CURRENT TRENDS AND FUTURE DIRECTIONS FOR MULTI-STOREY TIMBER BUILDINGS

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Keywords: Architecture; timber construction; digital design; wood processing

1. INTRODUCTION

Up to the 19th century, wood was irreplaceable as the most important fuel and raw material for all types of construction. However, due to large city fires in Europe, fire protection measures, including legislation, were introduced in several European countries during the late 19th century to discourage or restricted the use of timber in the construction of multi-storey buildings. This resulted in a considerable reduction of new-built wooden houses in the cities. Multi-storey timber buildings are not a new invention. In Japan, the more than 1400 year old Buddhist temple complex Hōryū-ji, includes a five-storey pagoda, with a height of 32 meters and approximately 20 x 20 meters in the basal area (Fig. 1).

Fig. 1. Examples of wood structures throughout history

In the past few years, the tall-building industry has become increasingly interested in the use of timber as a major structural element in skyscrapers. This has resulted in a now-worldwide wave of research, built projects, and ever more daring speculative proposals using “mass timber” – engineered wood products that are just as robust as their concrete and steel counterparts. Massive timber (tall wood), or mass timber construction (MTC) is the collective term for engineered wood products like glue laminated timber (glulam), cross-laminated timber (CLT), nail laminated timber (NLT) and dowel-laminated timber (DLT).
2. FUTURE TRENDS: A COMBINATION OF VISIBLE WOOD, DIGITAL DESIGN AND ADVANCED PROCESSING AS FUTURE TRENDS

The development potential and obstacles in multi-storey building is employing a combination of digital design and computer numerical control (CNC) processing. The construction engineers know-how to make use of the digital tools; they have geometric imagination capabilities and construction know-how while the architects have ambitious ideas for building extraordinary projects. Digital design and production using CAE (computer-aided engineering), CAD (computer-aided design) and CAM (computer-aided manufacturing) have allowed timber construction to forge ahead into new dimensions of design. Innovative connections, modern wood-based materials and cutting-edge CNC milling offer entirely new possibilities and shape wood into almost any conceivable form (Fig. 1, 2).

![Digital planning process CAD-CAE-CAM interfaces: New dimensions in complexity in timber construction.](image1)

![Kristiansand, Norway: Waterfront-facade clad follows the forms and creates a surface separating real world from the illusion.](image2)

3. DISCUSSION

Timber multi-storey building in recent years has gathered momentum in European countries. Construction of the first experimental buildings was completed and today the trust in new timber building is growing. European timber multi-storey building is progressing with regard to building performance, construction methods and building costs. It is becoming increasingly widespread, and the number, quality and types of timber buildings indicate progress towards their becoming a common construction practice in the middle-rise building environment of European countries. Positive aspects of wood as a structural material include its strength, environment-friendliness, simple handling and appropriateness for industrial use, but knowledge gaps have led to a reduction in the use of wood by structural engineers and architects. There are numerous challenges associated with the construction of wooden buildings; as an architect, you design for the present, with an awareness of the past, for a future which is essentially unknown. These challenges are best met through further research and more pilot projects to increase the knowledge of life cycle costs, construction costs, maintenance costs, sound and vibrations, through the general increase in the number of wooden buildings that are being erected.

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REFERENCES


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SUMMARY
In the past few years, the tall-building industry has become increasingly interested in the use of timber as a major structural element in skyscrapers. This has resulted in a now-worldwide wave of research, built projects, and ever more daring speculative proposals using “mass timber” – engineered wood products that are just as robust as their concrete and steel counterparts. There is a great market potential for the use of wood in all types of buildings employing a combination of digital design and CNC processing. Digital design and production using CAE, CAD and CAM have allowed timber construction to forge ahead into new dimensions of design. Innovative connections, modern wood-based materials and cutting-edge CNC milling offer entirely new possibilities and shape wood into almost any conceivable form.

Key words: Architecture; timber construction; digital design; wood processing

4. INTRODUCTION
Up to the 19th century, wood was irreplaceable as the most important fuel and raw material for all types of construction. However, due to large city fires in Europe, fire protection measures, including legislation, were introduced in several European countries during the late 19th century to discourage or restricted the use of timber in the construction of multi-storey buildings. This resulted in a considerable reduction of new-built wooden houses in the cities, especially buildings with more than two floors. Multi-storey timber buildings are not a new invention. In Japan, the more than 1400 year old Buddhist temple complex Hōryū-ji, includes a five-storey pagoda, with a height of 32 meters and approximately 20 x 20 meters in the basal area. The wood used in the central pillar of the pagoda is estimated through a dendrochronological analysis to have been felled in 594, so that this is one of the oldest wooden buildings in the world (Fig. 1).

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The construction of multi-storey timber-framed buildings was re-introduced in the early 1990s in several western European countries. Many countries refrained from using flammable materials because of uncertainty about fire risks in the buildings. This helped the concrete industry to dominate the building market in Europe, particularly in Central Europe with a market share of 70-80% (Winter 1995, Kitek Kuzman and Kutnar 2014). In the early 21st century, less than 10% of one- and two-family houses in Germany, France or the Netherlands were being built with wood, but more than 85% of such houses in Sweden and Finland (Eliasson at al. 2015). However, extensive research has shown that material-neutral building regulations are preferable and, for over a decade, function-based regulations have been common in many European countries. This has resulted in a considerable increase in wooden multi-storey buildings.

In the late 1980s, a construction product directive from the European Commission stipulated functional based requirements for the use of products in building construction with the aim to remove technical barriers to trade in construction products between member states in the European Union (Schickhofer 2013). This means that any material – wood, concrete, steel etc. – that fulfils the functional requirements as specified in the national building regulations can be used for the construction of multi-storey residential buildings. It has been nearly three decades since this European Commission construction product directive was issued, but the use of timber frames in the construction of multi-storey buildings is still low, even in the Nordic countries where it constitutes for about 10% of new multi-storey buildings.

Modern building regulations have however contributed to an increase in the construction of multi-storey timber buildings, mainly buildings up to eight floors (Table 1).

Table 1. World wide development and future suggestions for multi-storey timber buildings

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Design</th>
<th>Storey</th>
<th>Structure</th>
<th>Date</th>
<th>Location</th>
<th>Design</th>
<th>Storey</th>
<th>Structure</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1130</td>
<td>Shansi, China</td>
<td>3</td>
<td>1</td>
<td>wooden pillar</td>
<td>1130</td>
<td>London, England</td>
<td>9</td>
<td>Multi-storied wooden tower</td>
<td>2008</td>
<td></td>
</tr>
</tbody>
</table>
Multi-storey timber buildings can be given an outer architectural design that suits the location where the building is erected. There are different regulations regarding the permissible height of a wood building, mostly for fire-safety reasons (Fig. 2).

![Fig. 2. Maximum building height by regulation in different countries](image)

In the past few years, the construction industry has become increasingly interested in the use of timber as a major structural element in skyscrapers. This has resulted in a world-wide wave of research, built projects, and ever more daring speculative proposals using “mass timber”. Massive timber (tall wood), or mass timber construction (MTC) is the collective term for engineered wood products like glue laminated timber (glulam), cross-laminated timber (CLT), nail laminated timber (NLT) and dowel-laminated timber (DLT).

Figure 3 presents global production of CLT and the first 9-storey high-rise Murray Grove built in 2009.
Fig. 3. Global production of CLT 1995-2015 (left): today about 35 production sites worldwide and 95% of the production volume in Central Europe (Schickhofer, 2013 and Ebner, 2017), and the 9-storey high-rise Murray Grove, 2009, London (right)

Being able to build large and high with timber leads to several challenges. Multi-storey buildings become light and therefore wind loads become a bigger problem than for heavier materials. For the same reason, soundproofing between apartments is a more complicated problem. Risk of fire accidents and fire spreading must be minimized, and the structures must handle loads and deformations, regardless of building materials. There are however solutions. The building Treet or ‘The Tree’in Bergen, Norway set a world record with 14 floors. This project has become discussed from a structural point of view, since it makes use of a large-scale glulam truss, combined with CLT-based volume modules as living units stacked inside the glulam frame. To stabilize the structure against lateral loads, the structure was complemented with concrete floors decks on two intermediate levels and thus, in a way, the project represent a form of hybride. The same can be said about the currently tallest high-rise building in timber, the student apartment block Brock Commons in Vancouver, Canada. This building reaches 18 floors and is composed by two elevator shafts in concrete, stabilizing a timber-based structure of glulam posts and CLT floor decks with a concrete topping.

Figure 4 highlights several examples of tall-timber buildings currently built, under construction, or proposed around the world.
The increase of the use of timber in construction of multi-storey buildings can be attributed to several important factors; timber construction leads the way in terms of energy-efficient building, and wood is renewable and locally available; it is beautiful, sensuous and has superb technical characteristics. The main aspect is, however, the growing environmental awareness, where the choice is motivated by the fact that wood is a renewable material and that its use reduces CO₂ emissions, provided that the wood is harvested in forests where sustainable forestry, with replanting and management plans, is practiced. Although the development and implementation of timber constructions in multi-storey buildings is on different levels in different European countries, the trend towards an increasing use of timber is clear. Many responsible contractors, architects and businesses now choose a timber construction because of its efficient use of both resources and money.

A transition from traditional building practices to multi-storey timber buildings depends on several factors. Many different players such as architects, consultant engineers, constructors, contractors,
subcontractors, and suppliers are involved in the processes of design, engineering, construction, material supply, and activity coordination. The action of these actors, their beliefs and perceptions, knowledge and skills, and above all the institutional set up influence the development of construction system.

5. FUTURE TRENDS: A COMBINATION OF VISIBLE WOOD, DIGITAL DESIGN AND ADVANCED PROCESSING AS FUTURE TRENDS

The development potential and obstacles in multi-storey building is employing a combination of digital design and computer numerical control (CNC) processing. The construction engineers know-how to make use of the digital tools; they have geometric imagination capabilities and construction know-how while the architects have ambitious ideas for building extraordinary projects.

Digital design and production using CAE (computer-aided engineering), CAD (computer-aided design) and CAM (computer-aided manufacturing) have allowed timber construction to forge ahead into new dimensions of design. Innovative connections, modern wood-based materials and cutting-edge CNC milling offer entirely new possibilities and shape wood into almost any conceivable form. Nowadays, there are flexible planning-design tools and CNC processes that allow us to design and build extraordinary architectural structures (Fig. 5). The producers already offer all the stages of the construction process: from technical development to construction, service and maintenance.

Fig. 5. The Yeoju golf clubhouse in Republic of Korea under construction; digital simulation of the roof and a part of the roof during assembly

The coordination of the various steps, such as architectural design based on geometric structures, structural engineering, production, logistics, site facilities, installation and follow-up work, is a core element of contemporary project management.

In the new planning process, the production companies are becoming IT specialists, providing services and solving interfaces, while carpenters coordinate the building processes. There are intelligent machines: software components, machine technology, knowledge, production space, logistics concepts and available engineered raw material. The digital planning process (CAD-interface CAE and CAM) still needs a lot of detailed planning (Fig. 6).

Complex timber constructions can compete with traditional constructions but this requires a new modern production philosophy where components are planned and produced quickly, flexibly and precisely with digital processes in the factory: complete 3D modeling, static evaluation of complex building design, solving complexity within the factory, and pre-assembly of parts of the whole structure close to production. This will result in the rapid erection of the building on the building site with a low degree of complementary work.

In contemporary timber structural architecture, the structure remains visible. The structure is the dominant factor of the architectural expression, and is often based on the principles of nature. It shows a perfect match for timber and its variety of advanced possibilities.

Creating exceptional free-form structures requires an intensive and close cooperation between specialists. Developing the geometry, designing the supporting framework and generating production data are all decentralized, yet interconnected, processes. An integrated exchange of data with clearly defined interfaces makes seamless project management possible.
2.1. New modern production philosophy - production with minimum tolerances and maximum flexibility - free-form structures

The framework for producing components is full of mathematically exact, parameterized models of the structure and its components, which ensure that tolerances are kept to a minimum in the construction, processing and installation phases. 3D modeling, high-quality code and error-free information for CNC machines are also critical for prototyping parts and in the management of 3D printing. These models are part of the entire process from project development, feasibility studies and design, over the CAD/CAM processes, to the construction in service life.

Depending on the type and complexity of the structure, specialists on CAD and CAM software are needed to convert graphical data into machine codes, in general for steering of 5-axis CNC joinery machines. Programming expertise and skill in handling this equipment are needed to ensure the flexible and precise production of double-curvature timber structures: The wooden Wave as a free Form, Kristiansand, Norway (Fig. 7) and Tamedia 5-storey office building in Zürich, Switzerland (Fig. 8). Modern design and production methods open up many possibilities where complex structures and buildings become real. Free-form structures are distinguished by their cellular supporting structures and the unique nature of each component. They are exceptional – from the initial idea through to the design, production and installation with the required quality, in the specified time-frame and on cost-effectiveness from the perspective of the investor and builders.
Advanced timber structures save money at the construction site because they allow exact planning and quick assembly as a result of prefabrication. This is also an economic benefit for builders when the time between new construction and rental is short. For investors, it is important that advanced financing and the marketing of the property take less time and are accompanied by assured on-time completion. One of the main advantages of a modern production concept, in-factory rather than on-site, for timber structures is that the construction method is primarily dry, and there is a reduced risk of damage to the structure as a result of moisture.

We see opportunities for further development and future trends in high prefabrication, partnership and increased responsibilities for planning and construction, improved and systematic feedback of experiences, and team cooperation. Demonstration projects are vital to show the various actors, e.g. the wood industry, architects, builders, and housing associations, the technical and business potential of wood as a multi-purpose building material.

2.2 Roundwood construction - A way to sustainable architecture by new technologies

It is necessary to promote the different possibilities where wood can be used. Besides the utilization of high quality sawn timber for high-tech constructions such as halls, wide span covers and bridges, one should further develop the possibilities of using low quality timber for construction in combination with other materials like steel, concrete, glass or fibre glass (Natterer 2009). Some great example of massive wood construction are wooden towers planned by timber construction prof. Julius Natterer (Fig. 9). Sauvabelin Tower in Lousanne, Switzerland is 36 m high (the observation platform is situated at 30 m). 24 poles half round are distributed around the spiral staircase made of 20x40 cm Douglas sections. The spiral builds two independent staircases one behind the other. The upper platform and the two intermediates one are made of nailed laminated timber.
The use of roundwood, i.e. unprocessed logs, is another opportunity to develop construction elements based on the low-grade forest resource leading to sustainable architecture showing possibility to transform new technological arrangements and buildings into poetic living spaces for people (Fig. 10).

![Roundwood structural components](image1.jpg)

**Fig. 10.** Roundwood structural components used in a project Grocery store, Madison, WI, US (left) and innovative round wood joints (right) (Riesen 2017)

### 6. CONCLUSIONS

Timber multi-storey building in recent years has gathered momentum in European countries. Construction of the first experimental buildings was completed and today the trust in new timber building is growing. The number of projects, quality and importance, as well as the rising interest from different groups and customers show this trend. The reasons are two: economy and ecology. European timber multi-storey building is progressing with regard to building performance, construction methods and building costs. It is becoming increasingly widespread, and the number, quality and types of timber buildings indicate progress towards their becoming a common construction practice in the middle-rise building environment of European countries. The use of timber for multi-storey building construction varies widely however among the European countries. Positive aspects of wood as a structural material include its strength, environment-friendliness, simple handling and appropriateness for industrial use, but knowledge gaps have led to a reduction in the use of wood by structural engineers and architects. There are numerous challenges associated with the construction of wooden buildings; as an architect, you design for the present, with an awareness of the past, for a future which is essentially unknown. These challenges are best met through further research and more pilot projects to increase the knowledge of life cycle costs, construction costs, maintenance costs, sound and vibrations, through the general increase in the number of wooden buildings that are being erected.

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### REFERENCES


