

Article

Selected Aspects of Sustainable Construction—Contemporary Opportunities for the Use of Timber in High and High-Rise Buildings

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Abstract: Due to the favourable pro-environmental properties of timber, including the origin of the raw material from renewable sources, ease of reuse, negative carbon footprint, low specific weight, possibility of prefabrication, etc., there is increasing interest in the use of timber in construction. This paper takes a closer look at the new uses of timber as a load-bearing structure for high and high-rise buildings. Cases described in the literature concerning this type of building with residential and public functions erected worldwide were analysed. The first buildings of this type were put into use in 2009. The aim of this paper is to show new possibilities and to extend the use of timber as a load-bearing structure of high and high-rise buildings previously made of reinforced concrete or steel. The scope of the analysis includes two postulates of sustainable construction, directly related to the above-mentioned goals: limiting interference in the natural areas of cities through efficient use of building plots for high or high-rise buildings and the use of renewable materials—timber—for the load-bearing structure of buildings. A research method based on a case study was used. Conclusions were made on the pro-environmental spatial–functional and material–structural design of these high and high-rise buildings.

Keywords: sustainable construction; high-rise buildings; timber construction; prefabrication; material and construction solutions; spatial–functional solutions



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1. Introduction

1.1. Background

Vitruvius defined architecture as having durability, utility, and beauty. Nowadays, architectural works are designed taking into account a much broader range of additional criteria: social, environmental (ecological), and economic, aimed at a sustainable approach to building development [1]. Analyses and studies are being carried out to reduce the negative environmental impact of buildings over their entire life cycle (Life Cycle Assessment) [2], including reductions in the consumption of natural resources, energy, and emissions of harmful environmental pollutants. These analyses cover all stages of the investment process, from the conception and design of the investment to the production of the building elements and erection of the building, its use with ongoing repairs, dismantling, reuse, or disposal. In addition, environmental impact studies cover the period from the acquisition of the materials taken into account in the design concept, their transport, the manufacture of the construction products, and their subsequent delivery to the construction site, etc., i.e., according to the holistic “cradle to grave” idea (cradle to grave) [1].

Due to increasing amounts of construction waste, initiatives leading to rational waste management are being implemented, including [3] 3R, or reduce–reuse–recycle. This concept includes activities aimed at the following [4]:

- “Reduce”—reduce the consumption of building materials, natural resources, and energy required to construct a building.

- “Reuse”—the reuse of construction materials or pieces of fittings, etc.
- “Recycle”—processing waste materials and reusing them.
- The 3Rs concept has evolved over time to the 5Rs, encompassing further additional pro-environmental measures [5,6], i.e.;
- “Refuse”—refusing to accept goods in single-use packaging and promoting the use of reusable packaging.
- “Repurpose”—repurposing waste materials, also called upcycling.

A continuation of this approach is the idea, which refers to the laws of nature, of a so-called closed production cycle, in which recycled materials and raw materials are again taken into account to produce the next building, so-called “cradle to cradle” (cradle to cradle) [1].

On 25 September 2015, the United Nations General Assembly adopted the resolution “Transforming our world: The 2030 Agenda for Sustainable Development”, capturing the plan of action for people, the planet, and well-being—represented by the defined 17 overarching Sustainable Development Goals (SDGs) and 169 related targets [7].

In architecture and construction, the fundamental areas of sustainability include, among others [1]:

- Energy and water demand in all phases of a building’s life.
- Materials used in construction, finishing and furnishing, repairs, and renovations.
- The overall management of waste (including construction waste), its storage, treatment, separation, etc.
- The environmental impact of construction works, including biologically active areas.
- Transport related to the investment process of constructing a building and transport related to meeting the needs of building users.
- Costs relating to the entire life cycle of the building, including the investment process, operation, environmental, and economic costs.

The sustainable building design process is synthetically formulated as the 9Rs [1], or reduce, reuse, recycle, renew, report, regenerate, rethink, respect, and regulate. It takes into account in particular the following: reducing the use of natural resources; seeking to recover and reuse elements of a building or its fittings; renewing and regenerating previously used elements; “respecting” natural goods; and resources and being prudent in their use, respecting current binding legislation.

Sustainable construction issues are the subject of many scientific publications, including, among others, [8,9]. A case study of the environmental impact of investment projects is characterised, among others, in [10,11]. Most attention has been paid to the energy efficiency of buildings relating to their use phases and over the entire life cycle of buildings [12–14], as well as the energy performance of buildings with different material and functional solutions [15,16]. The issues related to sustainable energy systems are presented in [17,18], and they concern the reduction of the “embedded carbon footprint” relating to the building materials of fitting components and the load-bearing structure of buildings, among others [19–22].

The life cycle of building materials comprises three significant phases, as follows [2]:

- The first relates to the sourcing/extraction of raw materials, transport to the production facility, manufacture of the building material, and incorporation into the building. During this phase, there are many factors that have a negative impact on the environment, i.e., depletion of natural resources, land use due to the construction of a new building, use of industrial infrastructure, generation of waste, emissions from transport, machinery, and equipment, consumption of the so-called “embedded energy”, etc.
- The second relates to the operation and construction work (identical to phase one) associated with ongoing maintenance, repairs, possible alterations in construction, extensions, superstructures, etc., and the consumption of operational energy for heat-

ing, ventilation, air conditioning, lighting, electricity to power other appliances and equipment, etc. [14].

- The third phase is final disposal, i.e., demolition, recycling, and disposal. During this phase, there are factors adversely affecting the environment due to dust and gas emissions, the consumption of so-called processing energy related to transport, the operation of construction machinery and equipment, waste treatment, and management. During this phase, it is important to try to recover the materials used in a building and recycle, reuse, or change their function and reuse them [2,9,15].

Due to the favourable environmental properties of wood, such as the renewable nature of the raw material's origin, ease of reuse (recycling) in whole or in part, negative carbon footprint due to CO₂ absorption during tree growth, low specific weight (compared to other construction materials such as steel and concrete) and consequently cheaper transport, easy and quick assembly of components, the possibility of prefabrication, etc., there is a growing interest in the use of wood as a load-bearing construction material for housing. In such cases, the reduction of negative environmental impacts, with reasonable preparation of the investment process and implementation of sustainable construction principles, can concern all phases of the life cycle of building materials and erected structures [2,9,15].

It is worth mentioning that after 2000, timber began to be implemented as a load-bearing structure material in high, high-rise, and public buildings. So far, this type of construction has typically used steel or concrete structures, i.e., concrete, reinforced concrete, and pre-stressed concrete. The greatest achievements in this regard are in countries with a strong tradition of timber construction, a developed timber industry, and the availability of raw materials thanks to sustainable forest management, most notably in Sweden and Canada. Glued laminated timber (GLT) or cross-laminated timber (CLT) load-bearing systems are most commonly used for high and high-rise buildings or structures with large element spans.

1.2. Goals and Scope

The aim of this article is to provide an overview of the latest developments in the environmental aspects of sustainable construction and, in particular, new opportunities for the use of timber in the design and construction of high and high-rise buildings, i.e., pro-environmental construction to effectively meet the housing needs of society while reducing urban "sprawl" and land take.

The basis for the analyses included in the scope of this article are two selected aspects and, at the same time, postulates of sustainable construction [23], i.e.:

- Limiting interference with natural urban areas—through efficient use of the building plot for high or high-rise buildings;
- the use of renewable, recyclable materials for constructing the load-bearing structure of buildings—timber meets this requirement.

Due to the thematic scope of the article, the postulates of pro-environmental construction regarding energy sources, infrastructure and technical installations, recycling systems, and water management were not analysed.

High buildings are defined in [24] as those more than 25 m up to 55 m (inclusive) above ground level, residential buildings more than 9 to 18 storeys (inclusive) above ground level, and high-rise buildings as more than 55 m above ground level.

2. Materials and Methods

A research method based on a case study was used. The analysis covered high and high-rise buildings completed after 2000 whose structural system of the above-ground part is made of wood.

Literature analyses and research were carried out covering the subject of the article, including monographs and scientific publications, internet sources, etc.

The analysis covered, chronologically, high and high-rise buildings whose predominant function is residential and public buildings completed or in the final stages of the investment process.

2.1. *The Complex of Four Linnologen Residential Buildings in Vaxjo*

The complex of four Linnologen residential buildings in Vaxjo in Sweden was built between 2008 and 2009.

2.1.1. Spatial and Functional Solution

The buildings above ground are each 8 storeys high, with a height of 27 m measured from the ground surface. Overground storeys 2 to 7 have identical spatial solutions and dimensions in plan. The total floor area is 10,700 m². The complex houses 134 residential units, 33 or 34 in each building, with varying areas ranging from 37 to 114 m². The largest share is made of apartments with relatively small floor areas, and in particular, 6 one-room flats with kitchens, 40 two-room flats with kitchens, 44 three-room flats with kitchens, 28 four-room flats with kitchens, and 16 two-storey flats with three–five rooms and kitchens. Most of the dwellings are equipped with partially covered loggias and balconies.

The building's exterior finish and decoration consist of timber panels in the area of the southern elevations, the lower surfaces of the balcony slabs, partly in the internal vertical communication structures and the residential units, plaster in the area of the remaining elevations, and plasterboard on the internal walls [25,26].

2.1.2. Material and Construction Solution

Due to the complex soil and water conditions, intermediate pile foundations were used. The buildings' first storey above ground is made of reinforced concrete post-and-slab or post-and-beam. From the second to the eighth storey above ground, the load-bearing system is either wall-based with CLT cross-laminated timber surface elements (using Martinsons' system solutions) for structural walls and ceiling slabs or locally in the form of GLT (glued laminated timber) post-and-beam frame construction. The timber structure of the buildings was assembled from 30 different prefabricated elements, viz., 3-layer thick CLT ceiling slabs typically 2400 mm wide and 73 mm thick, supported on T-section GLT timber beams [26]. T-beams have webs with cross-sectional dimensions of 42 × 220 mm and a top flange of 56 × 180 mm [26]. The structural system is provided with spatial rigidity through a system of 48 vertical post-tensioned steel tendons anchored in the reinforced concrete structure of the first storey and "pinning" the full height of the structure within the load-bearing walls. The prefabricated timber elements were protected from the weather during transport and unloading with foils and tarpaulins, and during the assembly of the structure with a specially shaped steel temporary structure with a textile cover. The timber structure was assembled by a team of 10 workers using crane equipment (with a lifting capacity of 3.3 t) and approximately 10 working days were needed to erect one storey [25,26].

2.2. *A Complex of Two Residential Buildings in Portvakten Söder*

A complex of two residential buildings, with 8 overground storeys and a height of 27 m above the ground in Portvakten Söder in Sweden, was built in 2009 using passive house technology (according to Swedish requirements) [16].

2.2.1. Spatial and Functional Solution

The buildings have the same spatial and functional solutions. A total of 64 residential units have been designed in both buildings, including 18 two-room flats with kitchens, 30 three-room flats with kitchens, and 16 four-room flats with kitchens. Some units have been fitted with balconies.

2.2.2. Material and Construction Solution

The foundation of each building is directly on a reinforced concrete foundation slab. The first above-ground storey was designed as reinforced concrete with Martinsons system solutions above (similar to the Limnologen buildings), which are formed by CLT timber surface elements for walls and ceilings. The prefabrication plant fabricated the elements, including the external cladding, i.e., wall panels with internal plasterboard cladding and façade cladding, ceiling panels with plasterboard ceiling cladding. The increased degree of prefabrication and finishing of the building's elements accelerated the assembly of the above-ground part performed by 4 construction workers using lifting equipment over a period of 11 months [25].

2.3. *Stadthaus Building in London*

The Stadthaus building was erected in London in 2009 as a residential building with nine overground storeys and a height of 30 m above ground level [27].

2.3.1. Spatial and Functional Solution

The architectural concept of the building drew on a honeycomb construction, in which the residential units were located around a central core—the vertical communication structure. Each of the residential units has a loggia. The body of the building has the form of a cuboid. The facades were clad with cladding made from 70% recycled wood. The cladding panels are white, grey, and black and reflect on the façade a pixelated drawing of the shadows of the trees and surrounding buildings “painted by light” [28].

2.3.2. Material and Construction Solution

The building structure is fully made of CLT timber surface elements, i.e., load-bearing walls, ceilings, communication, and lift structure walls. The CLT surface elements were manufactured in Austria, according to the KLH system. The prefabricated wall panels had been fitted with window and door joinery and had penetrations for installation cables.

The structure was integrated using steel bolts and reinforced locally with steel angle sections—bevels. The timber structure was assembled using a crane in a relatively short time of nine weeks. The total time to erect the building was 49 weeks, which, according to [28], was a time saving of 5 months compared to traditional reinforced concrete frame construction solutions. The stated aspect of limiting the time of nuisance associated with the construction of new buildings in compact urban fabric, as well as the use of “dry” construction technologies and no dust emissions, were additional advantages of the material and construction solution used.

2.4. *Building B of the Building Complex Strandparken in Sundbyberg*

Building B of the building complex Strandparken was erected in Sundbyberg in the northern part of Stockholm in 2014 [10,25]. The building has one underground storey, eight above-ground storeys, and a height of 27 m above ground level.

2.4.1. Spatial and Functional Solution

It has been designed with 31 residential units, including one-bedroom units with kitchens, two-bedroom units with kitchens, three-bedroom units with kitchens, and three two-storey flats on the top two floors. Some of the apartments have balconies. The facades and roof were clad in cedar wood shingles. The shingle cladding within the first-floor elevation and the roof have been fireproofed. The building has a sprinkler system [25].

2.4.2. Material and Construction Solution

The foundations and structure of the underground part were made of prefabricated reinforced concrete, while the above-ground part was made of CLT timber according to the Martinsons system. There is a wall load-bearing structure.

The structural external walls are 120 mm thick, the structural internal walls are 170 mm thick, the walls of the vertical communication structures and lift shafts are 120 mm thick, and the ceiling slab structure is 70 to 170 mm, thick depending on the span.

2.5. Building “Wood Innovation Design Centre” in Prince George

The office and education building “Wood Innovation Design Centre” was erected in 2014 in Prince George, British Columbia, Canada. The building is located on the university campus, and it has 8 floors above ground (including a ground-floor mezzanine and a penthouse on the roof) and a height of 29.5 m above ground level [29].

2.5.1. Spatial and Functional Solution

The lower floors 1–5 house lecture theatres with 75 seats, laboratories and teaching rooms, and the university’s staff rooms for lecturers in which the Master of Engineering in Integrated Wood Design program is run, while the three upper floors are used for rent as office space for organisations and companies related to the wood industry. The façades were shaped as curtain walls with triple-glazed glazing and laminated veneer lumber (LVL) mullions [29]. The surfaces of the ceilings and interior walls have been coated with a clear varnish, exposing the natural aesthetics of the wood.

2.5.2. Material and Construction Solution

The building is founded on a 400 mm thick reinforced concrete ribbed foundation slab and 600 mm thick ribs. The structure is a post-and-beam frame shaped from GLT-glued laminated timber joined using aluminium profiles and steel anchors specially developed for this system. The ceilings, internal walls, walls of the vertical communication structures and lift shafts, and stair run panels were made of surface elements, i.e., panels of 3-, 5-, and 7-layer CLT. The timber was sourced from sustainably grown, local spruce pine plantations. The building was erected (including foundations) between August 2013 and October 2014, that is, within 15 months [29–31].

2.6. Residential Complex in the Vallen District of the Town of Vaxjo

A residential complex in the Vallen district of the town of Vaxjo was implemented in the period 2015–2018. The number of above-ground storeys in these buildings varies from 7 to 9, with the highest being 31 m high.

2.6.1. Spatial and Functional Solution

A complex with 172 residential units and a total floor area of 8016 m² [32].

The building blocks are integrated into a naturally attractive space and open out over the lake. All units have balconies, and nine of them additionally have green terraces located on the roofs [32].

2.6.2. Material and Construction Solution

The structure was designed with CLT prefabricated surface elements and GLT laminated timber bar elements. The two 9-storey-high buildings have similar architectural and structural solutions. The 2 lower storeys are reinforced concrete, with a further 7 above using a timber system building (Trä8-system by Moelven Töreboda). This is the GLT laminated timber space frame system. The frame rafters have spans of 5.7–8.0 m. The internal wall surfaces and ceilings have gypsum board cladding. The buildings have vertical communication structures and lift shafts of reinforced concrete. To ensure the spatial rigidity of the buildings, the structure of the inter-storey ceilings is anchored in the reinforced concrete walls of the lift shafts.

2.7. Brock Commons Dormitory in Vancouver

Brock Commons dormitory of the University of British Columbia (UBC) has been erected in Vancouver, Canada, in 2017 as an 18-storey building (without underground floor) with a height of 53 m above ground level.

2.7.1. Spatial and Functional Solution

The building houses 33 four-bedroom flats and 270 studio units for a total of 404 students, as well as social areas and, on the top floor, a student–community collaboration space [33,34]. The body of the building is cuboidal, and the interior is structurally and functionally shaped as a three-tier structure. The interior decoration consists of plasterboard wall cladding and concrete cladding [34]. The façades were made in a prefabrication plant in the form of CLT timber panel walls and fitted with window joinery [35].

2.7.2. Material and Construction Solution

The foundations and ground floor structure were constructed with reinforced concrete. The load-bearing structure from the second-storey level onwards consists of a timber post-and-slab structure and stiffening monolithic reinforced concrete vertical communication structures. The prefabricated ceiling slabs were made of 5-layer panels (166 mm thick) of CLT timber, while the posts were made of storey-height elements of GLT fused via steel joints [24]. The cross-section of the posts is square, with a side length of 260 mm.

The timber structure was assembled by a team of 4 workers in 8 weeks, and the total time to erect the building structure was 9.5 weeks [34–36].

2.8. Dalston Works Compact Residential Complex in Hackney in London

The Dalston Works compact residential complex in Hackney, London, erected between January 2015 and June 2017, forms a complex of contiguous rectangular building blocks with varying heights from 5 to 10 storeys above ground [37]. The highest building blocks have one underground storey, and the lower ones are without underground storeys.

2.8.1. Spatial and Functional Solution

In plan, the development has an irregular shape with an enclosed inner courtyard and an open outer courtyard similar to traditional quarters of compact residential development. The residential floor area of 121 residential units amounts to 8500 m², and the space dedicated to commercial services amounts to 2300 m² [37]. The four constituent blocks of this development complex and their orientation in relation to the world's directions were shaped with a view to providing natural light in the inner courtyard and the residential units. The scale, façade design, and architectural detailing constitute curtain walls with a masonry façade layer reminiscent of traditional material solutions characteristic of the Victorian and Edwardian periods [37–39].

2.8.2. Material and Construction Solution

All building blocks are founded directly on reinforced concrete foundation slabs. The structure of the first above-ground storey, including the ceiling above the ground floor level, was constructed as a reinforced concrete frame. The load-bearing structure of the above-ground section (above ground floor level) is made entirely of cross-laminated timber CLT with wall elements (internal and external walls and vertical communication structures) and ceiling elements (ceiling panels and stairs run panels) [38].

2.9. The Carbon 12 Building in Portland

The Carbon 12 building in Portland, USA, was commissioned in 2018. It has eight storeys above ground, one underground, and a height of 26.0 m above ground level.

2.9.1. Spatial and Functional Solution

On the ground floor of the building, premises with a commercial function are located, with residential units on the remaining floors. Each floor has two flats with loggias, separate lift entrances, and access to an automated car park with a capacity of 22 cars in the underground section of this building [40]. The north and south elevations are glazed, while the east and west elevations are designed to be 'green': planted with vegetation and equipped with an irrigation system. The residents of the building showed their satisfaction with living in Carbon12, complementing its aesthetic qualities: the bright colours of the façade and, in the interior, the prominence of natural materials, i.e., wood, which has a beneficial effect on human well-being. The benefits of lower utility and commuting costs have also been noted [40].

2.9.2. Material and Construction Solution

The foundation of the building is a reinforced concrete slab, and the structure of the underground storey is a reinforced concrete frame. The load-bearing system of the above-ground part is post-and-beam framing made of GLT glulam, while the ceiling slabs and walls are made of CLT cross-laminated timber. The beam and post connections to the GLT were steel. The components of the structure were made of wood from certified sustainable tree plantations. The installation of the timber structure averaged 5 days per storey [40,41].

2.10. "Perspective" Office Building in Bordeaux

The "Perspective" office building was completed in 2018 in Bordeaux, France. The building has 7 floors above ground and a height of 31 m above ground level. It is one of the first realisations of timber-framed high buildings in France. It advertises the local timber industry and the use of the region's wood resources as a renewable construction material. It has a projected area of 4438 m² [42].

2.10.1. Spatial and Functional Solution

The building consists of two basic blocks forming a quadrilateral plan. Each of the blocks is of varying heights, i.e., 7 storeys above ground in the central section and 4 in the remainder. The central part of the interior features an atrium with a monumental timber-framed staircase. The materials of construction, wood and concrete, are on display in the interior. The façades were assembled from 3-storey-high prefabricated modules [43].

2.10.2. Material and Construction Solution

The construction of the foundations and vertical communication structures is monolithic reinforced concrete. Above ground level, the load-bearing system is made of GLT laminated timber as post-and-beam. The ceiling structure consists of CLT cross-laminated timber panels supported on GLT beams [43,44].

2.11. The Complex of Buildings Puukuokka One, Two, and Three in Jyväskylä

The complex of three residential apartment buildings, Puukuokka One, Two, and Three, was commissioned in 2015, 2017, and 2018, respectively, in Jyväskylä, Finland [45]. The Puukuokka One building has 8 floors above ground, a floor area of 5334 m² (Figure 1), and 58 residential flats. Puukuokka Two is a building with 7 floors above ground, and a floor area of 4796 m², and it houses 70 residential flats. Puukuokka Three has 6 floors above ground, a floor area of 3695 m², and it contains 58 residential flats [45].



Figure 1. The Puukuokka One building (Author: Tiia Monto; [46]).

2.11.1. Spatial and Functional Solution

Each building has a similar plan, shape, and body but different heights. All buildings have been built on a common underground storey functionally dedicated to passenger car parking spaces. Among the main advantages of the adopted modular solution were easy assembly, repairs required during use, simple disassembly, and possible reuse in other locations. The material of construction and the predominant finishing element is wood, which is positively perceived by users as giving a feeling of cosiness, warmth, and closeness to nature [45,47,48].

2.11.2. Material and Construction Solution

The structure of the foundations and underground storeys was made of reinforced monolithic concrete, while the above-ground storeys have a prefabricated CLT timber structure formed from spatial modules. The walls and ceilings of these modules are constructed from CLT surface elements. Each of the apartments is made up of two types of modules: one containing a living room, balcony, and bedroom, and the other containing a bathroom, kitchen, and hallway. The first building was constructed from 116 spatial modules, the second from 91, and the third from 71 such modules. The prefabricated space modules were characterised by a high standard of finish and workmanship. The modules were fitted with window and door joinery, insulation, installations, and layers of wall and ceiling finishes. It took approximately six months to assemble the structure of each building [48].

2.12. *Arbo Office Building in Lucerne*

The Arbo office building was erected in Lucerne, Switzerland, in 2019, with 15 storeys above ground, 2 below ground, and a height of 60 m above ground level [49].

2.12.1. Spatial and Functional Solution

In plan, the building has a roughly rectangular shape, with dimensions of 40.9×18.9 m [49]. In the interior, the timber of the load-bearing structure and the concrete surfaces of the walls of the vertical communication structures are exposed. The façade surfaces are dominated by glazing.

2.12.2. Material and Construction Solution

The structure of the two-storey underground section is monolithic reinforced concrete. The above-ground part is post-and-beam framed. It consists of GLT and LVL laminated veneer lumber posts and prefabricated timber–concrete composite TCC ceilings supported on timber beams. The posts have different material solutions and cross-sectional dimensions depending on the loads to be carried and thus the location within the building plan and the height of the building; these include hybrid posts with LVL core of beech wood with cross-sectional dimensions of 320×360 mm (for storeys 1 to 4) and 320×340 mm (for

storeys 5 to 8), with 20 mm thick GLT cladding or GLT wood posts with cross-sectional dimensions of 360×400 mm and 360×380 mm, respectively. The ceiling beams have a height of 280 mm, and the prefabricated TCC ceiling slabs have a thickness of 160 mm [49].

In order to ensure the spatial rigidity of the building and to transfer horizontal loads, the vertical communication structures located in the central part of the building plan have been designed as monolithic reinforced concrete.

2.13. Mjøstårnet Building in Brumunddal

The Mjøstårnet building (Figure 2), commissioned in 2019 in the city of Brumunddal (140 km from Oslo) in Norway, was built with 18 overground storeys and a height of 85.4 m measured from the ground level [50,51].



Figure 2. The Mjøstårnet building (Author: Øyvind Holmstad; [52]).

2.13.1. Spatial and Functional Solution

The building is situated in a beautiful, forested landscape by Lake Mjøsa, hence its name, which is a translation from Norwegian: Mjøsa Lake Tower. This region of Norway is renowned for its well-developed timber industry and wood processing, which had a significant influence on the choice of the building's material solution: timber from local sustainable forest resources, but also the promotion of eco-friendly construction.

The building is rectangular in plan, measuring 37.5×17 m, with a total floor area of 10.500 m^2 . In terms of functionality, it is divided in height into four sections: the first, comprising floors 1 and 2, houses the conference room, banquet hall, and restaurants; the second, with floors 3 to 7, contains office space; the third, with floors 8 to 11, contains hotel rooms; and the fourth, with floors 12 to 18, contains residential flats and a conference room, as well as a partially public and partially private terrace located on the roof [51].

2.13.2. Material and Construction Solution

The load-bearing structure is a three-tier, mullion, and transom frame formed from GLT timber. The walls of the vertical communication structure, i.e., the staircase and lift shaft and the balcony slab were made of CLT or xlam timber panels.

The corner posts carrying the heaviest loads have a rectangular cross-section of 1485×625 mm, while the internal cross-sections are 725×819 mm and 625×630 mm.

The inter-storey ceilings are of varying construction. In order to stiffen the building and ensure adequate acoustic insulation parameters, the ceilings of the last seven storeys, i.e., from 12–18, are made as reinforced concrete slabs supported on GLT timber beams with cross-sectional dimensions of 625×585 mm and 625×720 mm.

The ceilings of 2–11 have a prefabricated timber construction with CLT panels, according to Trä8 system solutions, based on 395×585 mm and 395×675 mm GLT timber beams.

The façade elements were prefabricated with layers of insulation and cladding. The building was completed between September 2017 and March 2019 [51].

2.14. The HoHo Building in Vienna

The HoHo building was commissioned in Vienna in 2019 (Figure 3). It has 24 storeys above ground and a height of 84 m above ground level [53].



Figure 3. The HoHo building (Author: Alexander Migl; [54]).

2.14.1. Spatial and Functional Solution

The building's 25,000 m² of floor space includes residential flats, hotel rooms, restaurants, beauty parlours, a fitness centre, a spa, office space, and conference rooms [53,55]. The body of the building consists of three adjacent cuboids of varying heights, with 24, 15, and 10 storeys above ground. Functionally, the lower storeys up to level 3 are dedicated to lobbies, fitness, spa, and beauty parlours; storeys 4 to 9 contain office space; further storeys 10 to 17 contain hotel rooms; storeys 18 to 22 contain residential flats; and the top storeys have the function of technical rooms. In the interior, wood as a material of construction is on display, which is perceived as having a positive impact on the well-being of users [56].

2.14.2. Material and Construction Solution

The load-bearing structure is prefabricated timber with GLT, post-and-beam, with a reinforced concrete vertical communication structure located in the central part of the building plan, which, together with the system of perimeter beams (located along the outer contour of the building plan at the levels of the inter-storey ceilings), ensures the spatial rigidity of the building. The ceiling structure is based on GLT timber beams with cross-sections ranging from 400 × 400 mm to 400 × 1240 mm [55]. Prefabricated ceiling panels are positioned on these beams. They are of composite timber–concrete construction, with timber panels made of CLT. Exterior walls made of surface elements—xlam panels, together with window and door joinery—were fabricated with cladding at the prefabrication plant [53,55,56].

2.15. Sara Kulturhus Center Buildings in Skellefteå

Sara Kulturhus Center is a complex of public buildings commissioned in 2021 in Skellefteå, Sweden. It consists of a basic rectangular block of a 20-storey hotel with a height

of 80 m above ground level. Adjacent to this block are further cuboid buildings of smaller, varying heights up to 7 storeys.

2.15.1. Spatial and Functional Solution

The centrally located building block houses a hotel with 205 rooms from floor levels 7 to 20, while the lower part, together with adjacent smaller blocks, houses public buildings, i.e., 6 theatre halls, a museum, 2 art galleries, a public library, a conference centre, restaurants, a sky bar, and a spa [57].

2.15.2. Material and Construction Solution

The structure of the above-ground part of the building was designed using timber harvested from the regional boreal forest. In the hotel part, it was made of prefabricated spatial modules from CLT. The erection technology was divided into two main stages, i.e., in the first stage, two vertical communication structures and lift shafts were erected to the total height of the building, located along the extreme sides of its rectangular body, from surface CLT elements, and in the second stage, the assembly of spatial modules with dimensions corresponding to hotel rooms was carried out with the use of cranes in the space between these vertical structures [57].

The adjacent lower building blocks have a load-bearing system of GLT ceiling beam and post elements and CLT surface element curtain walling. In the case of long-span ceilings, such as theatre halls, etc., the load-bearing structure of these ceilings was trussed. The bars of these trusses carrying compressive forces are shaped from GLT timber, and the tension bars are made from steel [57,58].

2.16. *Haut Residential Building in Amsterdam*

The Haut residential building with 21 overground floors (73 m high above ground level) was erected in Amsterdam in 2021 [59] (Figure 4).



Figure 4. Haut residential building (Author: Tim Bindels; [60]).

2.16.1. Spatial and Functional Solution

The building is located in an attractive area of Amsterdam's suburbs along the Amstel River. The design of the building body and glazed elevations was based on the concept of opening up the view of the surrounding landscape and the city silhouette and providing natural daylight to the interior. In the interior decoration, wood is exposed on the surfaces of the ceilings and façades (excluding glazing) [59].

2.16.2. Material and Construction Solution

Due to the existing soil and water conditions, the foundation of the building is based on diaphragm walls located along the projection contour of the underground section and Tubex-type displacement piles. The structure of the underground part and the two lower floors above ground, as well as the vertical communication structure over the entire height of the building, is reinforced monolithic concrete. Above, the load-bearing system is wall-based, with walls made of CLT panels and ceilings made of TCC prefabricated concrete–wood hybrid panels. The TCC panels consist of an 80 mm thick concrete layer cooperating with a 160 mm thick 5-layer CLT panel [59].

2.17. Tallwood 1 Building in Langford

The Tallwood 1 building with twelve storeys above ground and a two-storey underground section with a garage function was built in Langford, British Columbia, Canada, and was scheduled for completion in 2022 [61]. It has a height of 41 m above ground level [62].

2.17.1. Spatial and Functional Solution

The building has a first-storey with retail units and eleven-storey with residential units for rent with varying floor areas and spatial solutions. The building is located in the city centre with efficient transport infrastructure [63]. The total area of the building is 18,300 m², and the area of a typical floor is 1175 m² [62].

2.17.2. Material and Construction Solution

The structure of the two-storey underground and ground floor is monolithic reinforced concrete post-and-slab. Above, the structure is a steel–wood hybrid [61]. The choice of a steel structure cooperating in the load transfer with a GLT and CLT glulam structure was based primarily on ensuring the resistance of the load-bearing structure to the loads resulting from, among other things, the high seismic activity of the Langford area, as well as ensuring the required short construction time possible with materials of similar manufacturing tolerances of the elements (prefabricated CLT with GLT and steel sections). The steel structure and rigid welded frames of I sections provide spatial rigidity to the building and resistance to horizontal and seismic loads. The timber frame post-and-slab construction consists of posts usually located in a 2.95 × 3.60 m grid [62]. The construction of the GLT timber posts, joined with steel joints, had cross-sectional dimensions of 263 × 266 mm on the upper floors and 314 × 304 mm on the lower floors [61]. Locally, additional GLT beams were introduced into the ceiling construction in the spaces of the larger spans (penthouses). Typical ceiling slabs were made of 5-layer CLT panels with a thickness of 175 mm [62].

2.18. The Ascent MKE in Milwaukee

The Ascent MKE building was commissioned in 2022 in Milwaukee, USA, as a residential apartment building with a height of 86.6 m above ground level and 25 floors above ground [64].

2.18.1. Spatial and Functional Solution

The building's retail, leisure, lobby, and parking facilities with 260 parking spaces are located in levels 1–5 above ground; a swimming pool is located on the sixth floor; 259 luxury residential flats are located within floors 7–24; and social spaces are located on the top 25 floors [64].

Internal wall and ceiling surfaces usually have no additional cladding, and the timber of the supporting system is exposed. The elevations are glazed [65].

2.18.2. Material and Construction Solution

The foundation of the building is indirectly on a foundation pile system. The structure of the six lower floors is a monolithic reinforced concrete frame with pre-stressed

concrete ceilings. The vertical communication structure and lift shaft are also of monolithic reinforced concrete construction. From storey 7 onwards, the structure is timber post-and-beam made of GLT laminated timber, and the ceiling slabs are prefabricated panels of CLT cross-laminated timber [64,65].

2.19. The T3 Bayside East Building in Toronto

The T3 Bayside East building was erected in Toronto, Canada, in 2023, with ten storeys above ground and one underground storey. It has a height of 42 m above ground level [66]. The construction of a second twin in terms of architectural and structural solutions in the immediate vicinity was also started in 2023.

2.19.1. Spatial and Functional Solution

The building contains office space in the above-ground part, car parking spaces, and technical and storage rooms on the underground level. Internal spaces have been designed to be open, with the possibility of modification and adaptation to the changing needs of tenants. The interior features exposed timber, and the façade surfaces are glazed [66].

2.19.2. Material and Construction Solution

The foundation of the building is intermediate. The structure of the underground storey, the first above-ground storey, and the vertical communication structure is monolithic reinforced concrete. The construction of the upper floors is post-and-beam timber frame GLT. The ceiling slabs, based on GLT beams, are made of 7-layer CLT panels [66].

3. Results

In general terms, Section 2 characterises the architectural (spatial–functional) and material–construction solutions of nineteen high and high-rise buildings erected with timber construction after 2000.

3.1. Results of Spatial–Functional Solution Analyses

The architectural solutions of the analysed buildings represent the basic postulates of environmentally friendly construction, including, among others, the following: [8,23]:

- The use of renewable materials with low embedded energy (needed for the production of the material) and recyclability. All analysed buildings have a load-bearing superstructure made of CLT or GLT, and a significant part of their finishes, i.e., façade cladding, ceilings, or internal walls, are made of CLT or cedar wood shingles.
- The use of structural solutions that are easy to dismantle and possibly erect in another location; e.g., Puukuokka buildings One, Two, and Three.
- The use of local materials and the consequent energy savings resulting from their reduced transport needs. Building structure and building fittings: Limnologen, Portvakten Söder, Strandparken, Wood Innovation Design Centre, Vallen, Carbon 12 w Portland, Perspective, Puukuokka One, Two, and Three, and Mjøstårnet were made of timber from local or national forest resources.
- Taking into account already in the spatial–functional design phase the possibility of the adaptation of buildings to new needs, resulting in better use of the existing building fabric and limiting the sprawl of built-up areas. The design of, e.g., the T3 Bayside East building has taken into account the possibility of adaptation to a new function in case the original function is exhausted.
- Environment protection, including, inter alia, through the efficient management of building plots for high and high-rise development, consequently preserving to a greater extent natural areas in urban territory in relation to extensive development (low-rise buildings). All the buildings analysed meet the mentioned requirements.
- The use of recycled materials; e.g., 70% of the facades of the Stadthaus building are clad with recycled timber cladding.

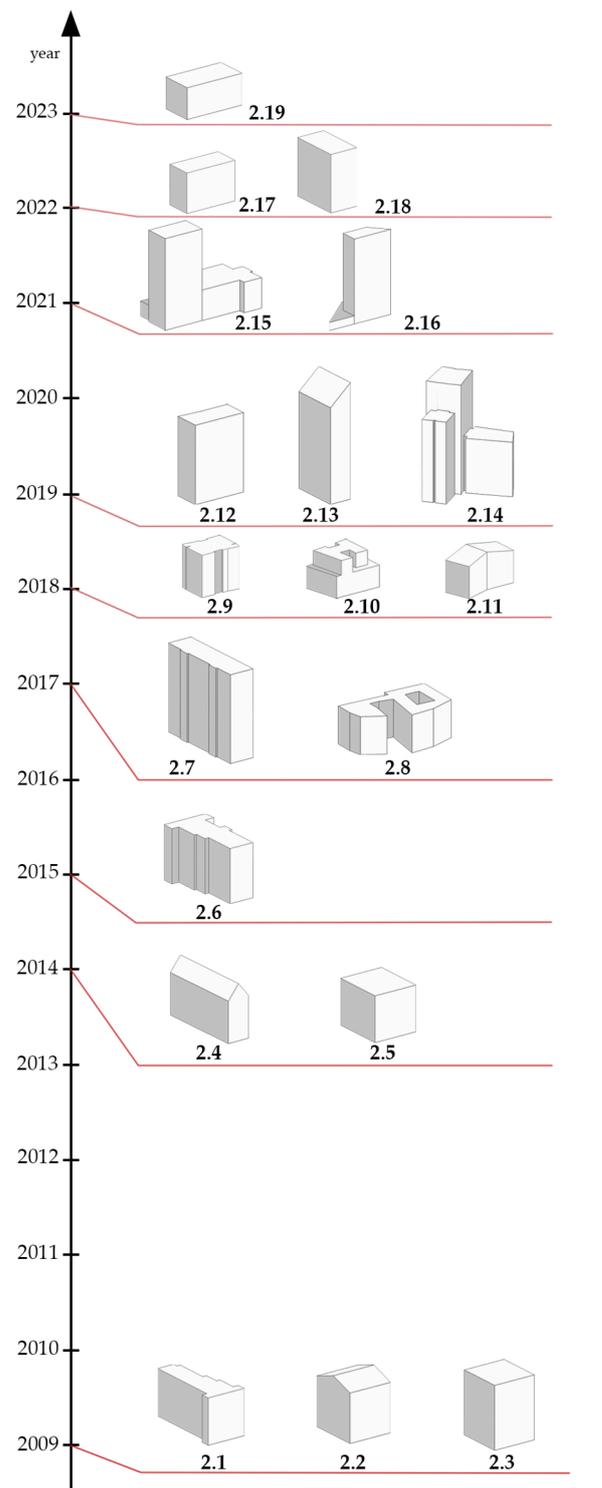
- Adapting the scale of buildings to meet the needs of the community, including, among other things, by introducing a diversified offer of residential apartments and providing the possibility of “flexible” interior design in accordance with the tenant’s expectations. All the buildings analysed meet the mentioned requirements.
- Well-chosen orientation of the building block with respect to the sides of the world in order to make better use of energy and sunlight. All the buildings analysed meet the mentioned requirements.
- Appropriate choice of building location to ensure convenient access to public transport and consequently reduce the need to use individual transport; e.g., Buildings: Carbon12, Tallwood 1.
- Saving water through the introduction of systems for the recovery and management of so-called “grey water” and harvesting water, e.g., rainwater; this issue has not been taken into account in this article.
- Reduced utility costs through the use of efficient energy sources, including renewables as a dominant energy source; the analyses of this issue have not been taken into account in this article.

There are diverse buildings’ spatial and functional solutions, i.e., adapted to users with different needs and ages, financial status, and lifestyle preferences depending, among other things, on the number of members in a given household, etc. Consequently, each building contains residential units with varying floor areas, room layouts, and furnishings. In the case of public buildings or spaces with separate functions of this kind, usually on the lowest floor levels of residential buildings, such interior space is designed “flexibly”, allowing for its changing arrangement to meet the changing time needs of its tenants.

One characteristic feature of the analysed buildings is their simple shape—usually a rectangular cuboid or an arrangement of several rectangular cuboids (Figure 5). The simplicity of the shape of the block is closely linked to the adopted structural solution and, in particular, the choice of construction technology, with a predominance of prefabricated elements. Implementing prefabrication to a large extent results in further pro-environmental benefits, including reduced land occupation for the construction site, rapid assembly, and limited nuisance resulting from construction for users of neighbouring properties and the city, as well as reduced pollution and dust emitted into the atmosphere due to the assembly and integration of the building from prefabricated elements.

In order to reduce on-site finishing work, reduce construction time, and commission buildings more quickly, a trend towards the use of prefabricated elements with a higher degree of surface finish can be observed.

In many cases, including buildings erected in Scandinavian countries (Sweden and Finland), the surfaces of prefabricated CLTs, i.e., (Table 1), external walls are fitted with external and internal cladding, window and door joinery; internal wall panels are fitted with cladding on both sides, e.g., from plasterboard; and ceiling panels are fitted with ceiling cladding, usually from plasterboard, etc. A characteristic feature of prefabricated building elements is the high standard and quality of their finish resulting from their manufacture under the strict technological regimes of the prefabrication plant.



2.3; 2.6 - number of building in text

Figure 5. General scheme of shapes of high and high-rise buildings with wooden structure.

Table 1. Summary of basic parameters concerning architectural solutions of the analysed buildings.

No	Name of Building	Architecture Designer	Height (m)	Type of Function	Shape of the Building Body and Roof Shape	Shape of the Building Plan	Interior Decoration/Wall/Ceilings Coverings	External Decoration—Façades
2.1	Limnologen (four buildings)	ArkitektBolaget	27.0	Residential.	Rectangular; flat roof.	Rectangle	CLT wood panels.	CLT panels with façade cladding and plaster.
2.2	Portvakten Söder	–	27.0	Residential.	Rectangular; pitched roof.	Rectangle	Plasterboard.	CLT panels with façade cladding and plaster.
2.3	Stadthaus	Waugh Thistleton Architects	30.0	Residential with services on the ground floor.	Rectangular; flat roof.	Square	CLT wood panels or plasterboard.	Painted wooden cladding.
2.4	Strandparken Building B	Wingårdh Arkitektkontor	27.0	Residential.	Rectangular; pitched roof.	Rectangle	CLT wood panels or plasterboard.	Cedar wood shingles.
2.5	Wood Innovation Design Centre	Michael Green Architecture	29.5	Public utility building.	Rectangular; flat roof.	Rectangle	Dominant—CLT wood panels or GLT wood.	Glass curtain wall; LVL mullions.
2.6	Vallen	Arkitektbolaget	31.0	Residential.	Composed of cuboids and flat or pitched roofs.	Composed of rectangles	–	Wooden cladding; cedar wood shingles or plaster.
2.7	Brock Commons Tallwood House	Acton Ostry Architects Inc.	53.0	Ground floor: shared space. other above-ground: residential floors.	Rectangular; flat roof.	Rectangle	Plasterboard, wood, or concrete surface cladding.	Glass curtain wall with wooden elements.
2.8	Dalston Works	Waugh Thistleton Architects	34.0	Residential with services at ground floor level.	Composed of cuboids/flat roofs.	Composed of rectangles	Plasterboard; wood cladding.	Brick façade cladding.
2.9	Carbon12	PATH Architecture	26.0	Residential and at ground floor level: shops.	Rectangular/flat roof.	Rectangle	Dominant—CLT wood panels or GLT wood.	Glass curtain wall on the south and north elevations and other “green walls” with climbing plants.
2.10	Immeuble ‘Perspective’	Laisné, Rousset architectes	31.0	Office.	Composed of cuboidal blocks of different heights/flat roofs.	Quadrilateral	Dominant—CLT or GLT timber panels; concrete surfaces.	Glass curtain wall with wooden elements.
2.11	Puukuokka One, Two, Tree	OOPEAA	27.0	Residential.	Composed of two quadrilateral prisms/pitched roof.	Composed of two quadrilaterals	Predominantly wooden CLT or plasterboard panels.	Wooden cladding.
2.12	Arbo	Manetsch Meyer Architects	60.0	Office.	Perpendicular/flat roof.	Rectangle	Mixed finish/wood; concrete surface; metal.	Glass curtain wall.
2.13	Mjøstårnet	Voll Arkitekter	84.5	Residential and public uses—offices, hotels, restaurants, conference rooms, swimming pool, etc.	Rectangular/flat roof.	Rectangle	Varied finish.	Wood panels.
2.14	HoHo Vienna	Rüdiger Lainer and Partner ZT GmbH	84.0	Services and residential.	Composed of three cuboids/flat roof.	Composed of three rectangles	Dominant—CLT wood panels or GLT wood.	Wooden cladding.

Table 1. Cont.

No	Name of Building	Architecture Designer	Height (m)	Type of Function	Shape of the Building Body and Roof Shape	Shape of the Building Plan	Interior Decoration/Wall/Ceilings Coverings	External Decoration—Façades
2.15	Sara Kulturhus Center	White Arkitekter	80.0	Public utility—hotels, conference rooms, museums, restaurants, spa facilities, etc.	Composed of multiple perpendiculars/flat roof.	Composed of multiple rectangles	Wood panels.	Glass curtain wall with wooden elements.
2.16	Haut	Team V Architecture	73.0	Residential with services at ground floor level.	Quadrilateral prism/flat roof.	Rectangular trapezoid	Dominant—CLT wood panels.	Glass curtain wall or wood.
2.17	Tallwood I	Jack James Architecture	41.0	Residential with services at ground floor level.	Perpendicular/flat roof and above part of building flat pitched roof.	Rectangle	Dominant—CLT wood panels or GLT wood.	Diverse cladding, including wood.
2.18	Ascent MKE	Korb and Associates	86.6	Residential with public utility—services, retail, and recreation.	Rectangular/flat roof.	Rectangle	Dominant—CLT wood panels or GLT wood.	Glass curtain wall.
2.19	T3 Bayside	3XN	42.0	Office.	Perpendicular/flat roof.	Rectangle	Dominant—CLT wood panels or GLT wood.	Glass curtain wall with wooden elements.

An important common feature of the external and internal decoration of the analysed buildings is the prominence of wood, i.e., the material used to shape both the load-bearing structure and the internal fittings and finishes.

It should be mentioned that biophilic design is being implemented in the construction of high and high-rise buildings. Wood is a material that has an impact on improving the quality of urban spaces, the aesthetics of cities, and the well-being of their inhabitants. There are many scientific findings confirming the beneficial effects of wood on human psychological well-being, including contributing to the restoration of a lost or neglected human connection with nature [67]. It has been noted, among other things, that displaying natural materials, including wood, in interiors reduces users' stress, improves their well-being, promotes relaxation and a good mood, supports creativity and productivity, gives a sense of warmth and cosiness, and has a beneficial effect on the human nervous and cardiovascular systems, among others [19,67].

A very important prerequisite for the choice of location of a plot of land for housing or public use for the local community, accommodating facilities with service, retail, leisure and recreation space, cultural functions (concert halls, museums, cinemas, etc.), offices, etc., is their openness to attractive spaces such as parks, landscapes, and vegetation.

The integration of buildings into spaces of high natural or landscape value has a significant impact on the degree of residents' satisfaction with the use of such apartments or spaces for public use. An additional common feature of all the buildings is that they provide close contact with the surrounding nature by providing residential or commercial units with balconies, loggias, roof terraces with plants, etc.

3.2. Results of Analyses of Material and Construction Solutions

3.2.1. Foundation and Underground Part

All of the buildings analysed have foundations formed of reinforced concrete (Table 2). This is usually a direct foundation on a foundation slab or ribbed slab foundation.

Table 2. Summary of basic parameters relating to the material and construction solutions of the analysed buildings.

No	Name	Structure Designer	Foundation/ Underground Floor Construction	Construction Type of the Above-Ground Part	Load-Bearing Wall/Post Construction	Ceiling Construction	Construction of Vertical Communication Structures
2.1	Limnologen	Martinsons Byggsystem (woodproducts), Tyréns (concrete)	Intermediate foundation on piles.	First storey above ground—reinforced concrete frame above, timber-framed wall system (locally timber-framed).	Walls made of prefabricated CLT panels, according to the Martinsons system (locally framed layout with GLT).	Slab ceilings of 3-layer CLT based on GLT beams.	Monolithic reinforced concrete.
2.2	Portvakten Söder	–	Direct foundation on reinforced concrete foundation slab.	First storey above ground—reinforced concrete frame; above, timber-framed wall system.	Walls made of prefabricated CLT panels, according to the Martinsons system.	Slab ceilings made of 3-layer CLT, according to the Martinsons system.	–
2.3	Stadthaus	Techniker Ltd.	–	Wooden wall bearing system.	Walls made of prefabricated CLT panels, according to the KLH system.	CLT panelled ceilings.	Walls made of prefabricated CLT panels, according to the KLH system.
2.4	Strandparken Building B	Martinsons (wood floors 2–9); Tyréns (concrete floor 1 and geotechnical engineering)	Foundations and structure of underground part—prefabricated reinforced concrete.	Wooden wall bearing system.	Walls made of prefabricated CLT panels, according to the Martinsons system.	Slab ceilings with CLT panels, according to the Martinsons system.	CLT panelled walls.
2.5	Wood Innovation Design Centre	Equilibrium Consulting	Direct foundation on reinforced concrete ribbed foundation slab.	Timber frame post-and-beam construction.	GLT timber posts.	CLT panelled ceilings based on GLT beams.	Stairway walls and slabs made of CLT panels.
2.6	Vallen	–	Foundation—reinforced concrete structure.	Storeys 1 and 2 above ground—post-and-beam reinforced concrete frame construction. Above—Trä8 timber frame load-bearing structure.	GLT timber posts.	GLT timber frame transoms; CLT ceiling panels.	Reinforced concrete walls.
2.7	Brock Commons Tallwood House	Fast and Epp Structural Engineers	Foundation—reinforced concrete structure.	Reinforced concrete structure at ground floor level, and timber post-and-beam structure above.	GLT timber posts.	5-layer CLT ceiling panels.	Monolithic reinforced concrete.
2.8	Dalston Works	Ramboll (CLT and façade), PJCE (concrete and civils)	Direct foundation on reinforced concrete foundation slab.	Reinforced concrete frame structure at ground floor level, and timber wall structure above.	Walls made of prefabricated CLT panels.	Prefabricated CLT panel ceiling slabs.	Stairway walls and panels of prefabricated CLT panels.
2.9	Carbon12	Munzing Structural Engineering, LLC	Foundation on a reinforced concrete foundation slab; underground storey construction—reinforced concrete frame.	Reinforced concrete structure at ground floor level, and timber frame structure above.	GLT posts; CLT walls.	GLT timber ceiling beams; CLT panelled ceiling slabs.	–
2.10	Immeuble 'Perspective'	–	Foundation—monolithic reinforced concrete construction.	Timber post-and-beam bearing system.	GLT posts.	CLT ceiling slabs based on GLT beams.	Monolithic reinforced concrete construction.
2.11	Puukuokka One	Pertti Ruuskanen Oy, SWECO rakennetekniikka Oy and A-Insinöörit Oy	Reinforced concrete monolithic foundation and underground construction.	Load-bearing system assembled from prefabricated timber spatial modules.	Prefabricated spatial modules (ceilings and walls) in CLT wood.	Prefabricated spatial modules (ceilings and walls) in CLT wood.	–

Table 2. Cont.

No	Name	Structure Designer	Foundation/ Underground Floor Construction	Construction Type of the Above-Ground Part	Load-Bearing Wall/Post Construction	Ceiling Construction	Construction of Vertical Communication Structures
2.12	Arbo	–	Reinforced concrete monolithic structure of the foundations and two underground storeys.	Timber frame post-and-beam construction.	GLT or LVL timber posts.	TCC prefabricated timber/concrete floors supported on GLT beams.	Monolithic reinforced concrete construction.
2.13	Mjøstårnet	Moelven Limtre, Sweco	Intermediate foundation on a pile-supported reinforced concrete slab.	Timber frame post-and-beam structure.	GLT posts.	Storeys 12–18: reinforced concrete slab ceilings supported on GLT beams; storeys 2–11: ceilings of CLT panels, according to the Trä8 system on GLT beams.	CLT walls.
2.14	HoHo Vienna	HoHo Vienna	Reinforced concrete foundations and construction of two underground floors.	Timber post-and-beam load-bearing structure.	GLT posts; CLT external walls.	Composite wood–concrete (CLT)—ceiling supported on GLT beams.	Construction of vertical communication structures and stairways—reinforced concrete.
2.15	Sara Kulturhus Center	Dipl.-Ing. Florian Kosche AS	Intermediate foundation on piles topped by a reinforced concrete slab.	Load-bearing structure assembled from prefabricated CLT spatial modules.	CLT prefabricated spatial modules (walls and ceilings).	CLT prefabricated spatial modules (walls and ceilings).	CLT vertical communication structures and lift shafts.
2.16	Haut	Arup	Intermediate foundation on diaphragm walls and Tubex foundation piles and two-storey underground structure—monolithic reinforced concrete.	Reinforced concrete monolithic structure of the two lower storeys above ground; above: timber–concrete hybrid wall system.	CLT walls.	TCC concrete/wood hybrid panel floors.	Vertical communication structures: monolithic reinforced concrete.
2.17	Tallwood I	Aspect Structural Engineers	Foundations and construction of two underground floors—monolithic reinforced concrete structure.	Ground floor construction—reinforced concrete monolithic post and slab structure; above, steel and timber hybrid frames.	GLT posts and steel stiffening frames of I sections.	Ceiling slabs made of 5-layer CLT panels based on GLT beams	Vertical communication structures: monolithic reinforced concrete
2.18	Ascent MKE	Thornton Tomasetti	Indirect foundation on piles.	Construction of the six lower floors—monolithic reinforced concrete frame with pre-stressed concrete floors; timber beam-and-post construction above.	GLT posts.	CLT panelled ceilings	Vertical communication structure and lift shaft: monolithic reinforced concrete
2.19	T3 Bayside	WSP Denmark A/S	Intermediate foundation on foundation piles; structure of underground storey—monolithic reinforced concrete.	Reinforced concrete monolithic ground floor structure; timber post-and-beam frame above.	GLT posts.	Ceiling slabs made of 7-layer CLT panels based on GLT beams	Vertical communication structures: monolithic reinforced concrete

Where there are complex ground conditions (e.g., building Linnologen) or high loads from the building being transferred to the ground (this usually applies to buildings higher than 40 m above ground level, e.g., buildings T3 Bayside, Haut, Sara Kulturhus Center, Mjøstårnet, and Ascent MKE), the foundation is intermediate on foundation piles.

The buildings mostly have a one- or two-storey underground part made of monolithic reinforced concrete frame construction and, in only one case, Strandparken Building B, as prefabricated reinforced concrete. The choice of a skeletal load-bearing layout is primarily driven by the functional solution of the underground parts, i.e., a garage with either traditional (car-powered) or automated car parking.

In the case of buildings with two underground storeys, the excavation enclosure and, at the same time, the structure of the external walls of these underground parts are slurry walls constructed in situ.

3.2.2. Material and Construction Solution for the Above-Ground Part

In about half of the cases analysed, the lower storeys of the above-ground part are formed as skeletal (post-and-slab or post-and-beam) monolithic reinforced concrete (Table 2). In the cases of buildings Carbon12, Portvakten Söder, Limnologen, Dalston Works, Tallwood I, T3 Bayside, and Brock Commons Tallwood House, there is one ground floor; in the cases of Vallen and Haut, there are two floors: the ground floor and first floor; and in the case of Ascent MKE, there are six lower floors above ground.

The upper floors above ground are erected with the use of the following timber and prefabricated structural elements (Table 2):

- Bars (mullions and beams) made of GLT-glued laminated timber or LVL laminated veneer lumber.
- Surface panels (wall panels, ceiling panels, and stairway panels) made of CLT cross-laminated timber.
- Spatial made of cross-laminated timber CLTs with a volume equivalent to the volume of a hotel room (e.g., the Sara Kulturhus Centre building) or part of an apartment (e.g., a spatial module containing a living room, balcony, and bedroom), i.e., in the spatial-functional solutions of Puukuokka One, Two, and Three buildings.

In the case of a post-and-beam or frame load-bearing structure, the bar element posts made of GLT or LVL and rafters made of GLT form the basis for the shaping of the intermediate ceilings and the flat roof. The ceiling slabs of CLT panels are supported on these beams or frame rafters. Depending on the span of the ceiling structure and the value of the load applied to the ceiling slab, panels of 3-, 5-, or 7-layer CLT are used.

For the highest buildings (e.g., Arbo, Haut, and HoHo buildings), the ceiling panels are shaped as timber–concrete composite TCC hybrid prefabricated elements. The introduction of such solutions has the effect of increasing the resistance of high-rise building structures to horizontal forces from wind pressure.

3.2.3. Construction of Vertical Communication Structures

The design of vertical communication structures (staircases and lift shafts) ensures the spatial rigidity of the building and was mostly realised as monolithic reinforced concrete, including in the Ascent MKE, HoHo Vienna, Haut, Arbobrock Commons Tallwood House, T3 Bayside, Tallwood I, Immeuble ‘Perspective’, Vallen, and Limnologen.

In the case of the Mjøstårnet (84.5 m high), Sara Kulturhus Center (80 m high), Dalston Works (34 m high), Stadthaus (30 m high), Wood Innovation Design Centre (29.5 m high), and Strandparken Building B (27 m high), vertical communication structures were fully formed from prefabricated CLT panels.

4. Discussion

On the basis of the authors’ own analyses and literature research, as well as the information made available in online publications, it was concluded that timber load-bearing structures have been increasingly implemented in high and high-rise construction since 2000 (Figure 6). Previously, this type of structural material solution was used only in low- and mid-rise housing.

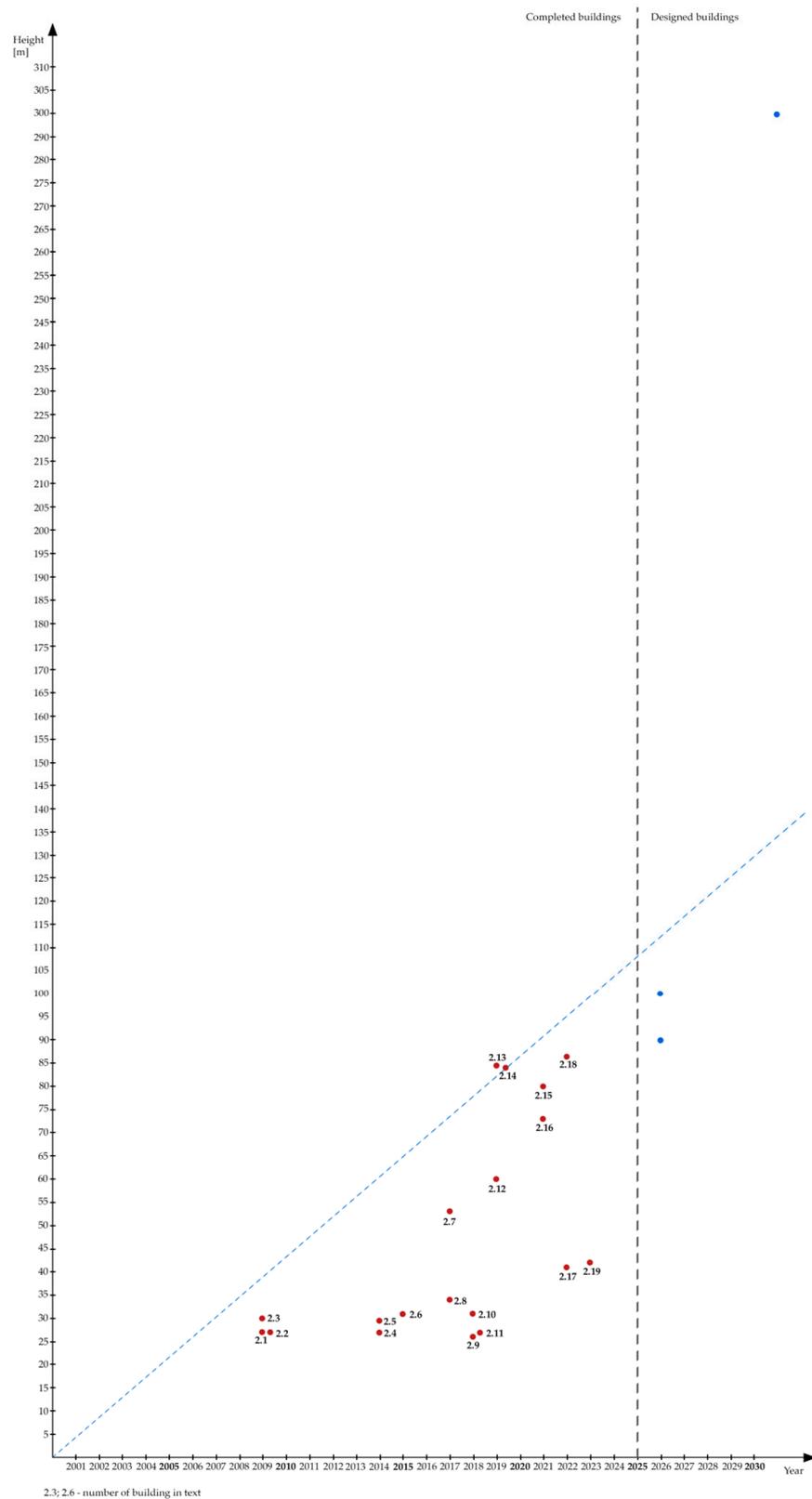
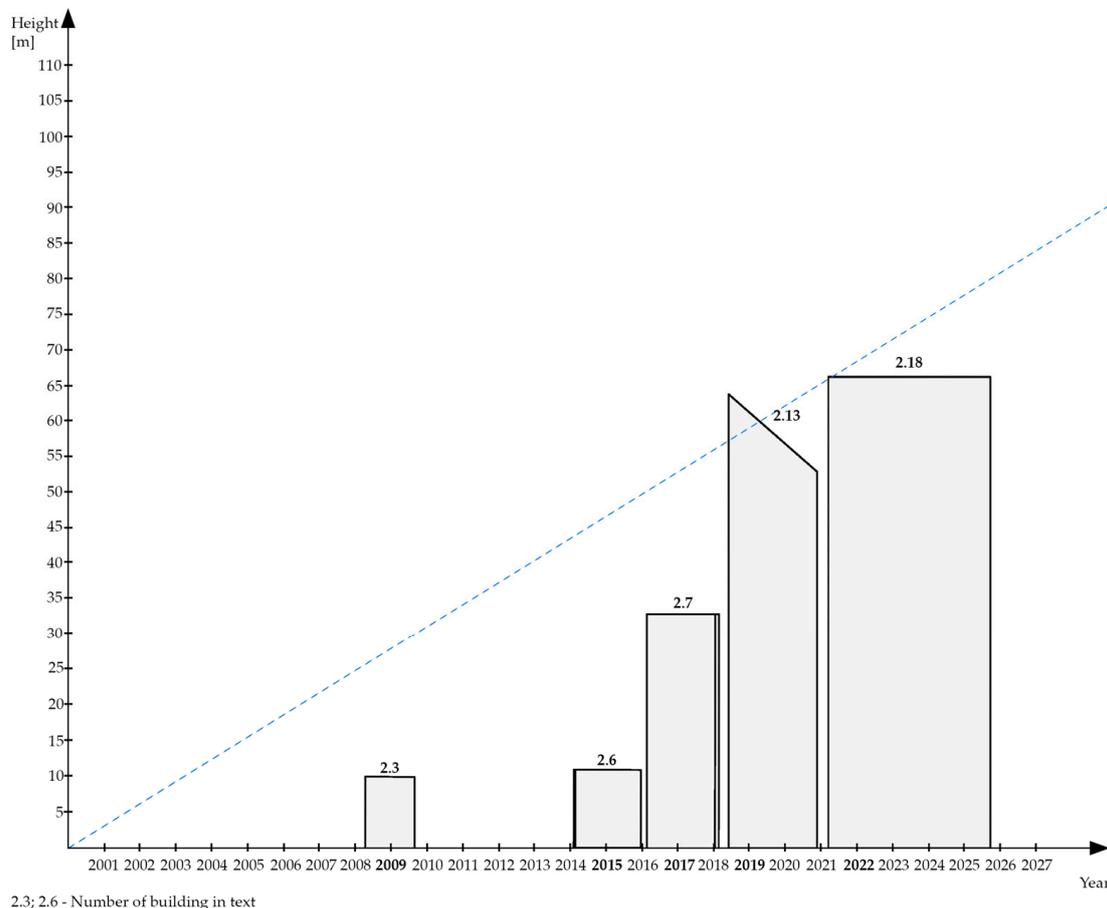


Figure 6. Graph showing heights of completed and designed buildings—the dashed line indicates the upward trend over time of timber-framed buildings. Blue dots—designed buildings.

Currently, the tallest timber-framed buildings erected reach a height of 86.6 m (Ascent MKE building in the USA, 2022); however, there are published announcements of the

completion in 2026 of a residential building in Switzerland with a record (for this type of construction solution) height of 100 m, designed by the Danish studio Schmidt Hammer Lassen, as well as a building with a height of 90 m and 31 overground storeys in Toronto, designed by the Canadian studio Icon Architects [65] (Figure 7).



2.3; 2.6 - Number of building in text

Figure 7. Graph showing the greatest heights of completed buildings—the dashed line indicates the upward trend over time of timber-framed buildings. 2.3–2.18—number of building in text.

It should be mentioned that “The Centre for Natural Material Innovation at the University of Cambridge” has developed a research project entitled “Super Tall Timber” to determine the feasibility of using timber structures to construct buildings up to 300 m high. The work of the interdisciplinary team resulted in a design concept for the “Oakwood Tower” in London with a height of 300 m [68]. The body of the building is formed by a soaring central tower with a projection of 20×20 m, to which other towers of different heights, i.e., 65, 125, 190, and 250 m, are attached at the four vertices. These towers form the bracing of the superstructure and also have square projections with side lengths of 15 m. The gross floor area of this proposed building is $90,000 \text{ m}^2$ [68].

The design concept for the “Oakwood Tower” in London has been submitted to the Mayor of London, the public, and the developers for comments. According to [68], most of these comments were positive, which also confirms the high public awareness and interest in pro-environmental measures and the widest possible use of renewable materials in construction.

In [68], a very favourable value for a building’s mass by its gross volume quotient of 125 kg/m^3 for a timber-framed building, the Oakwood Tower, was indicated, while an equivalent steel-framed building with reinforced concrete ceilings would have a value for this quotient of 160 kg/m^3 and for a reinforced concrete structure: 300 kg/m^3 . As a

consequence of the above, the timber load-bearing system is characterised by a lower specific weight, lower loads transferred from the building to the ground, and more favourable conditions for shaping the foundation zone of the building.

The most significant advantage of wood, which forms the basis for multifaceted interdisciplinary research on this material, is the significant reduction in CO₂ emissions compared to traditional material solutions, i.e., steel and concrete. Calculations of this kind relating to, for example, the T3 building (the building is LEED Gold certified) show a carbon dioxide reduction of 40–50% compared to a traditional material solution [66]. According to [27], wood, as a renewable material, stores 0.8 t of CO₂ in 1 m³ while concrete and steel release large amounts of carbon dioxide into the atmosphere. In the case of the Murray Grove building, it was calculated that changing the material solution of the structure from a reinforced concrete frame to a timber frame resulted in a 125 t reduction in atmospheric CO₂ emissions [28].

An important aspect of the implementation of timber in construction is the need to promote (an aspect cited for Scandinavian, Canadian, and US construction, among others) the timber industry and crafts based on local sustainable plantations and significant timber resources, as well as to develop research on wood and wood-based construction technologies [25].

5. Conclusions

High and high-rise timber construction is based on the use of prefabricated GLT, LVL, or CLT components, usually with a high degree of finishing. Consequently, this factor has a significant impact on speeding up the investment process and, in particular, the installation of structures and building components. Excluding work on foundations and the construction of underground parts, usually made of reinforced concrete, the erection of timber-framed buildings with prefabricated elements, so-called “dry” construction technologies, does not emit additional pollutants into the environment and constitutes less of a nuisance to users of neighbouring properties.

The above information testifies to the significant progress in the design and implementation of timber structures, as well as to their environmentally friendly qualities, also referred to as green construction.

The two selected principles of sustainable construction analysed in this paper, i.e., limiting interference in the natural areas of cities by efficient use of the building plot for high or high-rise buildings and the use of renewable materials—timber—for the load-bearing structure of buildings, are integrally linked. Their implementation in the spatial–functional and material–structural design of this type of building requires a holistic approach, which involves interdisciplinary research and cooperation from many scientific disciplines.

It should be mentioned that there is now public acceptance of implementing and expanding the use of timber-framed green buildings in high and high-rise construction.

On the basis of our own research and analysis of the available literature, we can conclude that there is a significant increase in interest in the use of timber in construction, and its use as load-bearing systems for high and high-rise buildings is expanding.

The example of the design concept for the “Oakwood Tower”, with a height of 300 m, can herald further development of this type of building, which is positively regarded by the public and beneficial in terms of environmental impact.

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