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HIGH-RISE BUILDINGS MADE OF WOOD. OVERVIEW OF SUCCESSFULLY COMPLETED PROJECTS FOR SUSTAINABLE URBAN DEVELOPMENT

VÝŠKOVÉ BUDOVY Z DREVA. PREHĽAD ÚSPEŠNE REALIZOVANÝCH PROJEKTOV PRE UDRŽATEĽNÝ ROZVOJ MIEST

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Autor sa venuje výskumu na Katedre pozemných stavieb Stavebnej fakulty Slovenskej technickej univerzity v Bratislave. Evgenii Slivets skúma tému „Moderné drevené stavebné materiály vo vzťahu k moderným mestám".

Abstract
The use of wood as a construction material is experiencing a resurgence due to the growing trend in sustainable architecture. Its unique selling point lies in its combination of mechanical, thermal, and aesthetic properties, as well as its easy workability and the ability to create precise, intricate wooden prefabricated elements. The prefabrication method results in a faster construction process and instant load-bearing capacity. Additionally, the eco-friendliness of wood, as a renewable resource with minimal toxic substances, is becoming increasingly important. Additionally, the eco-friendliness of modern building materials made of wood, as a renewable resource with minimal toxic substances, is becoming increasingly important. The article discusses the current regulatory restrictions for high-rise wooden housing construction in Slovakia. The very valuable experience of using modern high-rise buildings made of wood in other countries and how these projects were carried out are considered. The article also reflects further prospects for the use of modern wood materials in the Slovak Republic and what can contribute to this trend.
Key words: high-rise wooden buildings, sustainable buildings, modern wood building materials

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Abstrakt
Používanie dreva ako stavebného materiálu zažíva opätovný rozmach v dôsledku rastúceho trendu udržateľnej architektúry. Jeho jedinečná výhoda spočíva v kombinácii mechanických, tepelných a estetických vlastností, ako aj v jeho ľahkej opracovateľnosti a možnosti vytvárať presné, zložité drevené prefabrikáty. Výsledkom prefabrikácie je rýchlejší proces výstavby a okamžitá nosnosť. Okrem toho je čoraz dôležitejšia ekologickosť dreva ako obnoviteľného zdroja s minimálnym obsahom toxických látok. Okrem toho je čoraz dôležitejšia ekologickosť moderných stavebných materiálov z dreva ako obnoviteľného zdroja s minimom toxických látok. Článok sa zaoberá súčasnými regulačnými obmedzeniami pre výstavbu výškových drevených domov na Slovensku. Zohľadňujú sa veľmi cenné skúsenosti s používaním moderných výškových budov z dreva v iných krajinách a spôsob realizácie týchto projektov. Článok sa zamýšľa aj nad ďalšími perspektívami využívania moderných drevených materiálov v Slovenskej republike a nad tým, čo môže k tomuto trendu prispieť.
Kľúčové slová: výškové drevostavby, udržateľné budovy, moderné drevené stavebné materiály

Introduction
The resurgence of wood as a construction material is largely due to the current focus on environmentally conscious design. From an energy consumption perspective, wooden structures place a lesser burden on the natural environment in comparison to structures made from metal and concrete. Research [1] compared the environmental impact of low-rise buildings using various construction methods during both the production of building materials and disposal phases. Results showed that the environmental impact of traditional masonry buildings was up to 2.7 times greater than that of wooden structures.
Wood possesses a unique property of carbon sequestration, allowing it to absorb and store carbon in the form of biomass and forest soil. As a result, forests play a role in reducing atmospheric CO2 levels, resulting in a negative carbon footprint, as depicted in Table 1.

Material	Amount of kg of CO_2 released / absorbed per m^3 of material
Concrete	333.6
Structural steel	12207
Glued laminated timber (GLULAM)	-714.4
Cross laminated timber (CLT)	-678.3

Table 1- Comparison of CO2 released / absorbed balance for different materials
Source: [2]

The utilization of wood in construction has sparked fears of deforestation and potential environmental harm, however, careful forest management can ensure a steady supply of woody material. As a natural material, a well-designed and treated wooden structure can maintain a healthy indoor climate and bring positive psychological benefits to its occupants.

One of the most significant challenges of wooden structures is their susceptibility to decay from wood-rotting fungi and insects. This can be caused by poor design, incorrect installation, or use of untreated wood. Excessive moisture levels are usually the main culprit behind these issues, which is the biggest weakness of wood. While wood naturally expands and contracts with changes in humidity, it is crucial that it is allowed to dry and not be sealed in an environment with no means of regulating humidity and airflow. Ideal ventilation should permit the wood to transpire and regulate its humidity and air volume.

Wooden structures in architecture are built on two fundamental principles, a closed or an open system. Regardless of which principle is chosen, the key factor is that the materials used in the construction must allow for the release of water vapor and must exhibit decreasing levels of diffusion resistance from the interior to exterior. This prevents the buildup of moisture within and allows it to escape. Additionally, proper insulation design ensures that condensation does not occur in the insulation or near wooden elements, preventing the growth of mold. It is worth noting that mold growth can often go unnoticed, making it a dangerous issue.

The most widely utilized system is the sandwich or solid wall support system. The market provides a broad spectrum of treated wooden building materials aimed at enhancing mechanical properties and making optimal use of residual materials from the initial processing of grown wood. Engineered Wood Products (EWP) made of treated wood, such as Glued Laminated Lumber (Glulam) for beams and columns, Laminated Veneer Lumber (LVL) for sheathing, and Cross Laminated Timber (CLT) for solid walls, offer the highest quality due to their advanced manufacturing technology. Defective portions of the wood structure are removed, and the wood is dried to the appropriate humidity, ensuring robust and durable products. Although made up of numerous smaller parts, these materials exhibit a solid behavior due to their toothed edges, cross-layering, and high-pressure bonding, and they are highly resistant to moisture.

Wooden structures are known for their potential for high levels of prefabrication and systematized element solutions, not just in the rough construction phase. It is vital to have suitable connecting elements, as these joints must provide stability, prevent air leaks, and ensure thermal and sound insulation for a comfortable indoor environment. Along with traditional angles and strips, there is also a wide range of advanced joint systems available (Fig.1)

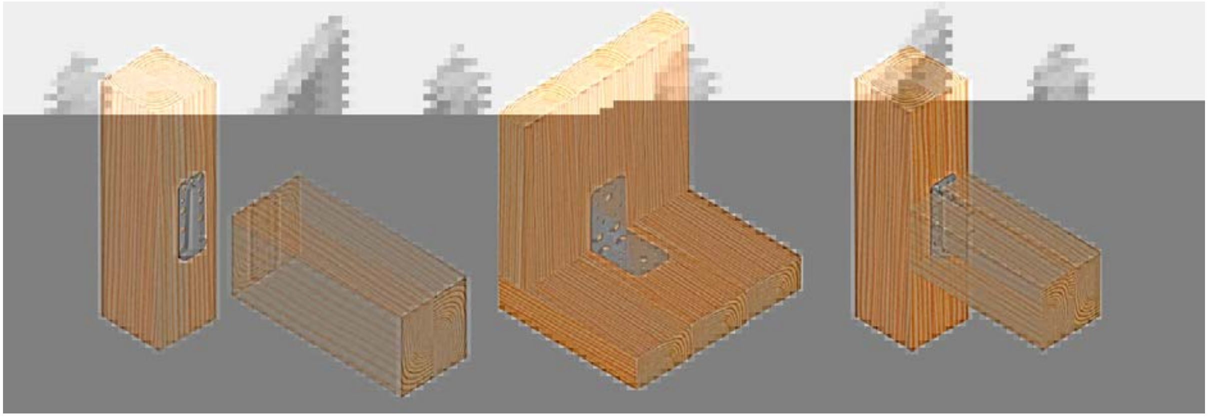

Figure 1 - Examples of connection points for CLT panels
Source: [3]

When it comes to fire protection for wooden buildings, the design is regulated by the Decree of the Ministry of Interior of the Slovak Republic no. 94/2004 Coll. and standards STN 92 0201-1 to 4 [4] and STN EN 13501-1 [5]. The thickness of solid wood elements is crucial in providing fire resistance as it has been shown that wooden structures made of solid wood burn to a depth of approximately 0.5 to 0.7 mm per minute during fire tests. Enlarging the dimensions of a wooden column beyond the static calculation requirements increases its fire resistance, and fire protection cladding or coating can also be used. An untreated solid wooden column can withstand a fire better than a noncombustible steel column, which loses its yield strength when the temperature exceeds 500°C. In a fire, flammable interiors can reach a temperature of 500°C in 5-6 minutes, causing a sudden loss of strength in a steel column without fire protection, risking collapse. A wooden column can withstand fire if oversized or its fire resistance is increased, but the speed of fire spreading over the surface and through joints and cavities (in sandwich elements) is a concern. To prevent the spread of fire, cavities must be divided and filled with non-combustible material like mineral wool, especially when electric wiring is present. It is necessary that each fire compartment must be separated from others with the help of a fire door, fire seal or fire damper to keep the fire from spreading into other fire zones [6].
In Slovakia, the fire safety regulations remain stringent in comparison to other nations, even though the availability of wood-based building materials and proximity to the lumber industry presents numerous benefits. However, previous legislation in Slovakia has only permitted the construction of residential buildings with a maximum of 3 above-ground floors and production buildings with a maximum of 2 above-ground floors. This restriction was only relaxed with the update of the «STN 92 0201-2 Fire safety of buildings. Common provisions. Part 2: Building structures» [7] standard in 2017.

A major change in the fire safety standard allows for the reclassification of flammable components (type D3) to mixed components (type D2) if certain conditions are met. If the structure is built using mixed elements (type D2), residential buildings can have up to 5 above-ground floors. Type D2 components will not worsen the fire during the required fire resistance, as materials with a fire reaction class other than A1 or A2 are enclosed by materials with a fire reaction class A1 or A2, preventing ignition and heat release. Within components of types D1

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and D2, combustible materials and components should not reach the flash point during the required fire resistance, with a default flash point of 180°C if not clearly determined [7].

The criteria for the use of a wooden structure in building construction requires that the sandwich style structure's voids be filled with a non-flammable substance. The material should be able to withstand a minimum temperature of 1000°C and should not collapse or settle out. An example of a fireproof element that meets the criteria of reaction to fire class A1 and A2 is fireproof plasterboard. The exterior wall surface treatment must also meet the requirements of reaction to fire class A1 or A2, which prohibits the use of flammable materials for insulation or cladding. If all the fire protection criteria are met, the building structure can be considered mixed type, allowing for the construction of residential wooden buildings with up to five floors, and non-production buildings with a fire height of up to 12 meters.

Examples of completed projects with using massive wooden structures

«Suurstoffi site»

According to [8], a complex of buildings called «Suurstoffi site» was erected in in the town of Risch-Rotkreuz, Switzerland, which were built using concrete and wooden structures to make a hybrid building. In this case, it is necessary to consider this project in more detail to study the specifics of using these structures together and how it was possible to implement this project. Consider how it was possible to create such a building and what materials, structures and engineering systems, in particular fire protection, were involved.

Figure 2 - The Suurstoffi development with the 60m high skyscraper Arbo
Source: [8]

The Suurstoffi site in Switzerland is an example of a large-scale sustainable project aimed at operating without CO_2 emissions. The buildings are equipped with photovoltaic or solar thermal systems and the energy network is designed for heat and cold exchange between the buildings. The use of local wood also helps reduce greenhouse gas emissions. The newest and the highest building on the site, Arbo, is the tallest wood-concrete hybrid building in Switzerland. All load-bearing elements in the building such as supports, joists, and ceiling panels are made of wood, making the building aesthetically impressive and comfortable for users in terms of building physics. Arbo was created with a focus on sustainability and the highest possible proportion of visible wood. The building is connected to two other buildings, also made of wood and concrete, via an underground car park. The interior of the building consists mainly of wood, which leads to a comfortable indoor climate.

How is the use of combustible material - wood - achieved in this project? The cornerstone for tall structures with visible wooden support was established with fire safety regulations. Switzerland has undergone significant changes in its fire safety guidelines in recent years, going from a limit of only two-story buildings 20 years ago, to allowing six-story structures in 2005, and having no height restrictions since 2015. Research conducted by ETH, Empa, and Swiss applied science universities, along with successful reference projects, have shown that fire-resistant buildings can be constructed using combustible materials, and have been acknowledged by relevant authorities[9,10]. The fire protection standard of 2015 even mandates the presence of a fire protection expert to ensure quality assurance in multi-story buildings. This professional is responsible for creating the fire safety plan, assisting specialists during the planning phase, and monitoring the implementation of fire safety measures. This provides clients with dependable advice, and aids in the decision-making process for innovative building plans, particularly in the new field of timber high-rise construction.

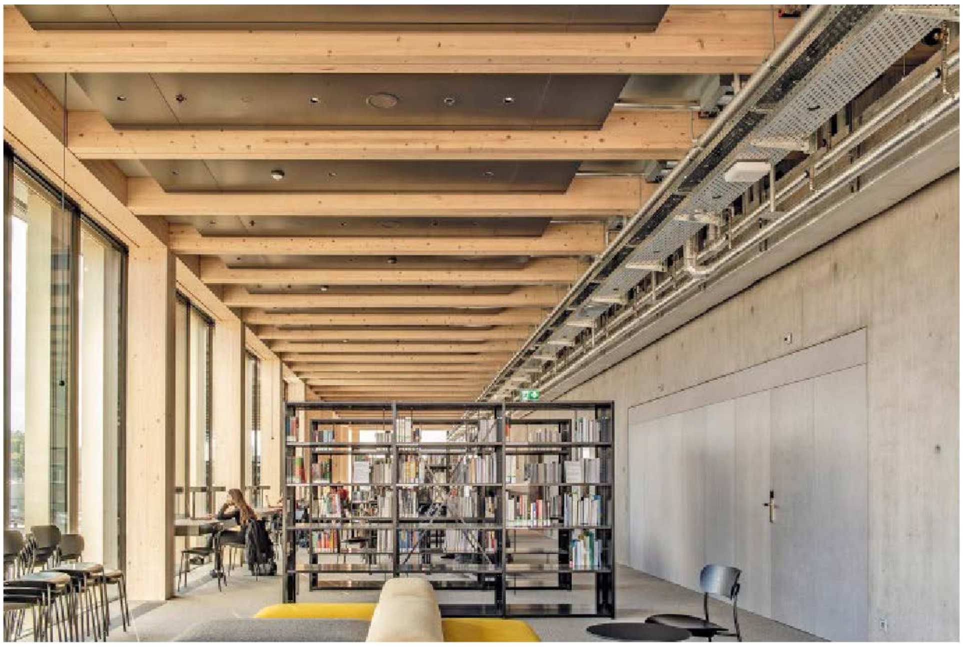

Figure 3 – Interior of Arbo
Source: [8]

The fire protection for a hybrid construction building is regulated and includes a safety stairwell, fire brigade lift, and an extinguishing system. The combustible components are cladded with gypsum fibers on all sides to meet fire-resistant requirements. The building is fully protected by the sprinkler system and the required fire resistance is reduced to 60 minutes. The linear load-bearing components, such as columns and beams, were left visible due to the technical fire protection measures and full sprinkler protection. The fire protection concept does not apply to wooden ceilings and the engineers planned to use concrete slabs and wooden beams to create a composite structure with good sound insulation and resistance to load. The ceiling elements were produced in a factory and the assembly time on site was reduced through prefabrication. The space between the ribs is reserved for building services installations. A cement screed with footfall sound insulation is installed on the ground floor up to the third floor.

Figure 4 - Installation of a 2.70 m x 6.65 m floor panel
Source: [8]

The interaction between wood and concrete in the building structure required a complex design for power transmission. Loads were transferred from the ceiling to the core either in a linear manner through overlay concrete (as planned) or through the permanent ribs of the wood-concrete composite ceiling. Gaps in the concrete wall were prevented for structural stability and earthquake protection. The different building materials had varying construction tolerances, with joints required at the interface for fire protection and stability. Brackets were concreted into the concrete walls to support the composite floor elements and screws transferred transverse forces from the wooden ribs to the overlay concrete. Reinforcement was added to prevent risk in the open joint between the ceiling and wall in case of fire. Steel parts were protected with encapsulation for 60 minutes of fire resistance. The connection detail is practically invisible as steel parts are either embedded in concrete or hidden under the layer of ribbed wood (Fig.5).

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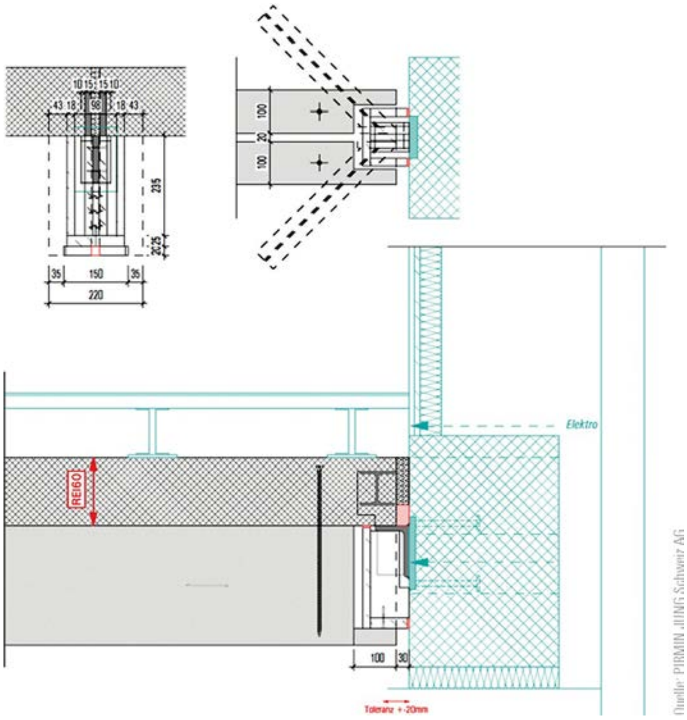

Figure 5 - The most critical point from a structural, fire protection and building physics point of view: the bearing of the floor panels to the concrete core wall
Source: [8]

The load-bearing elements of Arbo, including vertical and horizontal beams, ribs, and columns, are made of either spruce or beech laminated veneer lumber, with the most heavily loaded elements made of beech. The visible load-bearing elements were designed to have almost the same size across all floors, with optimized cross-sections to meet the required strength. The concrete in the core and the wood of the supports deform differently over time, so compensation measures were required. The Institute for Structural Analysis and Construction at ETH Zurich conducted research on the deformation behavior of the heavily loaded wooden columns in the building and found that the highest vertical deformations occur in the middle of the building height. The engineers corrected the assembly process by installing the ceilings 10-20 mm higher and developed a height-adjustable detail with threaded rods and nuts.
The use of additional fire protection measures and more adapted fire protection legislation in Switzerland with the use of modern wood materials made it possible to realize the «Suurstoffi site» building complex. These buildings are not the only ones in Switzerland itself, and far from being the first. But with the trend towards the implementation of this kind of projects, as well as the accumulated practical and experimental experience, it helped to draw the attention of the government to this problem and revise the regulatory framework regarding the use of combustible building materials in construction since 2015.

«Ascent MKE»
Another great example of a hybrid building is the building called "Ascent MKE" built in 2022 in Milwaukee, USA. It is a 25-storey residential building built using mass wood and monolithic concrete structures. From the first to the fifth floor, the building is made entirely of reinforced concrete structures. Such a measure was necessary to achieve a rigid building frame and spatial

rigidity. The mass timber residential floors are situated above five levels of concrete parking garage, which are reinforced by glue-laminated timber (glulam) beams and columns that hold the cross-laminated timber (CLT) floors using innovative connectors that are hidden in the wood itself. That allows protecting metal components from fire in case of fire. In addition, fire stairs and elevator shafts are made of reinforced concrete for fire safety and increase the spatial rigidity of the building, in total, the building has two spatial reinforced concrete cores for stability. Ascent MKE is currently the tallest mass timber building.

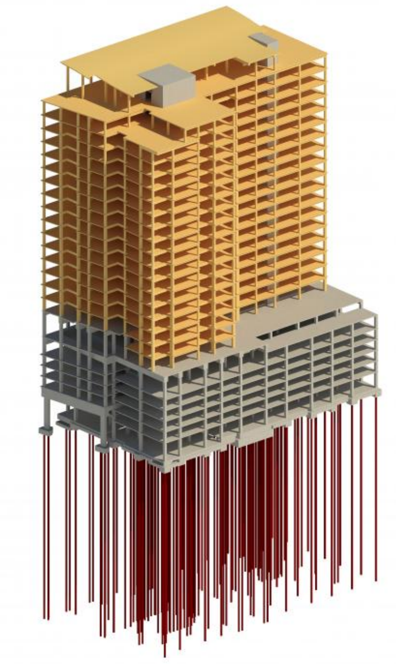


Figure 6 – Ascent MKE, on the left structural model – yellow denotes timber framing, with gray for concrete and red for steel
Source: [11]

The design showcases the mass timber construction, highlighting its natural features. Extensive fire testing confirmed that the timber members surpass the fire rating code standards. Loads from the timber residential floors are transferred to the concrete garage structure below through a system of post-tensioned concrete beams. The superstructure of Ascent MKE rests on concrete-filled steel pipe piles, which are the strongest piles built in Wisconsin till date, and this system reduces material usage and installation time, leading to substantial cost savings. Additionally, the use of sustainable mass timber helps the building to exceed the energy conservation code requirements set by Milwaukee[11].

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Figure 7 – Building Ascent MKE in the process of assembling structures
Source: [11]

To carry out this project, a team of developers and engineers did a lot of work to meet building codes in terms of fire safety. The main safety evacuation routes are additionally treated with refractory boards, which can resist fire for more than 90 minutes. Moreover, additional full-scale fire tests of CLT panels and Glulam beams were carried out, which also confirmed the compliance of these materials with the required standards. The building has a sprinkler fire extinguishing system. The reinforced concrete part of the building was made at the request of fire engineers. In addition, the building also meets the current requirements of the LEED Energy and Green Building certification and has a silver certificate (the 2 of 4 possible).

Figure 8 – Exterior and interior of the building Ascent MKE
Source: [11]

In this project, modern wood materials were used in combination with reinforced concrete cores of the building and, in addition, the foundation in the form of piles. Thus, a hybrid building was obtained, however, the bulk of it is made of massive wood. In this project, for its implementation, additional fire resistance tests of structures were performed, which in practice showed compliance with the required building codes in the field of fire safety in the United States. However, in this case, it should be noted that the funding for the testing was done with a government grant in order to encourage this kind of projects more often among developers.

Conclusion and prospects for the use of international experience in the Slovak Republic

In recent years, there has been a growing interest in mass wooden structures in Europe, leading to the creation of new regulations and changes in the legislative framework. European countries are recognizing the benefits of using wood as a construction material, such as sustainability, low carbon emissions, and renewable resources. In response to this growing trend, many European countries have revised their building codes and regulations to allow for the construction of taller wooden buildings. For example, countries like Sweden and Norway have been pioneers in this field, with their high-rise wooden buildings reaching up to 14 stories [12]. In general, the construction of high-rise wooden buildings has been gaining popularity globally due to the increased demand for sustainable and environmentally friendly construction methods. The use of wooden elements in the construction of high-rise buildings has been made possible with advances in fire protection standards and technology.

The examples discussed above of the use of modern building materials made of wood in the implementation of modern building projects can serve as a basis for a wider distribution of such projects, including the implementation of similar projects in the Slovak Republic. The reviewed project «Suurstoffi site» in Switzerland provides confirmation of how this topic should be further developed in the modern scientific community. After all, it was on the example of Switzerland, taking into account the accumulated practical and theoretical studies, that the improvement of the regulatory framework in fire safety was achieved, which in the future allows the use of mass wood more widely and in a much larger number of future projects. Since earlier, many developers did not want to deal with this due to difficulties with the regulatory framework. However, now this trend is gradually changing for the better.

In the same way, it is possible to promote this idea in Slovak Republic. Slovakia is rich in timber and the use of timber is very important in this country. This will help reduce shipping costs. However, it is worth modifying the regulatory framework and probably trying to implement some real full-scale projects. Which at first can also be made hybrid using reinforced concrete and wooden structures, such as solid wood, but in the future, theoretically, it is possible to use wood as the predominant and main building material in the building.

Overall, the prospects for the construction of high-rise wooden buildings in Europe are very positive, with the changing legislative framework and supportive policies. The use of sustainable and renewable materials such as wood is becoming increasingly popular and widely accepted, leading to the development of new and innovative designs and construction methods.

Further directions of research

It is necessary to study the environmental aspects of this construction in more detail. Highlight the main disadvantages and advantages in terms of environmental friendliness of the construction of hybrid buildings and buildings consisting of wood only, and compare them with indicators for buildings made of reinforced concrete. Explore the possibility of constructing buildings consisting entirely of timber structures.

Very important for any developer is the cost of using these materials in construction, which in the future affects the cost of real estate for the consumer, which in turn is also important. Thus, it is also interesting to compare the cost characteristics and labor input required for the implementation of projects using CLT panels and glulam beams and other mass wood representatives with traditional building materials.

In addition, it is also necessary to consider each new project from the point of view of energy efficiency and environmental friendliness. In addition, an interesting area for research seems to be the comparison of energy costs throughout the life cycle of a building made of modern wood building materials and traditional building materials.

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