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Towards sustainable construction: Methodology for wood content assessment in buildings

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ABSTRACT

Globally, the construction sector is responsible for 34 % of global energy demand and 37 % of CO_2 emissions from the construction and operation of buildings. In the EU, buildings account for approximately 40 % of energy consumption and one third of greenhouse gas emissions. The aim of the study is to develop a methodology for determining the use of wood and/or other organic materials made from renewable natural resources in construction products in buildings by proposing assessment criteria, thereby contributing to the promotion of sustainable building construction and the establishment of a circular economy in the construction sector (or supporting the implementation of circular economy principles in the construction sector). The study contains a structural analysis of the tensile, compressed and bending elements taking into account different strength classes and various cross-sections. It was found that relative values of volumes and masses of wooden, reinforced concrete and steel structures differ significantly and cannot be applied to assess of wood in buildings. Therefore, in the proposed methodology the wood amount is assessed not according to the ratio of the physical properties of structures, but according to stored and released CO_2 of these structures. Moreover, the methodology takes into account not only the durability of different structures, but also the rational use of it.

1. Introduction

Data on energy, water, material consumption, waste generation, greenhouse gas emissions, and other pollutant emissions reveal that the construction sector has a significant impact on the environment. Globally, the construction sector is an important energy consumer, responsible for 34 % of global energy demand and 37 % of CO_2 emissions from the construction and operation of buildings [1]. In the EU, buildings account for approximately 40 % of energy consumption and one third of greenhouse gas emissions [2]. Furthermore, the construction industry consumes enormous amounts of non-renewable resources, with an estimated 40–50 % of the world's material resources being used for buildings and infrastructure in developing countries [3]. The sector also generates significant amounts of waste, with construction-related waste accounting for 38 % of total waste in the EU [4]. The environmental role of the construction sector becomes even more evident when considering that the floor area of buildings worldwide is predicted to increase by 75 % between 2020 and 2050 [5].

Based on the above facts, it is clear that sustainable solutions in the construction sector are very important to achieve the goals of

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the EU in energy and climate change. Unfortunately, the Global Buildings Climate Tracker shows [1] that progress towards the planned decarbonization goals is lacking, with a very large gap (almost 40 %) between the current situation and the desired decarbonization level for 2030. The EU Buildings Climate Tracker [6] shows that the EU is also significantly behind in achieving the 2030 and 2050 climate goals, with CO_2 emissions in the construction sector having decreased only 14.7 % in 2022, compared to a target of 27.9 %. The observed 13.2 % delay and the overall trend of progress raise concerns that the 2030 goal will not be achieved at the current pace. The urgent need to reduce building-related greenhouse gas emissions and improve other sustainability indicators is driving the search for ways to accelerate the sector's environmental awareness and sustainability. When it comes to sustainable buildings, an area of focus is the replacement of fossil fuels in the construction sector with renewables, as the use of environmentally friendly (less harmful) materials could be a long-awaited solution to mitigate the climate impact of the construction sector.

A systematic bibliometric analysis of scientific articles devoted to the assessment of the sustainability of structures built based on circular bio-based building materials has shown that interest in this issue has increased significantly in recent years [7].

In the search for alternatives to replace traditional building materials, such as steel and concrete, their replacement with wood is widely studied. Tupenaite et al. found that interest in the possibilities of mitigation of climate change in construction using timber as a sustainable material has not been high for a long time, and the number of publications devoted to this topic has started to increase since 2018 [8]. Research covers the areas of the use of wood as a sustainable building material, carbon storage and reduction of greenhouse gas/CO_2 emissions, and the circular economy in the construction sector. Many researchers [8–12] emphasize the benefits of wood as a sustainable building material, i.e., wood is a naturally renewable, ecological, durable, recyclable material with a lower impact on the environment and, consequently, on climate change. Analysis [13,14] suggests that as the volume of timber increases, more kilograms of CO_2 are stored in the buildings. However, the use of more timber also leads to higher emissions during transport, because the distance from the transport and recycling of materials also plays a significant role in reducing emissions during the construction stage. If the structural design of the building is more efficient, requiring less wood, less CO_2 is stored in the building, and fewer environmental benefits are achieved, even if the saved wood remains in forests or is used elsewhere. The study pointed out that further studies are recommended to evaluate both standard criteria together. Other researchers also claim that more detailed research is needed, reviewing research into many aspects of mass timber use as a building material and demonstrating the feasibility of mass timber construction, to increase its uptake and change international and local building codes to include specific requirements for timber structures [15]. The authors of a study [16] suggest that to fully realize the ecological benefits of the system, it is essential to increase the global use of mass timber to store as much carbon as possible in solid form and to use wood efficiently to replace carbon-intensive materials such as concrete and steel. Additionally, the environmental assessment does not account for forestry stocks and harvest rates. Proper and mindful forest management will be the key to effectively sequestering atmospheric carbon, especially in the context of a more sustainable construction industry.

In addition to sustainability, advanced technological solutions mean that wood has good mechanical and physical properties, which allow it to establish itself in the construction sector. It has been established [17–26] that the use of cross-laminated timber (CLT) in buildings during the construction phase produces significantly less CO_2 compared to conventional construction materials (concrete, steel) and clearly has more other environmental benefits, such as a lower carbon footprint, greenhouse gas emissions, and shorter construction time. The study revealed [27] that the value chains of glue laminated timber and sawn timber from raw material extraction to production using the same methodology have a lower environmental impact, especially when analyzing greenhouse gas emissions, energy use, waste generation and water use, compared to the value chains of site-cast concrete and precast reinforced concrete, and also observe positive socio-economic benefits of construction timber. Against the backdrop of economic and environmental challenges facing the construction industry, this study [28] aimed to explore and highlight the advantages of an innovative construction approach. Mass timber construction offers a forward-thinking and eco-friendly solution that significantly shortens on-site construction durations.

The establishment of wood in buildings is also related to the prevalence of wood interiors due to the positive effect of wood on the measurable and subjectively perceived quality of the indoor environment, which can be described by indicators characterizing chemical compound emissions, indoor air humidity, antibacterial, acoustic effects, psychological and physiological human well-being [29–32]. A review of 140 scientific publications (1993–2019) [33] showed that visually and tactilely, wood is most often perceived as a positive and natural material and therefore is preferred compared to other building materials. Differences in physiological reactions between the effects of wood and other materials have been identified and most studies have shown that wood materials can create a less stressful environment. The European Economic and Social Committee (EESC) sees Directive 2024/1275 on the energy performance of buildings as the main policy tool for setting requirements to reduce carbon emissions over the full life cycle of buildings. The EESC calls on the European Commission to develop a carbon certification scheme that takes full account of the role that wood products play in offsetting emissions [34]. In Opinion of EESC on 'Wooden construction for CO_2 reduction in the building sector'' it is stated that, taking into account the public sector's ability to lead by example, the EESC calls on the Member States to use more wood in public buildings. [35] To achieve the objectives of a circular economy and climate neutrality and to transform the construction sector through eco-innovation and technological progress, various initiatives and measures are being promoted that open up opportunities for the efficient use of natural resources, including wood, for the production of products that do not have a negative impact on the environment and for the development and implementation of sustainable business models and services.

In Finland, the Wood Building Programme (2016–2023), coordinated by the Ministry of Environment, aims to increase the use of wood in urban development, public buildings, and large-scale construction, such as bridges and halls, and aims to diversify and expand the various wood applications, creating as much added value as possible. This is planned to achieve the energy and climate goals set out in the National Energy and Climate Strategy and to reduce Finland's carbon footprint by 2030. The targets set for the share of wood in all new public construction and for the types of building with the highest construction volume are: 15 % in 2019, 31 % in 2022, and

45 % in 2025 [36].

The French government is implementing a new sustainability law that requires all new public buildings to contain at least 50 % wood or other sustainable materials. The Agency France-Presse noted that the regulatory codes apply to all French government-funded buildings and were in force in 2022 [37]. Following the Croatian Construction Act, the national chamber of commerce issued special building instructions that established the 30 % wood requirement in public buildings as a formal legal provision [38].

The Slovenian regulation on green public procurement states that the share of recycled or reused construction wood in wooden wall panels must be at least 10 %. The share of wood or wood products in buildings must constitute at least 30 % of the volume of installed materials, and in noise-absorbing road fences the share of wood or wood products constitutes at least 55 % of the volume of materials used for the production of noise-absorbing road fences [39].

The increasing use of wood as a structural and finishing material in architecture reflects a larger shift toward ecological thinking in building design. Wood, as a renewable and carbon-sequestering material, inherently supports the principles of environmental sustainability. Recent theoretical frameworks [40] emphasise the importance of systemic thinking in sustainable construction. Within this context, wood serves as a component of an ecological model, as it supports modular construction, promotes circular material flows, and reduces the embodied energy. Research [41] demonstrates that wood-integrated buildings can be modelled with greater environmental sensitivity due to the thermal inertia and adaptive characteristics of wood. As highlighted researches at [42], dynamic evaluation of building performance, particularly with regard to indoor comfort and energy efficiency, benefits from materials that can passively regulate temperature and humidity. Due to its hygroscopic properties, wood can buffer interior conditions, functioning similarly to biological systems that self-regulate in response to external stimuli.

In Lithuania, there is a state-level resolution [43], the essence of which is that procurement entities purchasing design services and contracting works for the new construction of public buildings classified as special and non-special structures must use at least 50 % of wood and other organic materials from renewable natural resources in construction products. It is expected that this state-oriented resolution will serve as an example for other market participants and will encourage solutions that will reduce the impact of the construction sector on climate, especially in relation to fossil resources. However, during the implementation of this resolution, the question of the criteria and methodology according to which the amount of wood in the buildings would be determined arisen.

It is seen that countries plan to use more wood in buildings in order to save part energy that is used for various traditional building products manufacture and to reduce CO_2 footprint. But still are unclear what criteria will be applied for determination of wood application by each country. And this is the main problem since the different evaluation of wood will have different effect on the environment. A conclusion of this kind could be found in evaluation study of 45 real life wooden buildings [44]. Since the countries basically plan only to increase the amount of wood in buildings, rather than improving the efficiency of the use of wooden structures, no plans to develop certain standard methodology to assess environmental and economic criteria. Thus, the aim of the research is to develop a methodology for determining the use of wood and/or other organic materials made from renewable natural resources in construction products in buildings by proposing assessment criteria, thereby contributing to the promotion of sustainable building construction and the establishment of a circular economy in the construction sector. In response to the need, the methodology is focused on determining the amount of construction products made from renewable natural resources in public buildings; however, the assessment concept and principles formulated during the study are, in principle, also suitable for calculating the amount of wood in buildings for other purposes. The methodology must include assessment criteria not only for wood but also for other organic materials, e.g., plant materials (fibrous hemp, straw, fibrous flax, etc.), used as integral construction products or parts of composite products. In the methodology, the evaluation indicator for wood and other building components is the percentage of construction products made

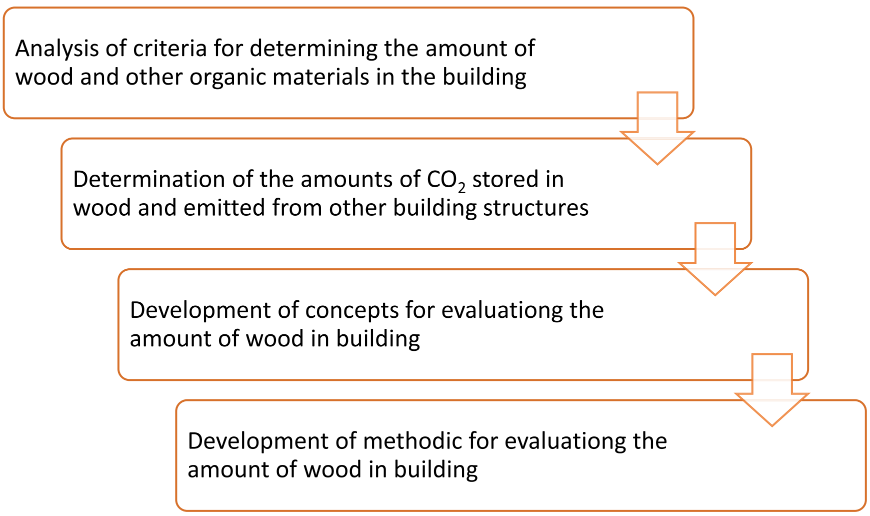


Fig. 1. Essential stages of methodology development for assessing the amount of wood and of others organic origin materials made from renewable natural resources in buildings.

from wood and other organic materials made from renewable natural resources in relation to the entire public building.

The impact of wood or organic based building materials on the building's energy efficiency should be studied separately, as in this case the various thermal isolated materials and the purpose of rooms play a greater role [44,45].

2. Stages of methodology development

The methodology for assess the amount of the wood and of other organic materials based on renewable natural resources in buildings was developed in several stages (Fig. 1). Initially, the criteria for determining the amount of wood in the building were defined: analysis of the correlations of the strength and physical parameters of wooden structures, analysis of the lifespan of different types of construction structures, analysis of significance of various criteria for wood and organic origin construction elements not only from an economic but also from an ecological perspective. In global warming potential comparison analysis seems that impact of structures material to GWP vary in quite wide range [46,47]. Actually, this is determined by quantities of building structures that are selected according to various structural, technological and thermal requirements. Nevertheless, some countries have planned to increase the wood in buildings specifying the particular percentage values [36–40]. However, the published regulations do not detail the parameters that should be used to determine the mentioned percentage values. Generally, the quantities of structures and products in the buildings are expressed by mass or volume, but only in regulation adopted by Slovenia it is stated that in the building structures and products should contain at least 30 % of the wood volume. As well known that the density of different structures varies, so their ratios by mass and volume will also differ. In order to determine how the percentage values of these structures change according to their volume and mass, these two cases were analyzed.

In the second stage, a concept for assessment the amount of wood has been developed, based on mechanical resistance, durability, fire resistance, economic and ecological factors. In order to summarize the principles of determining the amount of CO_2 emitted by prevalent building structures and the amount of CO_2 stored by wood during its growth and their impact on global environmental effects, a review of the CO_2 footprint of various structural components at different stages of the life cycle of structures was conducted in the third stage.

In the final stage, a methodology for assessment the amount of wood in buildings has been proposed, involving the most significant advantages of wood and other structures and their ecological impact.

2.1. The analysis of criteria for determination the content of wood and others organic materials in the building

The evaluation of physical (volume and mass) and mechanical wood parameters was carried out on the basis of tensile, compression and bending wood, reinforced concrete and steel members strength analysis. Due to rare occurrence in the practice of tensile reinforced concrete members, these members were not included in the analysis. The comparative analysis of the geometrical and physical parameters of the tensile wood and steel members was performed for each member type with the lowest and the highest strength classes. In this way the three types of members were distinguished: solid wood, glue wood and steel. The properties of these members, used in the analysis, are presented in the Table 1.

The analysis of compression members was performed with the inclusion of reinforced concrete members. Since the cross-section of compression members is selecting not only according to stability condition, but according to resistance condition also, the relationship of compression force and cross-section could be nonlinear. Due to this the 2 cases were distinguished: when the slenderness of members $\lambda < 50$ and $\lambda > 50$. For calculations of the members with slenderness $\lambda < 50$ from 4 MN compression force the square cross-section was selected for wood and the HEA and IPN section type – for steel. The reinforced concrete members were selected as symmetrically reinforced square cross section members with various ratio of reinforcement. The cross-section of C20/25 concrete strength class

Table 1
The parameters of analyzed tension members.

Element type	Strength class	Characteristic strength, MPa	γ_M	k_{mod}	design strength, MPa	Density, kg/m^3
Solid wood	C14	$f_{t,0,k}$= 8.0 $f_{c,0,k}$= 16.0 $f_{m,k}$= 14.0	1.3	0.9	$f_{t,0,k}$= 5.5 $f_{c,0,k}$= 11.1 $f_{m,k}$= 9.7	350
	D70	$f_{t,0,k}$= 42.0 $f_{c,0,k}$= 34.0 $f_{m,k}$= 70.0	1.3	0.9	$f_{t,0,k}$= 29.1 $f_{c,0,k}$= 23.5 $f_{m,k}$= 48.5	1080
Glued wood	GL24h	$f_{t,0,g,k}$= 16.5 $f_{c,0,g,k}$= 24.0 $f_{m,g,k}$= 24.0	1.25	0.9	$f_{t,0,k}$= 11.4 $f_{c,0,k}$= 16.6 $f_{m,k}$= 16.6	380
	GL36h	$f_{t,0,g,k}$= 26.0 $f_{c,0,g,k}$= 31.0 $f_{m,g,k}$= 36.0	1.25	0.9	$f_{t,0,k}$= 18.0 $f_{c,0,k}$= 21.5 $f_{m,k}$= 24.9	450
Steel	S235	$f_{y,k}$= 235.0	1.1	–	213.64	7850
	S355	$f_{y,k}$= 355.0	1.1	–	322.73	7850
Concrete	C20/25	$f_{c,k}$= 20.0	1.5	–	$f_{c,d}$= 12.0	2000
	C25/30	$f_{c,k}$= 25.0	1.5	–	$f_{c,d}$= 15.0	2000
	C50/60	$f_{c,k}$= 50.0	1.5	–	$f_{c,d}$= 30.0	2000
Reinforcement bar	B500	f_{yk}= 500.0	1.15	–	$f_{y,d}$= 435.0	7850

members was chosen as 0.5 × 0.5 m and 0.45 × 0.45 m and of C50/60 – 0.35 × 0.35 m. For calculations of the members with slenderness $\lambda > 50$ from 1MN compression force the square cross-section was selected for wood and the tube and IPN section type – for steel. The cross-section of C20/25 concrete strength class members was choosed as 0.35 × 0.35 m and 0.30 × 0.30 m and of C50/60 – 0,30 × 0,30 m. The concrete class members were reinforced by 0.5, 1.3, 2.0 and 2.5 % amount of reinforcement. The length of compressed members was 4 m (when $\lambda<50$) m and 9 m (when $\lambda>50$).

In the case of combined bending and axial compression the cross-sections were determined from the maximum 3 MN axial force (without bending). The cross-sections were selected as square for reinforced concrete members, square and rectangular – for wood members and square tubes – for steel members. Steel strength classes were assumed to be S235 and S355 and C20/25, C25/30, and C50/60 concrete classes – for reinforced concrete members. The members of 4 m and 9 m length were examined. After calculations the steel square tubes were selected of 400x400x10 and 350x350x8 profiles for members of 4 m length while 400x400x12 and 400x400x8 profiles – for members of 9 m length. Reinforced concrete cross-sections were selected of 0.4 × 0.4 m and 0.30 × 0.30 m for 4 m length while 0.5 × 0.5 m – for 9 m length members. The reinforcement ratio was 0.41, 0.28 and 1.0 %. respectively.

During the analysis of bending members, the beams and slabs were distinguished. The exceptional case is cast-in-place concrete slabs which economically are more effective than precast concrete slabs. The flat slabs or steel-concrete slabs can be considered as exceptional case also, but analysis in this case should be a complex, i.e., covering the frame, not the members of floor. Since the reinforced concrete floors are most widely used in the public buildings in Lithuania, the ribbed reinforced concrete and wooden floors were analyzed only. For the comparison of the material quantities, separate floor members. i.e., beams and plates, were analyzed. In this analysis the ratio of beam height and width was assumed equal to 2. The 6 m and 8 m span slabs, loaded by 2, 4 and 6 kN/m^2 characteristic variable load, were examined. Floor structure load accepted as 0.3 kN/m^2. The wood floor is made up of secondary beams placed every 0. and main beams, placed every 6 m and 8 m. The laminated OSB and polyurethane panels are installed on the beams. In the case of reinforced concrete floor, the secondary beams were placed every 1 m and the main beams – every 6 or 8 m. The thickness of slab was accepted minimum – 60 mm. The strength class of wood members was accepted GL24h and the members of concrete – C25/30. The strength class of reinforcement bars – B500.

2.2. Principles of determination of CO_2 stored by wood and emitted by other structures

In order to assesses the relationship between the amount (volume and mass) of wooden structures used in the building and ratio of the amount of CO_2 stored in wood and the amount of CO_2 emitted during the production of other load-bearing structures, an analysis of CO_2 emission assessment was performed. On the analysis basis the total CO_2 balance of the buildings load bearing structures was assessed, i.e, it was evaluated how the volumes and masses of wooden and non-wooden structures correlate with the ratio of stored and emitted amount of CO_2. At the beginning of this stage the stored amount of CO_2 was suggested to determine according to standard EN 16449 [48]. However, taking into account that this standard methodology was developed in 2014, it was decided to analyze the EPD declarations of various wooden structures and on this basis to propose use the average value of stored CO_2 amount. The average value was proposed taking into account possible uncertainties at the design stage, when the specific manufacturer of wooden structures is not yet known, as well as the wooden structures production technology that describes the final stored CO_2 amount. In this stage the average values of CO_2 emission of production of steel, masonry and reinforced concrete structures were reviewed also.

2.3. Principles of determination of wood amount in building

From an ecological perspective, the amount of wood can be determined using a standardized methodology (LCA), which evaluates the environmental impact of products and services throughout their entire life cycle [49]. However, for wood and bio-based products, where carbon sequestration occurs gradually over time, this methodology may not accurately reflect the temporal dynamics of biogenic carbon sequestration in regrowing forests. In this case as alternative methodology was supposed dynamic LCA methodology [49,50].

From a structural perspective, the amount of wood can be evaluated taking into account the physical and mechanical properties of the various structures. Analysis of these properties allowed to assess how the different strength classes of structural materials influence the quantities of load-bearing structures, and at the same time the relative values of the amount of wood in relation to other type of structures. In this analysis the standard requirements of separate type of structures (wood, steel and reinforced concrete) were taken into account, what also correct the ratio of the quantity's structures.

Finally, was formulate the concept of dual assessment (ecological and structural) of wood amount in buildings taking into account the CO_2 amount stored by the wood and emitted by other type structures.

Anyway, the regular periodic study of the new various type construction product properties and its impact on the environment can help develop strategies to supplement certain construction material with other alternative construction material [51].

2.4. Regularities for the development of a methodology of wood amount determination

The methodology of determination amount of wood and other organic building material from renewable natural resources in building, was created according to obtained results. The assessment of wood amount in the buildings is based on the harmonized principle of application of the ecological, economic and structural criteria. From an ecological point of view, it would be seemed that the higher amount of wood in building, the lower CO_2 emission of building structures. However, such an assessment is not always correct, because it also depends on the various condition of building maintenance. If in some premises of building there are unfavorable environmental conditions (e.g., increased relative humidity, etc.) or if they are subjected to stricter fire resistance requirements, the use of wooden structures is not the most rational solution in such case. If wooden structures are used in the outside part of building, they will require more maintenance compared to concrete structures. This, of course, is reflected in the operating cost of the building. In addition, the wearing surface of such wooden structures will require periodical upgrade, removing the worn protective coating and coating the new one. And it will reflect not only from economic point of view, but also from ecological point of view, since the production of the new coating materials and the mechanisms used for upgrade emit additional amounts of CO_2. Therefore, the methodology for assessing the amount of wood takes into account the durability of the various types of structures, their advantages and disadvantages, which affect the functionality of structures throughout the life cycle of the building.

3. Results

3.1. The influence of structural requirements on the physical parameters of wood

In the analysis of the physical assessment criteria of the percentage of wood in buildings, two main criteria are distinguished: The volume and mass of structures, i.e., what part of volume or mass of all building structures consists of wooden structures. The main wooden structures are load-bearing structures, therefore when analyzing the criteria for assessing amount of wood in buildings, such as volume or mass, it is necessary to compare wooden structures with other types of structures not only according to cross-section parameters, but according to mechanical parameters also. Different cross-section parameters are resulted by the mechanical properties of structural materials, cross-section shapes and specific requirements for separate type of structures (steel, wood and reinforced concrete). For example, there are requirements for minimum concrete cover [52] of flexural reinforced concrete members, what do not affect the load bearing capacity, but impact the volume and mass of member. The impact of concrete cover is even greater for tensile reinforced concrete members. The different densities of structural materials can also have a sufficiently influence. The density of wood can vary within quite wide range according to strength class, while the density of reinforced concrete and steel, in principle, does not depend on the strength. The density of C14 class of wood is 350 kg/m^3, and of C40 class –500 kg/m^3, while the density of D70 class of wood is 1080 kg/m^3. Flexural strength of these classes is 14, 40 and 70 MPa respectively (Table 1).

3.1.1. Requirements for load-bearing structures

The principles for determining the amount of wood in buildings are examined in the context of essential performance requirements, such as mechanical resistance and stability, fire resistance, resistance to environmental exposure, energy efficiency and insulation and sustainability, which must be satisfied (Fig. 2). As can be seen from Fig. 2, this study also included reinforced concrete and steel structures, which, together with timber structures, are typical examples of structural systems used in modern building construction. These materials are fully standardized according to the Eurocode framework (EN 1992 for concrete, EN 1993 for steel, and EN 1995 for timber), which allows for consistent assessment and comparison of mechanical, environmental, and other characteristics. Other organic building materials, such as straw bale systems, cork insulation boards, or bio-based composites, are increasingly recognized in

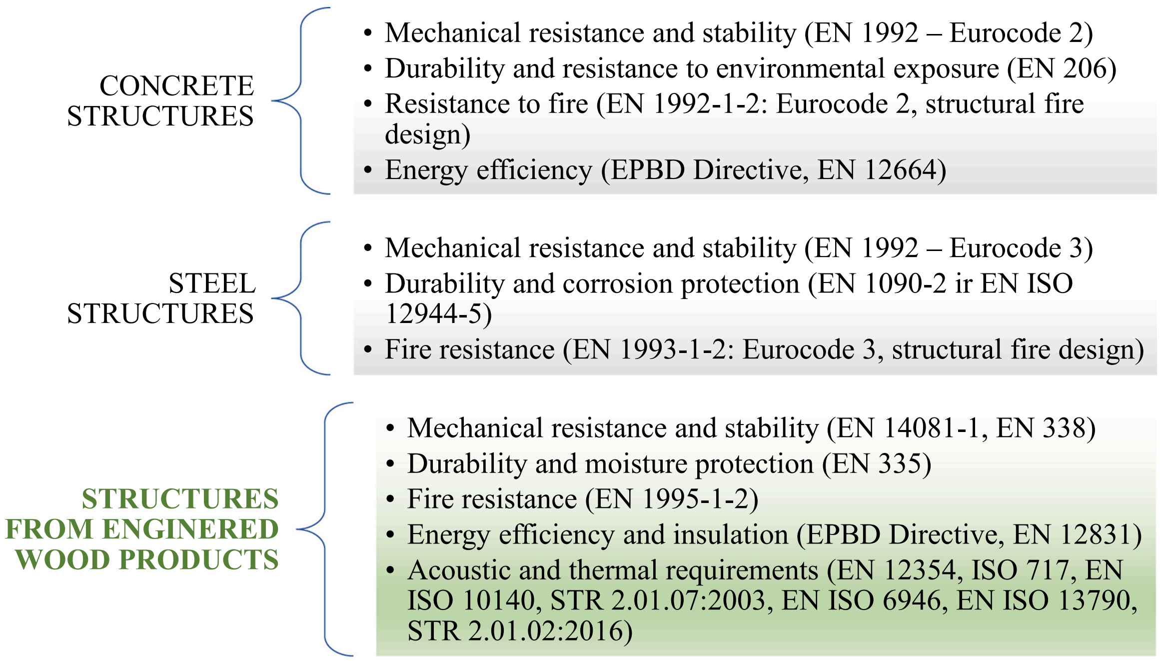


Fig. 2. Main requirements for concrete, steel, and wood structures.

the construction sector for their environmental potential, but their application is still limited by the lack of harmonized standardized methodologies. Therefore, in the initial stage of the development of the methodology, wood was used as the main organic material, while concrete and steel were included for comparative analysis and scientific justification purposes. This methodology ensures both scientific reliability and practical applicability under the current regulatory framework.

As a rule, load bearing structures must withstand the various loads that affect them (permanent load, variable loads, environmental loads, etc.) Depending on operating conditions the reinforced concrete structures must be resistant to carbonization, chlorides and other chemicals penetration, exposure to freeze, etc. In the design of steel structures, it is important to take into account the ultimate slenderness, deflection control ant the strength of joints. Steel structures are more prone to corrosion, which can reduce their durability, therefore the it requires additional special coating. When it comes to fire resistance, both steel and wood usually require an external refractory coating.

Various international and national standards are applied to building structures among which can be mentioned EN 1995–1–1 (Mechanical resistance), EN 1995–1–2, EN 13501–1 (Fire resistance), EN 335 (durability), EN 12831 (Energy efficiency), EN 15804 (Sustainability, life cycle of materials). In addition to standards, the various certification systems (LEED, BREEAM or DGNB) can be applied, to better assess the building sustainability. If wooden structures are designing in the buildings, it is necessary to take into account the specific requirements imposed on them. Wooden structures must be designed to avoid the direct accumulation of water, to protect them from moisture (EN 335 – Wood resistance classes), to prevent them from swelling, rots and biological damage. In addition, according to fire resistance requirements the wooden structures must meet the REI classification (EN 1995–1–2 – Eurocode 5, fire safety). Therefore, replacing part of reinforced concrete or steel structures with wooden ones (in order to reduce CO_2 emission of building structures), it is necessary to guarantee that these structures will meet not only requirement of mechanical resistance, but all other essential requirements.

3.1.2. Relative assessment of the physical and mechanical parameters of load-bearing structures

One of the main load-bearing structures properties is their strength, therefore, in the methodic for assessment the quantities of structures, it is important to determine the relative masses and volumes of reinforced concrete, steel and wooden structures. The strength analysis of the tension, compression and flexural structural members showed how the relationship between strength and the physical parameters changes and how the various criteria influence it. The cross-section areas of members are influenced not only by the strength, but also by the cross-section shapes, while the cross-section areas of reinforced concrete members are also influenced by the reinforcement ratio and the concrete covers. Therefore, in some cases, when the strength classes and the section shapes changes, the volumes and masses of the same strength members may differ several times. It has been taken into account in the development of the methodology for assessment the wood amount in buildings. In this study separately were examined the axial tensile, axial compressed, eccentrically compressed and flexural members with various strength and geometrical parameters.

Since the wood properties (strength and stiffness) depends on load duration and moisture content for analysis the wood elements were assumed of service class 1 which characterized by a moisture content in the materials corresponding to a temperature of 20 °C and the relative humidity of the surrounding air only exceeding 65 % for a few weeks [53]. In service class 1 the average moisture content in most softwood s will not exceed 12 %. The wood design strength value was calculated applying the modification factor as [53]:

$$f_d = k_{\mathrm{mod}} \frac{f_k}{\gamma_M} \tag{1}$$

where k_{mod} is modification factor taking into account the effect of the duration of load and moisture content; γ_M is the partial factor of a material property.

For solid wood the partial factor was taken equal to 1.3 and for glued – 1.25, see table 2.3 of EN 1995- 1 [53]. The modification factor k_{mod} was selected taking into account the effect of short- term action.

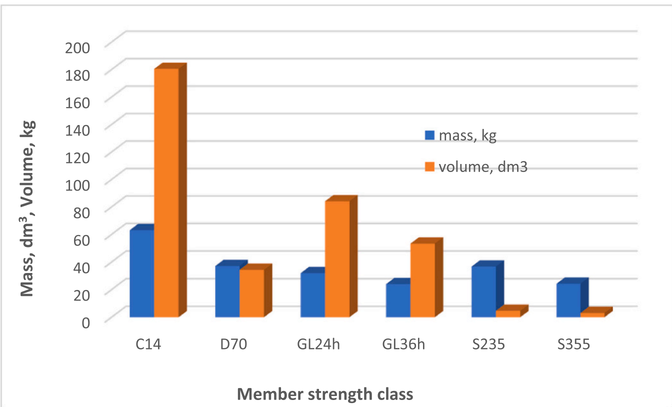


Fig. 3. Masses (kg) and volumes (dm^3) of 1 m length members calculated from 1 MN tension force.

Axial tensile members. The cross section of wooden and steel members linearly depends on the tension force and of reinforced concrete members – on the reinforcement area only. Due to linear relationship between cross-section of members and axial tensile force, the ratios of calculated masses and volumes of wooden and steel members remains constant. When the lengths of all members are the same, the distribution of the cross-section, according to strength classes corresponds to distribution by volume. The distribution of masses and volumes of wood and steel 1 m length members according to strength classes is presented in Fig. 3. In this figure it is seen that ratio of wood volume and mass is higher than 1, and of steel – significantly less. So, the weight of tensile steel members is similar to wood, but the volume is significantly less. Therefore, when replacing the steel tensile members by wood ones, a significant part of the volume is lost, while the masses remain similar. In the case of replacing the S355 class steel member to D70 class wood member, the volume would increase by 11 times, and in the case of replacing to the C14 class – almost 60 times.

The compression of 4 m length (slenderness $\lambda < 50$) members were calculated selectively from the same compressive force equal to 4 MN. The slenderness of selected members was obtained within the following limits:

- For wood members from 10 to 35;
- For steel members from15 to 30;
- For reinforced concrete members from 30 to 40.

The percentage of reinforcement of reinforced concrete members was obtained at 1.3, 2.0 and 2.5 %. The distribution of masses and volumes of wood, steel and reinforced concrete 4 m length members according to strength classes is presented in Fig. 4. In this figure the reinforced concrete members are labeled according to concrete class and the percentage of reinforcement.

An evaluation of distribution of the selected cross-section areas of each member shows that for wood members the ratio of load bearing capacity to the volume is less than the ratio to the mass, while for steel and reinforced concrete members in all cases the ratio of load bearing capacity to volume is greater than the ratio to mass. The ratios of load bearing capacity to the volume and to the mass for reinforced concrete members differ almost 2 times and for steel members – even up to 8 times. Comparing the calculated ratio of volumes of different types of members, it is obtained that the volume of steel from 8 to 26 times smaller than that of wood, and the volume of reinforced concrete members up to 3 times is smaller. Meanwhile, the masses of wood and steel members are obtained relatively similar. The mass of glued wood is about 2 times lower, while the mass of solid wood is ~2 times higher than the mass of steel. The mass of reinforced concrete in all cases was obtained bigger than that of wood from 1.3 to 6 times. Thus, it could be concluded, that the masses of steel and wood members are similar, while volumes of wood and reinforced concrete members are similar.

The compression of 9 m length (slenderness $\lambda > 50$) members were calculated selectively from the same compressive force equal to 1 MN. The slenderness of selected members was obtained within the following limits:

- For wood members from 60 to 90;
- For steel members from 75 to 95;
- For reinforced concrete members from 90 to 100.

The obtained values of mass and volume are presented in Fig. 5. The results show, that the values of concrete mass and volume vary in a narrow range, due to a similar cross-section selected for all reinforced concrete members. Similar to the case of axially compressed stiffer members ($\lambda < 50$), the masses of slender ($\lambda > 50$) steel and wood members remain similar, and the volumes of wood and reinforced concrete members remain similar also. Evaluating these values of masses and the volumes, it is important to take into account the fact that steel profiles were selected from the assortment, and the selected cross-section of concrete member was reinforced with different reinforcement ratio, which results the different strength safety of members.

The cross-sections of eccentrically compressed members are determined not only by the compressive forces, but also by the bending

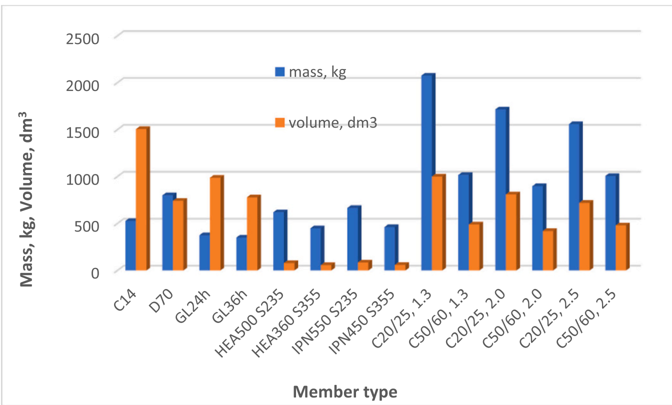


Fig. 4. The masses and volumes of 4 m length members.

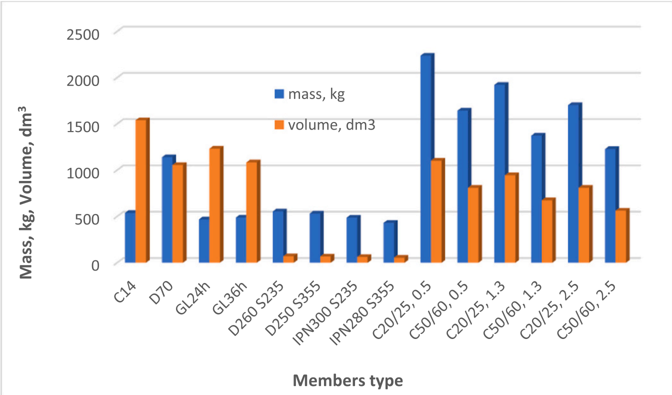


Fig. 5. The masses and volumes of 4 m length members 9 m.

moments. Therefore, the cross-sections were determined by compressive force taking into account the ratio of bending moment and compressive force. The bending moments of members were determined by the cross-sections selected from compressive force equal to ~3 MN. The cross-sections of members of 4 m and 9 m length were selected according to strength and stability criteria. The cross-sections of wood members were dimensioned according to the actual widths and heights, thus obtaining the smallest possible cross-section.

The slenderness of selected members was obtained within the following limits:

- For wood members of 4 m length from 25 to 40, and of 9 m length – from 45 to 70;
- For steel members of 4 m length ~25, and of 9 m length ~55;
- For reinforced concrete members of 4 m length from 30 to 50, and for length ~60.

The obtained masses and volumes of members of 4 m and 9 m length are presented in Fig. 6. These figures show that increasing the length of members from 4 m (Fig. 6a) to 9 m (Fig. 6b), the volumes and masses of wood members increase from 3 to 4 times, and of steel and reinforced concrete ~2.5 times. If steel members of 4 m length were replaced by wood ones with rectangular cross-section, their volume would increase from 5 to 15 times and from 10 to 25 times if replaced by square cross-section. Replacing the reinforced concrete members by wood ones with rectangular cross-section, their volume can reduce or increase about 2 times. Replacing the reinforced concrete members by wood ones with square cross-section, their volume can remain similar or increase even up to 3 times

Somewhat unlike volumes, the masses of members change. In case of rectangular cross-section, the masses of wood members reduce up to 3 times compared those of steel while in case of square cross-section, it can reduce up to 3 times (for glued wood) or increase up to 2 times (for solid wood). The mass of reinforced concrete members in all cases obtained bigger compared it with wood, and reaches from 1.2 to 8 times.

Evaluating the obtained cross-section parameters, it is seen that the variation of volumes and masses of axial and eccentrically compressed members is different.

The volumes ratios of the wood and reinforced concrete bending members of the floor were evaluated taking into account their dimensions, types of floors and the load level. The calculations examined 6 and 8 m span slabs and beams, which are loaded with a characteristic load of 2, 4 and 6 kN/m^2. The resulting volumes of beams and slabs are presented in Fig. 7 and Fig. 8. From these figures

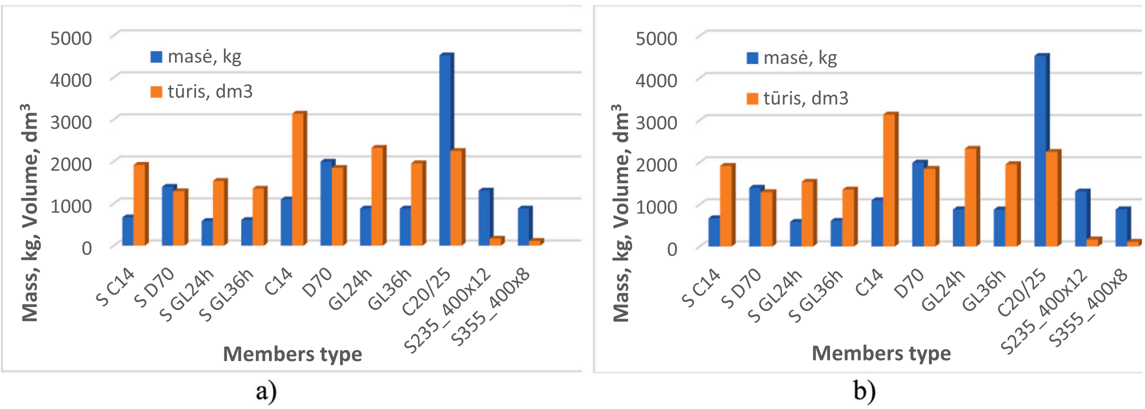


Fig. 6. The masses and volumes of a) 4 m length members; b) of 9 length members.

it can be seen that at a load of 2 kN/m^2, the ratio of volumes of wood and reinforced concrete secondary beams varies from 0.9 to 1.6 times (Fig. 7a), for main beams – from 1.3 to 2.5 times (Fig. 7b) and for slabs – from 0.5 to 0.8 times (Fig. 8). The ratios of volumes of axial compressed wood and reinforced concrete members was from 1.0 to 2.0, and of eccentrically compressed – from 0.5 to 1.7.

Overall, from the strength point of view, the assessment of separate structural members shows that the volume of wood members, in most case, is larger than that of reinforced concrete members, and the mass is greater than that of steel members. However, the evaluation of separate members does not fully reflect the actual parameters of cross-sections in the context of entire frame, since the members are usually calculated depending on the distribution of internal forces in frame members. Forces in load-bearing structures depend not only on external load, but also on the stiffness of joints or boundary conditions. The internal forces acting in the steel, reinforced concrete or wood structures of the same frame may differ, due to which the relative values of volumes and masses will be different also. Therefore, in case of replacing some reinforced concrete or steel members with wood ones, the redistribution of internal forces should be taking into account which occurs in the frame during to this replacement.

3.1.3. Life cycle of building structures

Since the building structures must meet not only the requirements of the strength, but also the durability, fire resistance and other requirements, the wood amount could not be evaluated only in terms of strength (although it is one of the main ones that describe the mechanical resistance of the entire building), therefore, it is appropriate to take into account all the main criteria that influence the properties of structures.

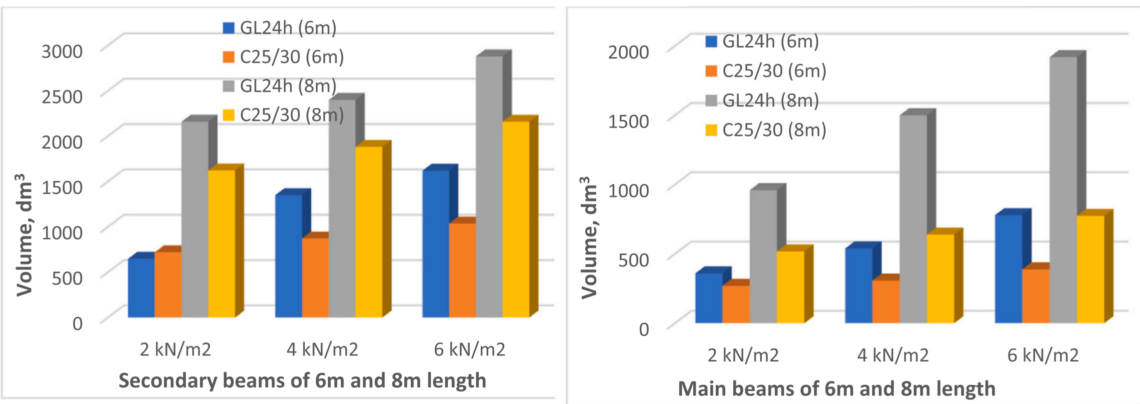
When the different types of structures are evaluating from the point of view of durability, it is worth to pay attention to their different life cycle (service life), which is defined in EN 206, EN 1990, EN 1992–1, EN 1993–1, EN 1995–1 and STR 1.12.06:2002 „Purpose and service life of building [52–57]. The latter regulation defines the life cycle of reinforced concrete, masonry, wood, steel and other construction products from which the structures are built (STR annex [57]). An overview the life cycle of structures used in the buildings for commercial, science, culture, sports and other public purposes show that the defined life cycle of masonry, panel and concrete block buildings is 100 years, cast-in-place concrete buildings – 120 years, wood frame buildings – 40 years and steel frame buildings – 35 years. Since the service life of reinforced concrete and masonry buildings is 2.5 times longer than that of buildings with wood frame, it is appropriate to evaluate this in calculation of wood amount in building.

3.1.4. The significance of the criteria for the physical assessment of wood and organic construction elements

After evaluating the analyzed physical parameters of various types of structures and their relationships, the amount of wood and organic material products for public buildings would be more accurately estimated by volumes, since the majority of public buildings are made from reinforced concrete, not steel, and their strength per unit volume is more similar to that of wood. However, in this place, the different service life of different types of structures should be taken into account.

In the assessment of wood amount in buildings, it is appropriate to single out the above-ground load-bearing structures as the most important building elements according to which the wood equivalent is determined. Taking into account the operating conditions of the underground structures, it is proposed not to include the foundation in the structures amount assessment, as these conditions do not meet the requirements set for the wood. The thermal resistance of modern building partition structures is subject to quite strict requirements, which must be met in order to achieve the desired energy class of the building. In addition, the partitions must also meet the acoustic requirements. Since the wood and the materials of organic origin cannot effectively replace neither thermal insulation materials nor acoustic, it is not appropriate to include these materials in the assessment of the structures amount.

In the modern buildings, the volumes of thermal and acoustic insulation materials are usually larger than the volumes of load-bearing structures. To get a better idea of the relative volume of the buildings partitions and load bearing structures, let's explore a 3-storey (high height is 3 m) 54x18 m wooden frame building (with an arrangement of internal columns 6×6), which roof is single-pitched. The strength class of wood load-bearing structures – GL24h. The snow load is 1.6 kN/m^2, the variable load is 2 kN/m^2, the roof



a) b)

Fig. 7. Volumes beams of 6 m and 8 m length a) of secondary beams; b) of main beams.

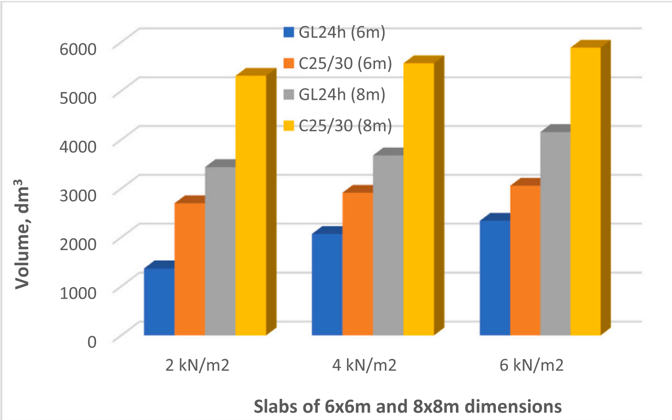


Fig. 8. Volumes of slabs of 6x6m and 8x8m dimensions.

covering load is 0.1 kN/m^2, the floor covering load is 0.2 kN/m^2. The external walls are equipped with wooden studs (45 ×200 mm), between which 200 mm thick thermal insulation is placed (Fig. 9). The studs on both sides are clad with OSB panels. According to preliminary calculations, the secondary beams placed every 0.6 m have a cross-section 45 × 240 mm, the main beams – 120 × 500 mm, and the columns – 400 × 400 mm. It is accepted that 70 % of the wall area consists of window and door openings, i.e., such a part of the area is not insulated with thermal insulation. In the building the partitions of SIP wood panels (between the columns in both directions) was accepted.

After preliminary calculations of the amount of wood structures, it was found that even if OSB cladding panels of partitions would be taken into account as a wood product, the volume of wooden structures of the building would be only ~ 1/3 of the total volume, which consists of wooden structures and materials of thermal insulation (walls and roof) and acoustic insulation (floors). If the cladding of partitions panels were not OSB, but another (not wooden), then the proportion of wood would be only ~25 %. Such a small relative volume of wood was obtained despite the fact that the entire frame of building is wooden. As already mentioned, since the wood does not have such thermal properties as polyurethane or rock wool, the replacing it by wood would be not energetically effective. Therefore, it is not correct to estimate the amount of wood in buildings only by volume ratio, because the volume of thermal insulation of an energy-efficient frame building will almost always be larger than the volume of wooden structures. And if the foundation structures would be evaluated additionally, then the relative volume of wood structures would decrease even more. Thus, the question arises about the concept of rational assessment of the amount of wood in buildings.

3.2. The concept for assessment of amount of the wood and organic building products in the building

If the separate building structures members would be examined by comparing them with the alternative members of wood or other organic materials, the question would arise due to significance of the compared parameters. At the beginning of the article, after analysis of load-bearing structures, we found that even from the strength point of view the wood cannot be correct evaluated according to volume or mass parameters, let alone the non-bearing members whose main parameters relate to thermal or acoustic properties. One of the most difficult parts of study was the definition of the assessment concept, i.e., what kind of modern building could be evaluated as 100 % wooden. And how to justify such a definition. After all, in addition to the main structural members, in the buildings there are also various engineering networks or mechanical equipment, such as elevators, etc., which are also attributable to the immovable part of the building and should be evaluated. Therefore, if one considers that a log house with a thatched roof meets the concept of a 100 % wooden building, then such a building would not meet the thermal, acoustic and other essential requirements that are imposed on

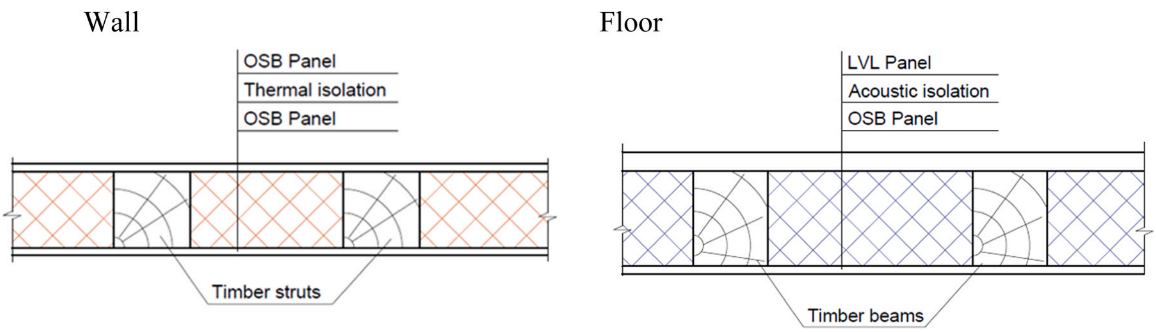


Fig. 9. Cross section of wall and floor.

modern buildings. Due to this, it was decided to evaluate the members by their functional efficiency and to distinguish those members whose replacement with alternative wooden members would be inefficient from the physical, mechanical, structural and economic points of view. Such members were proposed to exclude from the assessment of wood content. First of all, it would be the same foundation structures, because from the point of view of durability, the most effective is a reinforced concrete foundation (Fig. 10). Replacing it with wooden one would be completely irrational and unreasonable. Secondly, it should be mentioned that the load-bearing frame is not dominant in terms of volume and mass of the all building structures. In addition to the load-bearing frame, a significant part of the volume of building structures consists of the façade, insulation and acoustic materials, partitions, floors, ceilings, windows, doors, etc. And all these structural elements cannot be just wooden. Although heat-insulating materials of organic origin are already offered, their effectiveness is no means comparable to traditional materials yet. Therefore, similar as to foundation structures, the thermal insulation members were proposed to exclude from the assessment of wood content also. There are also imposed the acoustic requirements for the interior walls or partitions of a building, which are usually not satisfied by solid wood partitions, therefore, they must also contain additional soundproofing materials. It should be noted that glass partitions are very popular in modern public buildings, which create a larger space image. From the point of view of interior design, such glass partitions cannot be replaced by wood. In addition, the special attention should be paid to the facade of building. The area of the building facade structures occupies a significant part of the building, so its assessment must be complex. In this case the advantages and disadvantages of wood and non-wood facade claddings should be taken into account. The durability is one of the essential properties of the facade cladding. The wood is that structural material whose strength and deformability influenced by the humidity of environment. Also, the durability of wood in wet conditions is much shorter than that of other facade cladding materials (glass, ceramic tiles, etc.). Due to these reasons, the wood facade claddings are impregnated abundantly to prevent rot, but despite this, it must be regular painted or re-impregnated. Comparing the costs of wooden facade cladding and its operation with facade cladding of other materials, raises the question of the overall rationality of the building both in economic and ecological aspects. On the whole, from a multifaceted point of view, it is more rational to use wooden structural members inside the building, not externally, thus extending their service life, but with due regard to the requirements of EN 1995–1–2 [58] for fire protection.

As can be seen, the search for the main criteria for the assessment of wood amount has faced many challenges, which include not only structural, functional, but also the architectural aspects, which are very important in the construction of public buildings. In addition, it is very important not to make the assessment of the wood amount too complicated, which would create a lot of uncertainty for designers and would be too time-consuming. The mere application of the wood amount assessment methodology will require additional time costs, especially in the first few years. Designers, especially architects, will have to consider a number of additional design versions if the prepared initial version of the project will not meet the required minimum amount of wood. Since the price of wood is higher compared to other construction materials, the use of a larger amount of wood would increase construction costs, which is not in the interest of the customers. From this point of view, it is possible that building designers will plan use the minimum amount of wood required according to the proposed assessment methodology, which in turn would complicate the design process itself due to appeared the factor of minimization. Therefore, in order not to overload the designers with search for additional design versions, it is appropriate to take into account the detail level of the sheets of materials currently presented in the project documentation when compiling the methodology for assessment of wood amount in buildings. As usual, the current sheets contain all the materials of the load-bearing structures and their amounts. However, the materials and amounts of windows, doors or facade members are often not

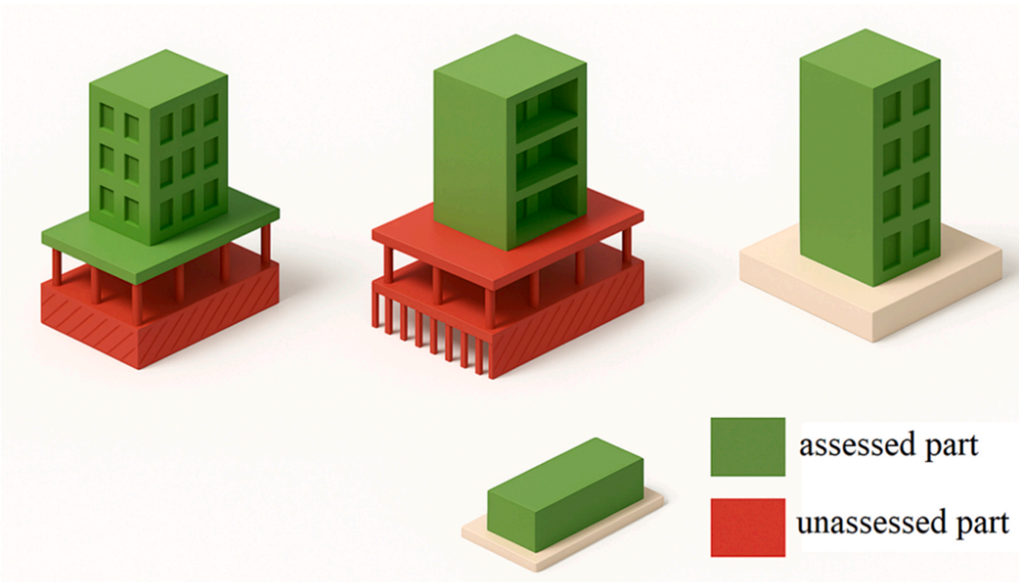


Fig. 10. Assessed and unassessed parts of foundation.

provided in the project, but only the required characteristic values of these structures are indicated. In this case, the designer envisages that the doors, windows or facade members will be installed by specialized companies that will ensure the quality of those structures and their compliance with the characteristics specified in the project. And this is a common practice defined by technical regulations. Therefore, in the proposed methodology, it was decided to evaluate only the main building structures, i.e., the load-bearing structures of the building and the internal walls, the specification of which is provided in the project. It was also decided to evaluate the glass facades, as the CO_2 emissions of glass are quite high compared to the emissions of other types of facade claddings. In addition, the facade is a significant enough part of the building in terms of its volume, so it would be inefficient from an ecological point of view not to evaluate out the influence of glass facades. This was decided after the conclusion was made that the assessment of the amount of wood must not be based on the relative volume or mass of wooden and non-wooden structures, but on the ratio of CO_2 amount conserved by the wood and emitted by other building structures. When proposing the concept for assessment of wood amount in a building, one cannot fail to take into account some significant shortcomings in the properties of wood. One of them is fire resistance, so it is proposed to take into account not only the strength of the structures, but also the additional fire protection measures required for wood. Thus, in the proposed methodology, it was decided not to evaluate the reinforced concrete or brick structures of evacuation zones and firewalls (including staircases), the replacement of which by the wooden ones would be ineffective from the point of view of fire. Another disadvantage is related to the property of wood to weaken under increased ambient humidity. In view of this, it is proposed not to evaluate sanitary premises and outdoor structures in the building, the replacement of which to wooden ones would affect the durability structures.

It should be noted that during the construction of new public buildings, the need of shields or shelters installations is arising. Taking into account the structural requirements for shields and shelters, the use of wooden structures in them is very limited. Therefore, these parts of the building are also excluded from the methodology for assessment of the wood amount.

3.3. Determination of CO_2 amount stored by the wood and emitted by main non-wooden structures

In the French wood quantity calculator SCORE-BOIS_v1, the amount of wood in building is assessed according to the volumes of different types of structures and the floor areas. However, as can be seen in paragraph 2 of the article, the volumes of different types of structures do not match to their strengths, therefore, the equivalent volume of reinforced concrete and steel members in relation to wood would not be assessed evenly, since the density of the separate structural members differs. If the amount of wood would be evaluated in terms of masses rather than volumes, the possibilities of using steel structures in buildings would be more limited due to their high density. Also very important is the question of how much detail should be evaluated the non-bearing structures and their elements. This question can be answered quite simply. This depends on how much detailed information about the amount of these structures at the design stage is available and how accurately their CO_2 emission values are known.

In general, one of the main objectives of the use of wood in public buildings is to reduce the amount of CO_2 that is emitted during the production of the non-wooden structures used in the building, therefore, in this case it would be appropriate to assess the amount of wood in buildings not in terms of equivalent volume or mass of wood in respect to reinforced concrete or steel structures, but in terms of the CO_2 emissions of these structures. Such an assessment is in line with the objectives of the XIV-72 program, according to which the Government of the Republic of Lithuania has planned till 2030 to reduce greenhouse gas emissions by 30 % compared to 2005. The methodology for calculating CO_2 based on biogenic carbon content can be found in the standard EN 16449 [48]. According to the calculation case in Annex A to this standard, the atmospheric CO_2 based on biogenic carbon is 17883 kg in 25 m^3 of wood (or 715.3 kg per 1 m^3 of wood). Of course, the more precise value of the CO_2 content should be adjusted according to the EPD declarations of wood producers, the preparation of which is carried out in accordance with ISO 14025 and LST EN 15804 standards. Declarations prepared in accordance with these standards include the amount of CO_2 that has the potential to contribute to global warming (GWP). When the equivalent volumes of structural materials are determining, the CO_2 stored content of wood should be assessed at the end of its life cycle. A review of some of the GWP (CO_2 e) content provided in the declarations of the German manufacturers of solid, glued (GL) and cross-laminated (CLT) wood shows that this varies from 745 kg to 767 kg [59]. The GWP (CO_2 e) content in the EPD declarations of laminated veneer lumber (LVL) of some Swedish manufacturers reaches even up to 817 kg [60]. These amounts of CO_2 stored by wood correspond to cases where wood is recycled or reused at the end of the life cycle of a building. After evaluating the reviewed GWP (CO_2 e) values, it was proposed not to assess the type of wooden structures separately, and apply the one value of 770 kg of CO_2 stored to all of them.

In this way, it remains to assess the CO_2 emissions of other non-wooden member materials and according to this determine the equivalent proportion of wood used in the building. The main non-wooden load-bearing structures are steel and reinforced concrete, which consists of concrete and reinforcement. According to the data of the Concrete Centre, we can see that 812 kg of CO_2 is emitted for the production of 1 ton of cement (EPDs and EN 15804). Taking into account the fact that depending on the class of concrete, about 300–400 kg of cement is consumed to prepare 1 m^3 of concrete, we would get that an average of 284 kg of CO_2 is emitted during the preparation of 1 m^3 of concrete mix. Due to the additional energy costs for the preparation of concrete mixtures and transport of aggregates, this value is increased by ~5 %, i.e., up to ~300 kg. In this way, we obtain that the amount of CO_2 emitted during the production of 1 m^3 of concrete is stored in ~0.39 m^3 of wood. In other words, the equivalent of 1 m^3 of concrete consists of 0.39 m^3 of wood, i.e. a volumes ratio is ~5:2. If we take masses instead of volumes, we would get that the amount of CO_2 emitted by 1000 kg of concrete will be accumulated in ~90 kg of wood, i.e., the masses ratio is ~11:1. As we can see, in the case of concrete structure change to a wooden one with the same strength, the volumes ratio does not correspond at all to the ratio of CO_2 stored and emitted quantities. Similarly, the ratio of masses does not coincide. It should be noted that such a comparison of the amounts of CO_2 stored by wooden structures and emitted by non-wooden structures would correspond to zero CO_2 emissions, i.e., ~180 kg of wood stores the same amount of CO_2 as is emitted by the production of 1 m^3 of concrete. And if we are talking about 50 % of the emissions, then the wood equivalent would be double reduced and the ratio of concrete to the equivalent volume of wood would be ~5:1, i.e., the amount of CO_2 stored by 1 m^3 of wood would make up half of the amount of CO_2 emitted into the environment during the production of 5 m^3 of concrete.

Steel's CO_2 emissions are much higher. The European Commission's website [61], states that CO_2 emissions of 1 t of steel are 1.6–2.0 t, while according to the IEA (International Energy Agency) the CO_2 footprint of 1 t of steel is 1.85 t [62]. Calculating the equivalent of wood in previous way, we get that the amount of CO_2 emitted to produce 1 t of steel is stored in 1190 kg of wood (ratio ~4:5) or the amount of CO_2 emitted to produce 1 m^3 of steel is stored in 20.3 m3 of wood (ratio ~1:20). As we can see, the equivalent of wood in relation to reinforced concrete and steel is different both in volume and in mass.

CO_2 emissions of bricks vary over fairly wide ranges depending on the type of brick and the methodology of production. In some sources, the CO_2 emission of bricks is ~230 g of 1 kg of baked clay bricks [63]. In this way, according to CO_2 emissions, 1000 kg of baked bricks would correspond to 147 kg of wood (ratio ~7:1), while 1 m^3 of baked bricks would correspond to 0.5 m^3 of wood (ratio ~2:1). According to the estimate of the amount of CO_2 emitted in brick production that affects global warming (GWP), the values for CO_2 emissions are slightly higher [64,65]. Taking into account that various types of hollow bricks (including concrete or silicate) are also used for masonry, it was decided to equate the CO_2 emission of bricks with the 300 kg/m^3 since the average CO_2 emissions of the finishing bricks presented in the EPD declarations are also ~ 300 kg/m^3. The amounts of CO_2 emissions of concrete, steel and masonry as well as the amount of CO_2 stored of by wood are presented in Fig. 11 below.

It is a bit more difficult to assess the CO_2 emissions of the production of various composite structures, since composite structures contains the different materials. Therefore, it is proposed to calculate the CO_2 emissions of composite structures by evaluating each composite material separately:

$$P_{comp}(CO_2) = \frac{\sum \left(P_{c,i}(CO_2) \bullet V_{c,i}\right)}{\sum V_{c,i}} \tag{2}$$

where $P_{c,i}(CO_2)$ is CO_2 emission of production of the i-th composite material, $V_{c,i}$ is volume part of the i-th composite material.

It is necessary to note that CO_2 emissions of building structures, including the composite ones, can only be assessed by their actual or at least approximate values. If CO_2 emissions for various type of concrete, steel and masonry structures change within narrow ranges and it is rational to use average values for them, then for other members of building, such as doors or windows, the CO_2 emissions change within wide ranges and even can depend on their size. Since the projects specify the technical specifications of the structures, rather than the for their CO_2 emissions, it would be difficult for designers to predict and assess the CO_2 emissions of the structures which will be proposed by contractors before or during the construction of the building. Therefore, as already mentioned, the methodology proposes to assess the quantities of load-bearing structures, walls, partitions and glass facades, which are always defined in the design documentation.

4. Proposed methodology for assess the amount of wood in the building

The calculation of amount of construction products made from the wood and other organic materials based on renewable natural resources is proposed to be carried out by assessing the amounts of carbon dioxide that are stored and emitted by the main load-bearing and non-load-bearing internal and external structures at the end of its life cycle. The coefficients of durability of structures and the factors of exterior facade structures are proposed to evaluate the amount of wood and other organic construction products in a building. Since reinforced concrete structures are not only more durable but also more resistant to moisture and fire than wooden ones, the amount of CO_2 emitted during the production of reinforced concrete structures could be compensated not only by the load-bearing wooden structures but also by the non-load-bearing wooden structures. Without this proposition can be that the glass facade buildings

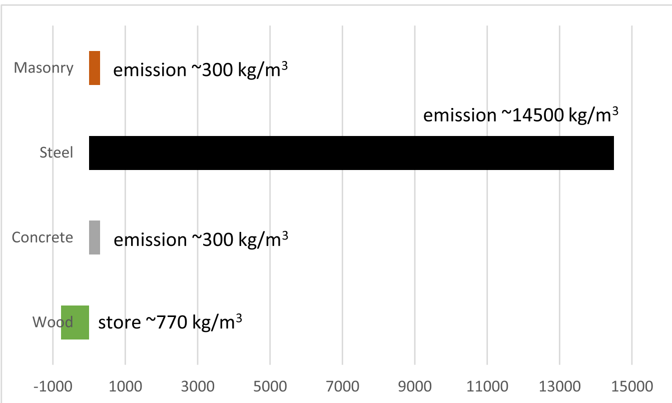


Fig. 11. The amounts CO_2 emissions of different structural materials and amount of CO_2 stored by wood.

will not meet the required minimum amount of wood even in case of entire a wooden frame and wooden partitions. After all, from the ecologic point of view, there is no difference which type of wooden structures store CO_2 from the environment, whether they are load-bearing or non-load-bearing. Therefore, there are proposed to evaluate the wood of the non-load-bearing structures (interior finishing, flooring, organic insulation materials, etc.) also if it is included in the project along with the amount of wood listed in the materials statement. Such an assessment will encourage designers to use the wood not only in load-bearing structures but also in other type structures. By this way there will be motivation to use more wooden interior elements, which will only deepen the feelings of a 'wooden house. Thus, when calculating the amount of wood and other organic construction products, bulk wood or organic insulating materials, wooden window frames, or wooden door elements and other segments of construction products are evaluated, as these reduce the total CO_2 emissions of the building. Other building structural elements made from various energy-saving materials (e.g., various composites, etc.) can also be evaluated, with their CO_2 emissions calculated separately based on the specific quantities of composite materials.

The percentage of the total volume of wood and other organic construction products in the building P_w is determined as follows:

$$\text{When}(PM(CO_2)+PNM(CO_2)) \leq \quad 0.5PN(CO_2), \tag{3}$$

$$P_w = \frac{100(PM(CO_2)+PNM(CO_2))}{PN(CO_2)}. \tag{4}$$

And when $(PM(CO_2)+PNM(CO_2)) > 0.5PN(CO_2)$,

$$P_w = 100(1-0.6\cdot e^{-s})\text{arba}P_w = 100(1-0.6\cdot EXP(-s)), \tag{5}$$

where $s = 0.4 \quad \frac{PM(CO_2)+PNM(CO_2)}{PN(CO_2)}$,

$PM(CO_2)$ is the amount of CO_2 stored in organic materials of load-bearing structures (kg), $PNM(CO_2)$ is the amount of CO_2 stored in organic materials of additional structures (kg), $PN(CO_2)$ is the amount of CO_2 emissions generated from production of main inorganic structures (kg).

The main structures are load-bearing structures, internal walls and partitions, and glass facade structures made of inorganic materials.

Additional structures are elements of the building's (internal walls, partitions, window and door frames, interior finishes, floor coverings, as well as facade frame and cladding), made from inorganic materials.

The amount of CO_2, stored in the organic materials of load-bearing structures, is calculated as follows:

$$PM(CO_2) = V_{ML}\cdot P_{CO2}, \tag{6}$$

where P_{CO2} is the amount of CO_2 (kg) stored in 1 m^3 of organic materials (recommended to accept $P_{CO2} = 770\ \frac{kg}{m^3}$), V_{ML} is equivalent volume of wooden load bearing structures (m^3), which is calculated as follows:

$$V_{ML} = (V_{KVM}+V_{KIM}+V_{PM}+V_{DM}+ \quad V_{ISM}+ \quad V_{VSM})k_{ilg}, \tag{7}$$

where $k_{ilg}$is coefficient evaluates the durability (recommended to accept k_{ilg} =1), variables V_{KVM}, V_{KIM}, V_{PM}, V_{DM}, V_{IZM}, V_{VSM} are

Table 2
Indicators of evaluating structures.

Main structures		**Main structures**	
Volume of the wood structures, m^3		Volume of eco-concrete of reinforced concrete structures, m^3	
V_{KVM}	Internal wood columns, studs	V_{KEVB}	Internal columns
V_{KIM}	External wood columns	V_{KEIB}	External columns
V_{PM}	Wood floor (slabs, beams)	V_{PEB}	Slabs, beams
V_{DM}	Wood roof	V_{DEB}	Roof
V_{ISM}	External wood walls	V_{ISEB}	External walls
V_{VSM}	Internal wood walls	V_{VSEB}	Internal walls
Volume of ordinary concrete of reinforced concrete structures, m^3		Volume of the masonry structures, m^3	
V_{KVG}	Internal reinforced concrete columns	V_{KVB}	Internal masonry columns
V_{KIG}	External reinforced concrete columns	V_{KIB}	External masonry columns
V_{PG}	Reinforced concrete slabs, beams	V_{PB}	Masonry units of beams
V_{DG}	Reinforced concrete roof	V_{DB}	Masonry units of roof
V_{ISG}	External reinforced concrete walls	V_{ISB}	External masonry walls
V_{VSG}	Internal reinforced concrete walls	V_{VSB}	Internal masonry walls
Mass of steel structures (reinforcement of the reinforced concrete structures), t		Volume of additional wooden structures, m^3	
M_{KVP}	Internal columns	Volume of wood members, m^3	
M_{KIP}	External columns	V_{FM}	Façade wood cladding
M_{PP}	Slabs, beams	V_{AM}	Interior wood finish
M_{DP}	Roof	V_{GM}	Wood cover of floors
M_{ISP}	External walls	V_{LDM}	Wooden doors segments, wooden window frames
M_{VSP}	Internal walls	V_{IZM}	Wood and other renewable organic insulation materials

described in the Table 2.

The amount of CO_2, stored in the organic materials of additional wooden structures, is calculated as follows:

$$PNM(CO_2) = V_{NML} \cdot P_{CO2}, \tag{8}$$

where V_{NML} is equivalent volume of additional wooden structures (m^3), which is calculated as follows:

$$V_{NML} = (V_{FM} + V_{AM} + V_{GM} + V_{LDM} + V_{IZM})k_{ilg}, \tag{9}$$

where $k_{ilg}$is coefficient evaluates the durability (recommended to accept $k_{\text{ilg}} = 1$), variables V_{FM}, V_{AM}, V_{GM}, V_{LDM}, V_{IZM} are described in the Table 2.

The amount of CO_2 emitted into the environment (kg) during production of inorganic main structures is calculated as follows:

$$PN(CO_2) = V_{GL} \cdot PG_{CO2} \cdot k_{\text{G,ilg}} + \frac{M_{PL}}{D_{PL}} \cdot PP_{CO2} \cdot k_{\text{P,ilg}} + V_{BL} \cdot PB_{CO2} \cdot k_{\text{G,ilg}} + V_{EBL} \cdot PEB_{CO2} \cdot k_{\text{G,ilg}} + A_{SF} \cdot PS_{CO2} \cdot k_{\text{P,ilg}}, \tag{10}$$

where PG_{CO2} is the amount of CO_2 (kg) emitted from 1 m^3 of ordinary concrete for concrete and reinforced concrete structures (recommended to accept $PG_{CO2} = 300\ \frac{kg}{m^3}$), PP_{CO2} is the amount of CO_2 (kg) emitted from 1 m^3 of steel structures (recommended to accept $PP_{CO2} = 14500\ \frac{kg}{m^3}$), PB_{CO2} is the amount of CO_2 (kg) emitted from 1 m^3 of masonry structures (recommended to accept $PB_{CO2} = 300\ \frac{kg}{m^3}$), PEB_{CO2} is the amount of CO_2 (kg) emitted from 1 m^3 of eco-concrete (concrete which CO_2 emission not more than 200 kg/m^3, recommended to accept $PEB_{CO2} = 150\ \frac{kg}{m^3}$), PS_{CO2} – the amount of CO_2 (kg) emitted from 1 m^3 of glass facade (recommended to accept $PS_{CO2} = 250\ \frac{kg}{m^2}$), V_{GL} is the total volume of ordinary concrete for concrete and reinforced concrete structures, M_{PL} is the total mass of the steel structures, D_{PL} is steel density (7850 kg/m^3), V_{BL} is the total volume of masonry structures, V_{EBL} – the total volume of eco-concrete, A_{SF} is the total area of glass façade (excluding the minimum required windows illuminance area).

The total volume (m^3) of ordinary concrete for reinforced concrete and concrete structures is:

$$V_{GL} = V_{KVG} + V_{KIG} \cdot k_f + V_{PG} + V_{DG} + V_{ISG} \cdot k_f + V_{VSG}. \tag{11}$$

The total volume (m^3) of steel structures is:

$$M_{PL} = M_{KVP} + M_{KIP} \cdot k_f + M_{PP} + M_{DP} + M_{ISP} \cdot k_f + M_{VSP}. \tag{12}$$

The total volume (m^3) of masonry structures is:

$$V_{BL} = V_{KVB} + V_{KIB} \cdot k_f + V_{PB} + V_{DB} + V_{ISB} \cdot k_f + V_{VSB}. \tag{13}$$

The total volume (m^3) of eco-concrete for concrete and reinforced concrete structures which made from it is calculating as follows:

$$V_{EBL} = V_{KEVB} + V_{KEIB} \cdot k_f + V_{PEB} + V_{DEB} + V_{ISEB} \cdot k_f + V_{VSEB}, \tag{14}$$

where k_f is coefficient of façade type, $k_{\text{G,ilg}}$ is durability coefficient of concrete, reinforced concrete and masonry structures, $k_{\text{P,ilg}}$ – durability coefficient of steel structures, k_{ilg} is durability coefficient of wood structures.

The facade coefficient is applied to external load-bearing structures to which ventilated or glass facade systems are attached. If ventilated or glass facade systems are used in a building, the coefficient for the load-bearing external walls of these facades is $k_f = 0.7$ and if not $k_f = 1$.

It is recommended to accept the following values for the durability coefficients used to calculate the amount of wood and other organic construction products: $k_{\text{G,ilg}} = 0.4$, $k_{\text{P,ilg}} = 1.0$, $k_{\text{ilg}} = 1.0$.

For the practical application of the proposed methodology, the real project of the building was chosen (Fig. 12). This is an administrative purpose building with a basement and civil shelter. The building consists of 9 blocks with a corridor and lobby.

Four blocks of building are three stories high, and the other four blocks are two stories high. The one block is one story heigh. The

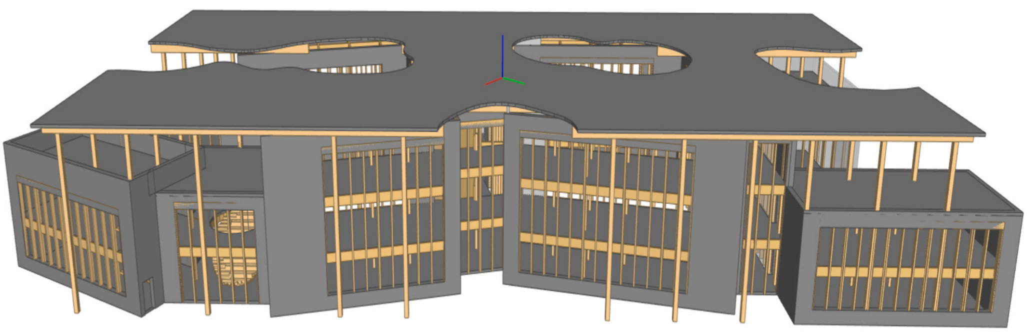


Fig. 12. Administrative purpose building with a basement and civil shelter.

perimeter bearing walls of the building's underground floor are planned to be made of monolithic reinforced concrete, which will take on the external soil pressure and vertical loads. The above-ground part of the building is designed with glued laminated timber, cross-laminated timber, solid wood structures, monolithic reinforced concrete, and brick walls. Vertical loads are distributed through slabs to the walls and beams, and through these to the columns, eventually collecting them into the foundations. The connections of the wooden structures are flexible. The monolithic reinforced concrete joints are rigid. The horizontal loads are taken by transverse and longitudinal walls. The building façade – wooden frame. The amounts of the main building structures are presented in the Table 3.

At first, the equivalent volumes of structures should be calculated. The equivalent volume of main wood structures is calculated follows:

$$V_{ML} = (V_{KVM} + V_{KIM} + V_{PM} + V_{DM} + V_{ISM} + V_{VSM})k_{ilg} = 2035.66 \cdot 1 = 2035.66 \quad m^3$$

In the project there is not separately presented the amount of the main (columns, beams etc.) and the additional wood structures (façade wood cladding, interior wood finish, wood cover of floors, wooden doors segments, wooden window frames etc.). In this case the façade structures are included into the external wall list and the value of V_{NML}.was taken equal to 0 ($V_{NML} = 0$).

The equivalent volume of concrete structures is calculated follows:

$$V_{GL} = V_{KVG} + V_{KIG}\cdot k_f + V_{PG} + V_{DG} + V_{ISG}\cdot k_f + V_{VSG} = 113.36 \quad m^3$$

In case of the non-glass façade the coefficient $k_f = 1$. The equivalent volume of masonry structures is calculated follows:

$$V_{BL} = V_{KVB} + V_{KIB}\cdot k_f + V_{PB} + V_{DB} + V_{ISB}\cdot k_f + V_{VSB} = 7.36 m^3$$

Finally, the equivalent mass of steel structures and the reinforcement is calculated follows:

$$M_{PL} = M_{KVP} + M_{KIP}\cdot k_f + M_{PP} + M_{DP} + M_{ISP}\cdot k_f + M_{VSP} = 28400.01 kg.$$

The ecoconcrete was not used in the building, so $V_{EBL} = 0$.

When the equivalent volumes and masses is known, the CO_2 emission of nonwooden structures is

$$PN(CO_2) = V_{GL} \cdot PG_{CO2} \cdot k_{G,ilg} + \frac{M_{PL}}{D_{PL}} \cdot PP_{CO2} \cdot k_{P,ilg} + V_{BL} \cdot PB_{CO2} \cdot k_{G,ilg} + V_{EBL} \cdot PEB_{CO2} \cdot k_{G,ilg} + A_{SF} \cdot PS_{CO2} \cdot k_{P,ilg}$$
$$= 113.36 \cdot 300 \cdot 0.4 + \frac{28400.01}{7850} \cdot 14500 \cdot 1 + 7.36 \cdot 300 \cdot 0.4 + 0 = 66945.02 kg$$

The CO_2 stored by wood

$$PM(CO_2) = V_{ML} \cdot P_{CO2} = 2035.66 \cdot 770 \cdot 1 = 1567458 kg$$

Because $(PM(CO_2) + PNM(CO_2)) = 1567458 kg > 0.5 PN(CO_2) = 66945.02 kg$,

The percentage wood amount of building

$$P_w = 100(1 - 0.6 \cdot e^{-s}) = 99.93\%$$

The percentage of wood volume according to the total volume of structures it would be 94.2 %. It is seen that durability of concrete and masonry structures slightly increase the percentage of wood in the building from the sustainable point of view.

5. Scientific discussion

The developed methodology provides a systematic approach to assessing the amount of wood or other organic materials used in building structures, contributing to the transition toward sustainable and circular construction practices. Furthermore, the methodology has a clear practical application in the implementation of state policy [40] in the field of innovative urban planning and the development of modern construction. From a scientific perspective, the methodology demonstrates how simplified CO_2 emission and storage indicators can be integrated into early-stage design decisions without the need for complex life cycle assessment tools.

However, a critical analysis performed has revealed several limitations. First, the proposed methodology currently applies average CO_2 emission values for structures to simplify the process of calculating the percentage of wood amount. As is known, construction

Table 3
The amounts of the main building structures.

	Wood, m^3	RC, m^3	Steel, kg	Masonry, m^3	Ecoconcrete, m^3
Internal columns	175.23	0	11700.74	0	0
External columns	62.44	0	7800.50	0	0
Slabs, beams	710.08	5.84	458.44	0	0
Roof	213.94	0	0	0	0
External walls	582.65	66.91	5252.44	7.36	0
Internal walls	291.32	40.61	3187.89	0	0
Total	*2035.66*	*113.36*	*28400.01*	*7.36*	

product manufacturers are constantly updating their production technologies and developing advanced construction materials, so the CO_2 emissions values of construction products are continuously decreasing. Although the methodology enables practical implementation, it does not account for ongoing technological improvements in construction material manufacturing. In future applications, the methodology will need to be adjusted, by supplementing it with refined expressions for calculating of average CO_2 emission values, and to include more detailed product-specific data, including environmental product declarations (EPDs).

Another limitation is related to the evaluation of carbon storage in wood. From an ecological point of view, the use of wood in buildings is effective only when it is recycled or reused after the building's service life. The methodology is based on this ecological scenario, which can be considered the most effective. In practice, this assumption may not always hold true, as part of the wood can be incinerated or biologically degraded, releasing stored CO_2 back into the environment. Similarly, if wood is burned to obtain energy of any kind, the amount of stored CO_2 will not match that is achieved in a case of reuse. It may also be the case that at the end of the life cycle of structures, part of the structural wood will be recycled, part will be utilized, and another part will be used to obtain energy. Furthermore, it is highly debatable whether this can be reliably planned, given that the wear of the structures and their reuse or recycling options would have to be anticipated without knowing what requirements will be placed on the buildings and their structures when the currently designed building reaches the end of its service life, that is, in approximately 30–50 years. These uncertainties highlight the need to develop dynamic assessment models that consider different end-of-life scenarios and their relative probabilities, consistent with the findings of other studies on wood circularity and carbon accounting.

Regarding the practical implementation of the methodology, it is relevant to emphasise that it was developed in order to achieve a state-level resolution in Lithuania [43]. To maintain a balance between the freedom of economic activity of the construction sector, environmental challenges, and the public interest in a healthy and clean environment, the application of the proposed methodology is currently limited to specific categories of public buildings, as listed in Table 4. Buildings with sleeping accommodation, such as kindergartens and pre-schools, and hotels, healthcare and leisure buildings are excluded from the scope of the methodology in the initial phase of implementation due to an ongoing discussion about compliance with fire safety requirements. Therefore, further alignment of sustainability objectives with safety regulations is necessary. This issue is particularly relevant in view of the current European standardisation discussions on the fire resistance of organic materials.

Another important aspect regarding practical implementation is that the proposed methodology currently focusses on quantifiable parameters such as average CO_2 emission values. However, recent studies emphasise the importance of including broader, nondirected impacts in sustainability assessments. For instance, [66] highlighted that considering non-energy impacts (NEIs) in energy efficiency projects allows for a more comprehensive evaluation of overall benefits and decision-making factors beyond direct cost or emission savings. Similarly, the evaluation of construction materials could be strengthened by integrating additional environmental and socioeconomic dimensions into the assessment framework.

The scientific discussion reveals that while the proposed methodology provides a valuable foundation for integrating bio-based materials assessment into building design, further refinement is required to enhance its precision and applicability. Future research should focus on integrating probabilistic life-cycle approaches, product-level environmental data, and dynamic CO_2 storage models to strengthen the scientific robustness of the methodology and its practical use in sustainable construction policy and design frameworks.

6. Conclusions

The assessment of the amount of wood based on the overall volume or mass of building structures is not adequate in terms of both the strength of various structures and their ecological viability. When replacing steel structures of the same strength with wooden ones, their relative volume becomes significantly larger than when replacing reinforced concrete structures. In such a way that to maintain about 50 % of the volume of wooden structures in relation to the volume of all load-bearing structures in building, it would be sufficient to replace less steel supporting structure members with wooden ones, compared to reinforced concrete, what does not meet the relation of CO_2 emissions criteria. The volume occupied by separate structures also depends on selected strength classes of these structures and the geometric parameters of the cross-sections. A bigger volume of wood in the building would be obtained by using the lower wood strength class (or by artificially increasing the cross-sections of wooden structures) Therefore, there is a probability of irrational design arising in order to meet the minimum requirements for the amount of wood used in the building. To avoid this, the methodology suggests to evaluate the ratio of CO_2 stored by wooden structures to CO_2 emitted by other structures, additionally including other non-load-bearing wooden members such as wooden floors, wooden doors, etc.

Evaluating the amount of wood in buildings based on the ratio of CO_2 stored by wooden structures to CO_2 emitted by other structures is effective not only from an ecological perspective. The methodology encourages the use of various other ecological materials in buildings, not just wood, thereby reducing the overall CO_2 emissions of the entire building. From an economic point of view, it is rational to use more "eco" concrete or various composite structures that are cheaper than wood and more resistant to the effects of the external environment. Therefore, if the wood amount is evaluating according to the proposed methodology, designers have more room to seek the most rational solutions not only from economic and ecological perspectives but also from a structural point of view.

The proposed methodology is also linked to the positive global impact on the environment – aiming for the goals of a circular economy and climate neutrality by transitioning to the use of materials and products from renewable natural resources, increasing the use of secondary raw materials, and reducing the generation of construction waste. Furthermore, it promotes sustainable building construction, green procurement, and related innovations and technological advancements in the construction sector. This methodology is significant in developing the European green economy, which the World Bank describes as economic growth that effectively utilizes natural resources, reduces pollution, and does not have a negative impact on the environment, being resilient, i.e., preventing disasters through environmental management. The goal of such an economy is sustainable development, maintaining a balance

Table 4
Public buildings subject to requirements that construction products use at least 50 % wood and other organic materials from renewable natural resources.

Purpose				
administrative	transport	culture	science	sport
Administrative buildings of state and municipal management institutions, prosecutors' offices, courts, and other institutions and organizations, post offices, employment services, information centers	airport, railway and bus station buildings, customs, transport ticket buildings	theatres, cinema theatres, cultural houses, libraries, museums, archives, exhibition halls, planetariums, radio and television buildings	institutes and research institutions, observatories, meteorological stations, laboratories (except for production), general education, vocational and higher education schools	sports halls, tennis courts, swimming pools, skating rinks, stadiums, arenas

between the economic freedom of the business entity and the societal interest in having a healthy and clean environment, i.e., the use of construction products made from renewable natural resources in public buildings promotes innovative economic activities, conserves natural resources, and preserves a clean and healthy environment.

7. Limitation of the proposed methodology

The proposed wood assessment methodology for buildings applies the structural and ecological criteria which contain manufacture, durability of building products and efficiency of mechanical and operational properties of different types of structures. The assessment is based on the ratio of stored and emitted CO_2 and durability of structures. However, in order to avoid complex and time- and labor-intensive costs, a number of assumptions were made to simplify the adaptation of the methodology in design. As a result, the methodology does not cover certain types of building products or structures and assess the wood impact only for the one end of wood life cycle scenario. Moreover, the proposed methodology does not assess the building's energy efficiency, i.e., the energy resource that will be required during the whole building's operation. It is possible that much more CO_2 will be released during the extraction of the energy needed for the operation of the building than during the production of the building's structures. In this case, a comprehensive assessment of buildings should be applied, covering the construction of the building and energy resources during whole operation. However, such methodology of evaluation may be too complex at the initial stage of assessing the ecological efficiency of buildings.

CRediT authorship contribution statement

Banionis Karolis: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Augonis Mindaugas:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vaida Dobilaitė:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Sakalauskas Artūras:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Milda Jucienė:** Writing – review & editing, Writing – original draft, Methodology, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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