer transporting concrete over 100 km is up to 60 litres.

The construction installation process (A5) has an environmental impact given the time and nature of the work. In this case, using CLT technology significantly reduces construction time and the use of machinery and labourers, while also eliminating pollution. Concrete technology requires more time and the involvement of more workers and machinery, as well as an additional drying process. This can be reduced by using precast concrete, but this in turn adds to the carbon footprint at the production stage and affects transportation.

Along with the use of the building, the energy associated with its use and maintenance can be analyzed (B1, B2). The analysis does not take into account these phases, since the facility is used for a short period of time, and the basis for the assessment is a reference to the completed facility. It is planned to monitor its energy efficiency as a further development of the study.

The analysis considers the carbon footprint of repair and replacement steps (B3-B5), assuming that over the 50-year life cycle of the building, the windows, doors, gas boiler, recuperator and photovoltaic panels would need to be replaced once – identical items for both analysis options. For the CLT technology variant, the occasional maintenance of timber, depending on the created cavities, is foreseen. Solid wood, as long as it is not mechanically damaged, or exposed to rapid environmental changes, retains its performance and appearance. It is stated that solid timber walls do not react to weather and climatic conditions in the same way as timber logs. For the concrete construction variant, the restoration of plaster defects and repainting of walls and ceilings were considered.

The carbon footprint of the use phase is at the same time directly the energy cost of using the facility, assuming monitoring of energy and water consumption (B6, B7), which is concurrently the same for both variants with an indicator correction in favour of wood, which has a higher heat storage capacity than concrete, allowing for a warmer effect on winter days and cooler rooms in summer. During the warmer days, according to the users' experience, the facility was comfortable to use without air-conditioning, and during the winter, heating energy costs were kept to a minimum. Due to the nature of the operation of the facility in the hours that do not extend into the evening (employees work until 3:00 p.m. and educational activities end simultaneously in the afternoon), the use of artificial lighting is limited, while LED products that meet energy-saving parameters have been used.

The indices for Embodied Energy (EE) and Embodied Carbon (EC) are being obtained from the ICE (Inventory of Carbon and Energy) databases, specifically versions V1, V2, V3, and V4.

Differences in the carbon footprint embedded in the components used are presented in the computational models. Boundary conditions were taken into account in the analyses to enable a comparable presentation of the technologies considered in energy terms. The parameters in both variants were modelled so that the heat transfer coefficient is maintained identically in all building envelopes. For the modelling of thermal bridges and critical connections, a simplified modelling scheme was assumed so that the design parameters in both variants, CLT panels and concrete structure, would be analogous and also comparable. As a result, calculation models were obtained to determine the embodied energy (PE) demand. Based on PE = 71.40 [kWh/(m^{2}year)], the amount of CO_2 emitted was estimated for the energy carrier – natural gas. A 17.6 kW heat pump system was used for the calculations, which resulted in reduced energy consumption. Data on the energy intensity and CO_2 emissions of the components used was obtained from current indices and by analysing the technical data sheets for each product.

The life cycle analysis foresees the potential for recycling (D2). By implementing the facility with CLT technology, it is possible to fully recover the raw material. It is then possible to recycle both the prefabricated, raw material and make biomass – a natural energy source. Being able to use recycling is a significant benefit, influencing the life cycle assessment of a building, whilst also fitting in with the growing trend of circular architecture. If a building is to be constructed using a 'closed loop' design, the first thing to consider is the use of materials that can easily be given a 'second life'. This means that the construction process must take into account the possibility of easy and convenient demolition, as well as the further processing or reuse. It is worth noting here that, unlike wood, concrete and reinforced concrete do not allow for recovery in the same way, which has a significant adverse environmental impact.

Finally, Tables 2, 3, 4 summarises the cumulative energy and carbon footprint. The various stages of the investment process include the production, logistics, construction and erection of the structure. This is followed by the structure's use, potential demolition and the reuse or recycling of its components, in line with the circular architecture trend. As can be seen, slight differences in the values are caused by discrepancies in the usable areas required for the calculations, which result from the specific nature of the technologies.

2.2. Economic assessment

The design process must be considered in economic terms, taking into account the benefits of the technology used, as well as the associated costs, time implications and environmental impact. CLT technology enables thinner structural sections to be used, directly impacting floor plans. As each CLT project is unique, the amount of wood can be optimised, maximising

Table 2. Summary of cumulative energy [MJ] in a 50-year cycle

Type technology	A1–A3 product stage	A4–A5 construction stage	B3–B5 use stage replacement	B6–B7 Energy, water consumption	D2 recycling potential	Total
CLT	567 057.04	106 086.50	78 215.09	4 737 375.72	3 221.92	5 491 956.28
Concrete	3 196 274.27	18 958.74	161 093.29	4 600 244.88	28 995.22	8 005 566.40 7

Table 3. Summary of cumulative carbon footprint [kg CO_2 e] in a 50-year cycle

Type technology	A1–A3 product stage	A4–A5 construction stage	B3–B5 use stage replacement	B6–B7 Energy, water consumption	D2 recycling potential	Total
CLT	–98 526.16	7 864.08	2 209.47	262 831.68	966.57	175 345.64
Concrete	267 732.22	1 405.39	4 550.66	255 222.63	7 818.23	536 729.13

Table 4. A comparison of the cumulative energy and carbon footprints of manufacturing, disposal and demolition

<table>
<tr><th colspan="3">Manufacturing</th><th colspan="3">Disposal and demolition</th></tr>
<tr><th>CLT</th><th>Concrete</th><th>Reinforcement</th><th>CLT</th><th>Concrete</th><th>Reinforcement</th></tr>
<tr><td colspan="3">Summary of cumulative energy [MJ]</td><td colspan="3">Summary of cumulative energy [MJ]</td></tr>
<tr><td rowspan="2">567 057.04</td><td>193 351.99</td><td>3 002 922.28</td><td rowspan="2">3 221.92</td><td>17 559.58</td><td>11 435.64</td></tr>
<tr><td colspan="2">3 196 274.27</td><td colspan="2">28 995.22</td></tr>
<tr><td colspan="3">Summary of cumulative carbon footprint [kg CO_2 e]</td><td colspan="3">Summary of cumulative carbon footprint [kg CO_2 e]</td></tr>
<tr><td rowspan="2">–98 526.16</td><td>28 480.23</td><td>239 251.99</td><td rowspan="2">966.57</td><td>5 619.06</td><td>2 199.16</td></tr>
<tr><td colspan="2">267 732.22</td><td colspan="2">7 818.23</td></tr>
</table>

usable floor space compared to traditional methods. Fig. 2 compares the floor plans of the building in Gdynia in the context of different construction, with an indication of the gain in usable floor area, while keeping the same outline of the total area.

Table 5 indicates the gain in area due to the use of different construction thickness, while Table 6 summarizes the cost of purchasing materials and labor taking into account the interior finishes, which are different. The comparison does not take into account the identical earthwork solutions for the foundation or the finishing solutions for the façade. It should be noted that CLT technology enables the thickness of the construction to be reduced relative to conventional concrete technology, gaining 9.70 m^2 (1.81%). This provides a significant advantage for investors, who can obtain additional usable space despite the initial total area remaining the same, while optimising the cost of purchasing materials.

Fig. 2. Floor plans. A comparison of CLT and conventional concrete construction

CLT technology also considers construction site ergonomics. The individual panels are prepared off-site and delivered in appropriately labelled and segregated packaging. This allows the elements to be assembled much more quickly, generally taking a few days. Opting for timber prefabrication means construction can be carried out in a way that reduces the negative environmental impact, as equipment use can be minimised during assembly and there is no noise or pollutants, such as dust. Using concrete increases the length of time the construction site is open, as well as generating environmental nuisances such as dust and noise.

CLT panels are applicable to both vertical and horizontal partitions, as well as roof slopes, possibly keeping the same cross sections depending on the constructor's calculations. The use of solid wood allows the use of panels of different thicknesses, with an idea to saving raw material and not leaving unused offcuts. At the same time, when ordering the product for building in Gdynia, the manufacturer analysed the 3D model again and found that it was possible to adopt even skinnier elements. Thin (mostly 8 cm) bonded panels can be used for partition walls, but aerated concrete blocks (mostly 12 cm) were considered for concrete technology.

CLT technology enables designers to achieve a particular aesthetic without the need for additional finishes. In the case of Marszewo, for example, natural wood is visible on the walls and ceilings, which are protected with oil. Conventional technology requires plastering and painting, as well as veneer board cladding to create a wooden interior. Suspended ceilings were not intentionally designed. The variety of materials used affects the cost of energy, labour, and their acquisition or transportation. CLT panels are used to meet demand while generating minimal waste, whereas conventional technologies inevitably result in leftovers.

Table 5. A comparison of floor area in relation to technology

No.	**Area specify**	**CLT technology**	**Conventional technology**
1	Total gross area	533.50 m^2	533.50 m^2
2	Usable floor area	335.10 m^2	325.40 m^2
3	Construction and partition walls	32.90 m^2	42.60 m^2
4	Percentage of floor area	62.81%	61.00%
5	Gain of floor area	9.7 m^2 (1.18%)	

Table 6. A comparison of the costs and savings relating to technology

No.	**Cost (PLN)**	**CLT technology**	**Conventional technology**
1	Overall materials	604 858.82	562 410.96
2	Construction walls + roof	253 806.54	160 167.20
3	Partition walls	12 705.63	72 901.28
4	Wall finishing	32 763.28	199 749.01
5	Total	904 134.27	995 228.45
6	Overall savings	91 094.18	–

2.3. Social assessment. Comfort of use

The building at the Forest Botanical Garden was intended to combine a workplace for foresters with an educational space for children, providing an opportunity to learn about the forest. Given its purpose, the building has characteristics that give it broad social impact; the use of wood further enhances this potential, as it evokes universally positive associations.

The aesthetics of the building are primarily a display of CLT technology and visible technical installations (Fig. 3, 4). The use of wood in the building is part of the biophilic trend, i.e., the construction of buildings broadly inspired by nature and its geometry. It is created through a clear opening up to nature, the use of assets resulting – in this case – from the forest location and biodiversity of the garden and access to the water pond, as well as the inspiration of the flora evident in the natural materials used, finishes and details, as well as through an appropriate approach to natural light and the rich sensations and diverse effects associated with the idea of so-called shelter, i.e., building safety. Wooden partitions provide both adequate structural statics and have enhanced acoustic and thermal performance compared to those made of conventional materials, which also has a positive effect on the user's well-being. In summer – as the foresters was able to experience personally – the rooms are pleasantly cool, and in winter, even without the heating on, there is no discomfort at the mild temperatures.

Fig. 3. Exhibition hall, photos: Fotomohito 2023

Fig. 4. The multifunctional mezzanine, photos: Fotomohito 2023

The authors conducted on April 2024 a survey [32] concerning a broader discussion about the building itself and attitudes to modern timber construction, and reflections on the use of the building were part of this survey. Surveys are a popular choice for building certification systems that assess environmental impact and sustainability, as well as well-being.

The survey included a variety of questions, ranging from selecting predefined options and rating items on a scale of 1 to 6 to providing personal comments. Both groups (a total of 36 participants) expressed notable interest in ecology (average score: 4.83 out of 6.00) and sustainable (average score: 3.72). However, the majority of respondents admitted that they had no prior experience of modern ecological construction, particularly CLT. Nevertheless, almost half of those surveyed had at least heard of the technology. The building itself received an overwhelmingly positive rating (average score: 5.30). Employees specifically noted in their individual responses that being in wooden interiors was both aesthetically and practically pleasing, indicating better air quality and a more pleasant working environment.

Durability and maintenance were identified as the main concerns, with 20 mentions in total. There were also a few comments about execution quality (3 mentions) and functionality (2 mentions). On a more positive note, aesthetics were considered the most significant advantage (24 mentions), followed by durability and maintenance (six mentions) and functionality (five mentions). Many participants remarked on the building's striking appearance in their individual comments, noting that interacting with wood in this way felt unique and incomparable to traditional construction methods. They also observed that the structure blended well with the garden setting and was eye-catching. However, a few respondents felt it was somewhat overwhelming, too dark or even unusual. Despite assurances from manufacturers that cross-laminated timber is resistant to weather conditions and less susceptible to pests than traditional wooden logs, concerns over maintenance remain a significant obstacle for wooden buildings. Respondents acknowledged that wooden buildings have a significantly smaller environmental footprint than traditional structures (average score: 5.03) and are more visually appealing (average score: 5.46). However, they also expressed reservations about construction complexity (average score: 3.22) and cost (average score: 3.14). Other barriers identified were the limited availability of CLT technology due to a lack of solid wood company representatives and production capacity, and a shortage of skilled professionals in Poland.

3. Results and conclusions

The paper presents a comparative analysis of building construction at the Forest Botanical Garden "Marszewo" in Gdynia, examining the use of cross- laminated timber (CLT) technology and conventional concrete technology. Table 7 shows a comparison indicating objective issues in terms of sustainability principles. Design and construction costs are shown in Table 8.

The paper aimed to present the construction of a building using CLT technology, alongside an environmental, economic and social analysis of this in relation to conventional reinforced concrete construction. Concrete was chosen as an alternative due to the technology's popularity and widespread availability. The building in Gdynia is a prime example of the implementation of CLT technology, enabling two archetypal blocks with gable roofs to be constructed. This type of design is possible with both CLT and RC technologies, but not with ceramic blocks due to the required spans and the inability to create analogous roof slopes. The study assumes that in- situ concrete is the method of operation analyzed, but the use of precast concrete may be an option, as indicated in Table 7, but affects the energy and economic costs.

Table 7. Comparing technologies in relation to sustainability

Type	CLT technology	Reinforced concrete (RC) technology
Environmental Impact	Wood has a negative carbon footprint. It sequesters carbon during its growth and after it has been used. This carbon sequestration makes CLT sustainable and renewable, allowing for reuse and achieving a lower carbon footprint.	The production of concrete has a significant environmental footprint. It releases CO_2 into the atmosphere and consumes vast amounts of water and energy. The manufacturing of cement, a key component of concrete, contributes significantly to global warming.

Continued on next page

Table 7 – *Continued from previous page*

Type	CLT technology	Reinforced concrete (RC) technology
Sustainability	CLT is made from renewable resources and contributes to the environmental performance of a building. It also has excellent performance in terms of energy, air and water pollution.	Incorporating recycled materials like crushed concrete and industrial byproducts like fly ash can significantly reduce the need for virgin resources and lower carbon emissions [33].
Market Availability	The availability of CLT may be limited in certain regions, which affects its accessibility for construction projects.	Concrete is widely available, easy to implement, and efficient in the long term.
Structural Strength	CLT panels are generally stronger than timber due to their manufacturing process and the materials used. Gluing layers together removes wood defects and ensures consistent strength throughout the entire section. The result is a material that is stronger and more stable than solid timber, particularly for larger sections. Although CLT is lighter than concrete, its strength-to-weight ratio is comparable.	RC is renowned for its high compressive strength and durability, making it suitable for a variety of construction projects. It is renowned for its high compressive strength and durability, making it suitable for a wide range of applications.
Construction Speed	Due to the prefabrication, CLT buildings can be constructed more quickly. This speed extends to the installation of large areas of CLT per day, which significantly accelerates construction schedules. Prefabrication enables the rapid installation of large areas, resulting in faster construction.	Concrete construction can be slower than prefabricated CLT particularly for complex designs. Concrete structures are generally heavier and may require more extensive work involving more workers and longer waiting times for the product to dry. In this case, it is more advantageous to use precast concrete.
Long-term Performance	As it is a relatively new material, its performance is still being explored.	Proven performance and durability over time.
Cost-effectiveness	Although CLT is often perceived as expensive, it can be cost-effective. Prefabrication reduces overall design costs and accelerates construction, decreasing labour requirements and ensuring savings. As long as the design involves displaying wood in the interior aesthetics, the structure does not require further finishing work.	Widespread availability does not negate the high cost of concrete production. Prefabrication involves manufacturing components such as walls, slabs and beams in a factory before transporting them to the construction site. While this method offers benefits such as increased speed and quality control, it also has an impact on costs. The structure requires further finishing work, the cost of which depends on the design.
Design Rigidity	CLT components are prefabricated, meaning there are no changes or adjustments required during construction. Preparation and planning are crucial steps in the implementation of CLT technology.	Concrete construction offers greater flexibility in terms of on-site adjustments. In contrast, precast construction requires strict adherence to the original design, with limited scope for changes.
Versatility in Design	While achieving arbitrary shapes and spans can be considered a limitation, there are also examples of introducing unusual elements.	Thanks to its malleability, concrete can be formed into a variety of shapes and forms, offering flexibility in architectural design.

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Table 7 – *Continued from previous page*

Type	CLT technology	Reinforced concrete (RC) technology
Fire Resistance	CLT offers a good fire resistance due to its construction and natural charring behavior. Additionally, fire-retardant treatments and protective coatings can further enhance CLT's fire resistance	Concrete is naturally fire resistant, making it a safe choice for various types of buildings.
Energy Consumption in Production	Production generally involves lower energy consumption than concrete, with the majority of energy being required for sawing and panel pressing.	The manufacturing process involves high energy consumption, including for cement production and heating materials.
Waste Generation	Prefabrication results in minimal on-site waste, as offcuts and sawdust can be reused or recycled.	Construction and demolition can generate significant waste, and while concrete can be recycled, this is often not cost-effective.
Pollution and Emissions	Lower energy consumption can reduce environmental impact and help to reduce air and water pollution compared to conventional i.e. concrete production.	The production of concrete contributes to air and water pollution, as the transport and processing of raw materials has an environmental impact.
Water Usage	It generally requires less water during production than other materials.	The production process generally requires high water use.
End-of-Life Considerations	Wood is recyclable or reusable, as well as biodegradable if left untreated.	Recycling possible but difficult and not cost effective. Not biodegradable

The CLT panels used in the design were produced by KLH Massivholz, a leading manufacturer of solid wood products which meets all criteria relating to sustainable forestry management and uses certified wood. The wood solutions are manufactured with users' health in mind and do not contain formaldehyde or volatile organic compounds. At the same time, the facility's furnishings and equipment are wooden products from companies with sustainable production management policies. Some furniture items, such as wardrobes, shelves and doors, have been made using thinner CLT panels as an alternative to MDF or plasterboard. Due to their layered gluing, CLT panels do not have the disadvantages of the aforementioned solid elements, nor do they require additional covering layers. Using wood for furnishings and fittings therefore guarantees a timeless aesthetic with minimal maintenance requirements, such as eliminating dirt and preventing potential damage. The CLT panels at KLH are manufactured from renewable resources, making them environmentally friendly. They are more energy efficient and generate less air and water pollution than conventional materials, and they can be recycled. Based on the research presented, it was concluded that using CLT technology significantly minimises CO_2 emissions into the atmosphere. Solid wood is one of the most important materials used in ecological construction nowadays, due not only to its low carbon footprint and its role as a CO_2 reservoir, but also to its sustainable production processes.

One factor limiting the popularity of CLT is the lack of a local market in many European countries, which requires the use of foreign manufactures. CLT technology requires designers to take a new approach i.e. use special software dedicated to the company that will manufacture the panels. This creates difficulties due to the software's limited availability, which affects development costs. In contrast, the design process in concrete technology is well understood and the material is readily available. With the lack of local availability, it is pointed out that the cost of transportation becomes significant and with an impact on the carbon footprint. Considering the experience at the construction site in Gdynia, it can be concluded that companies were reluctant to invest, hence several tenders remained unresolved and the construction company implementing the design was still gaining experience with the CLT technology. As a result, costs for CLT construction are higher, as Table 8 indicates.

In summary, both CLT and RC have their own distinct advantages and are suited to different design needs. The choice between them depends on factors such as environmental considerations, design requirements, construction speed, cost, and regional availability. For specific projects, using a combination of both materials may provide the best solution, combining the strengths and benefits of each.

Table 8. A comparison of carbon footprints, costs and savings

Technology	**Carbon footprintin the 50-year cycle**	**Material costs (PLN)**	**Construction costs (PLN)**
CLT	175 345.64	604 858.82	253 806.54
Concrete	536 729.13	562 410.96	160 167.20
Savings	361 383.49 = 206% saving	–93 639.34	–42 447.86

The authors aimed to highlight the advantages of CLT construction compared to conventional building technology based on concrete. While the findings demonstrate the economic benefits of conventional construction methods, the ecological aspects strongly favour CLT. The carbon footprint and energy requirements for producing a solid wood are significantly lower than for a reinforced concrete structure, with CLT having an impressive 206% lower CO_2 emissions. In recent years, attention to the carbon footprint has become almost standard. It is expected in architectural competitions and often favours the environmental impact and use phases over the economic aspect when selecting a project for implementation. While saving on construction costs may be an advantage, it is not the determining factor. Since its construction, the educational building in Marszewo has been very well received by both the investor and the facility's users, and has received numerous awards highlighting the uniqueness of its ecological credentials. Given Poland's abundant forests and the potential for sustainable forest management, there is an opportunity to develop a local market for sawmills and modern factories. This could provide a platform for the development of CLT technology.

As the building has been in use since 2024, the research has centred on its environmentally conscious design as an alternative to conventional technologies. Over the next five years, the authors plan to conduct a study to evaluate its use, carrying out a more in-depth analysis of its long-term efficiency, acoustics and thermics in relation to well-being and comfort.

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Środowiskowa ocena cyklu życia (LCA) modelu budynku z drewna masywnego i betonu. Wdrożenie drewna klejonego krzyżowo (CLT) w budynku edukacyjnym w Leśnym Ogrodzie Botanicznym „Marszewo" w Gdyni

Słowa kluczowe: zrównoważony rozwój, architektura drewniana, ocena cyklu życia, CLT

Streszczenie:

W drugiej połowie XXI wieku szczególnie odczuwalne stały się skutki zmian klimatycznych, związane ze wzrostem zaludnienia i agresywną urbanizacją pogarszającą naturalne środowisko. Dla rozwoju współczesnego budownictwa oraz w idei projektowania zrównoważonego za wartościowe uznaje się poddanie budynku analizie cyklu życiu (LCA), obejmując proces inwestycyjny od etapu projektowego, przez produkcję materiałów oraz wznoszenie obiektu i jego eksploatację, aż po potencjalną rozbiórkę. Pryncypia ekologiczne, ekonomiczne i społeczne zrównoważonego projektowania łączy drewno, surowiec naturalny, obecny w architekturze od wieków, ale dzięki współczesnemu, innowacyjnemu podejściu do jego obróbki, poprzez technologię drewna klejonego krzyżowo (CLT) wychodzący naprzeciw wyzwaniom nowoczesności. Zakładając coraz większy wzrost zainteresowania konsumenta postawami proekologicznymi oraz zaostrzenie się regulacji prawnych w obszarze Unii Europejskiej, należy uznać, że główny nacisk zostanie położony na wybór materiałów przyjaznych środowisku, a więc o niskim śladzie węglowym, korzystnym bilansie energetycznym i ostatecznie potencjale odzysku. Opierając się na tej hipotezie, artykuł przedstawia analizę porównawczą LCA obiektu w technologii CLT i betonowej w odniesieniu do realizacji budynku edukacyjnego w Leśnym Ogrodzie Botanicznym Marszewo w Gdyni.

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