WOODRISE 2022

RENOVATION, RESTORATION & REHABILITATION
OF URBAN BUILDINGS USING WOOD BASED TECHNOLOGIES

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BOOK OF ABSTRACTS

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Light up! – International Wood Student Competition for Standard Systems to Vertical Extensions

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Population and urban areas grow fast worldwide, so by 2050 1/3 of the global nation will live in cities (United Nations, 2018). European cities face the challenge of lack of buildable areas. Vertical extensions have great potential in condensed urban areas by easing additional living space and taking advantages of existing structures and infrastructures. The city of Vienna has experienced a strong growth within the last 30 years (City of Vienna, 2021) and is expected to house 2 million inhabitants by 2028 (City of Vienna, 2018). Strategies to exploit existing buildings, especially the so-called "Gründerzeit" buildings from the post-war period (1950-1970) are intensively promoted. Their low density, standardized layouts and row construction with sufficient open space represent great conditions for vertical extensions, wherethrough up to 7.600 additional flats could be built (Arbeitsgruppe Ressourcenorientiertes Bauen, 2017).

Timber is a great structural material for re-densification thanks to its strength to weight ratio, easing the erection of complementary storeys without compromising the existing structure. Its lightness and workability enhance the production of large highly prefabricated elements or modules delivering a fast, precise and uncomplicated on-site construction process, without disruptions to the neighbors. This project explores the potential of timber as main building material for urban vertical extensions within standardized prototypes framed in an interdisciplinary and international student competition, where master students of architecture and civil engineering from the Vienna University of Applied Sciences (VUAS) participated working collaboratively within an intensive Design Studio, supported by experts from different disciplines. The competition "Light up!" was organized by proHolz Austria, together with The City of Vienna, to which every master-student of architecture and civil engineering from European universities was invited. The project involved 2-storey extensions in timber or timber hybrid construction on 3 different existing residential buildings from the 1960s in Vienna, with 99, 172 and 446 flats respectively. Main goal was to develop standard solutions as basis for further applications within other residential buildings with similar typology.

Optimal utilization of living space and flexible options in compact floor plans were prerequisites aiming to deliver affordable flats and inclusive housing typologies. Communal areas, additional balconies, open staircases, greenery of facades and roofs were also promoted. The designs were elaborated by interdisciplinary teams within an integral planning process. The early involvement of different disciplines and their coordinated planning in the conceptual phase was crucial for the optimization of design in terms of economic, ecological and socio-cultural objectives throughout the lifecycle of the building, while enhancing creativity and reducing complexity. A total amount of 127 projects from 7 countries were submitted, wherein the jury selected 3 winning projects and 8 acknowledgements in a multi-stage selection process. Besides Austria with 43 submitted projects, Germany participated with a high share of submissions with 41 projects, followed by Italy with 14 and Slovenia with 14. The VUAS developed 13 projects within the design studio, wherefrom 8 were submitted for the international competition, being 2 of them priced due to their high feasibility and constructability. The project "Marie's Grätzl - Alles(s) unter einem Dach" convinced the jury due to its strong focus on people and its three-dimensional building landscape with a variety of open spaces designed according to different needs and functions (Fig. 1). The second award-winning project "Greenunity" is characterized by green open spaces on the roof and generous balconies for the new and existing storeys enhancing green facades for natural shading and microclimate improvement. The transferability of the system to all 3 buildings was ensured within well thought-out floor plans, based on a fix centered module containing wet rooms and bedrooms, and a flexibly adaptable living area. (Fig. 2).

Figure 1: *Rendering of the project "Marie's Grätzl - Alles(s) unter einem Dach" (VUAS)*

Figure 2: *Rendering of the project "Greenunity" (VUAS)*

This recognition meant a remarkable success for the students and the institution accrediting their expertise on timber construction and supporting their effort on its promotion. Parallelly, the students reported enormous satisfaction based on the learnings, the interdisciplinary approach, the expert support and the direct relation with the practice, generating enthusiasm and extensive know-how to its later implementation in their professional life. The impressive amount of submitted projects evidenced the great interest on modern and technology supported timber constructions and demonstrated their suitability and potential for urban vertical extensions delivering socially sustainable, climate friendly and resource efficient solutions. Besides, the competition promoted modern timber constructions within European universities and the need of specific education and training, what should enhance further countries to promote and support similar strategies.

Keywords: vertical extensions, standardized timber system, international student competition, sustainable urban development

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Wind Tunnel Test Timber High Rise: Kaj 16 Case study

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The construction industry is seeing a surge of ambitious timber tower projects rising all over the international market.

The adoption of a wealthier, greener structural material such as timber allows to sequester carbon from the environment as well as avoid carbon emissions derived from non-biogenic usual construction materials such as concrete or steel.

Ramboll is supporting visionary Client, Vasakronan, and Architect, Dorte Mandrup Architects, in the design of a 19-storeys, 76m meter tall tower in Gothenburg, Sweden.

The building fabric comprises two L-shaped stepping towers hosting a mixed-use program which caters from residential to office, from commercial to student accommodation.

The scheme is meant to be as flexible as possible with the intent of mitigating future refurbishment and change of use i.e., the tower is designed and imagined to cater for all needs from day one.

Give the height and the structural intricacies, a Wind Tunnel Test has been carried out to test:
- Structural loading
- Facade pressures
- Pedestrian comfort

Structural Loading are assessed to try and reduce the lateral loading from wind: Eurocode can overestimate wind forces and a physical test is the best way to certify no dynamic augmentation effect is induced on the tower due to the complicated geometry.
The presentation will focus on the modelling of the structure, the assumptions underlying the design and the testing procedure.

The study carried out particularly points out how the nature of timber construction leads to the need of careful considerations when it comes to high-rise buildings: in a typical post-and-beam solution, the timber elements are generally pinned to each other, this mean that the elements might grow bigger to resist the lateral forces.

Ram Ramboll carried out research on stability system for timber high-rises and a parametric study to investigate the most suitable solution for the building.

The conclusion was that a hybrid structure with timber deck, post and beams stabilized by in-situ concrete cores would be the most efficient structure in terms of sizes, comfort criteria, cost and carbon emissions.

The Wind Tunnel Test carried out on this solution can further reduce the effect of wind on the tower leading to increased savings.

Façade Loading are tested to mitigate costs arising from thick façade panels: Timber can represent increase in construction cost due to the material procurement so savings on the other part of the building might be crucial to fit in the budget.
Assumptions, results, and savings will be presented.

Pedestrian Comfort is an essential part of the study: timber is a great material to address some of the current megatrend such as climate emergency but is under scrutiny in terms of cost, availability, and impact on the construction overall.

As a whole study, we wanted to confirm that not only timber was the best solution for the structural system, for the project overall, but also suitable for the massing selected.
This means no adverse impact are generated on the surrounding public domain making the vision sound for tenants, users as well as pedestrians and members of the public.

Figure 1: *Kaj 16 Architectural Render*

Keywords: timber, wind, wind tunnel test, pedestrian comfort, structural loading

Radical Transparency: The Carbon Story for U.S. Wood Products

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Addressing climate change by reducing embodied carbon emissions is an important component of doing business in a number of sectors today, including construction. The built environment is a major source of greenhouse gas (GHG) emissions. It also, however, represents a massive opportunity for reducing GHG emissions and creating urban environments that serve as carbon sinks. While some construction materials may have high embodied GHG emissions and a limited capacity to sequester and store carbon, other materials have much lower footprints and the ability to store sequestered carbon for the long term, such as wood products.

As policymakers, architects, designers and builders explore carbon reduction opportunities, they are looking for data and data transparency tools that accurately calculate the benefits of choosing one building material over another. Using product level life cycle assessment (LCA), it is possible to quantify the potential GHG emissions associated with a given build-ing product through its entire life, as well as quantify any benefits related to biogenic attrib-utes the product may offer, including carbon the product may store.

The U.S. wood products sector is approaching sustainability questions from the standpoint of "radical transparency." In this spirit, the American Wood Council (AWC) has taken a lead role in the U.S. in researching and collecting product lev-el LCA data for North American wood products with the intent of having it third party verified per ISO standards. This data quantitatively demonstrates the embod-ied carbon and stored carbon benefits that come from specifying wood products in buildings, from single family homes to multi-story commercial structures.

Building off of earlier initiatives to develop the first third-party verified industry-wide Environmental Product Declarations (EPDs) for North American wood prod-ucts, AWC recently completed the development of a database that annually col-lects U.S. industry-wide data to ensure EPDs are current and statistically robust. This presentation will provide a window into the data platform, the method for collection, and lessons learned from platform development and the beta year of data collection.

Numerous jurisdictions in the U.S. have begun to contemplate and/or pass policies that aim at reducing embodied carbon in the built environment. The majority of these "Buy Clean" initiatives begin their assessment at the procurement phase, encouraging builders and speci-fiers to select the material, within a single material category, with the lowest embodied car-bon based on a product level EPD. While EPDs are effective in selecting the lowest embod-ied carbon product within a specific product group (e.g., concrete vs. concrete), this ap-proach doesn't necessarily result in maximization of decarbonization of the built environ-ment. This approach only permits siloed comparisons of embodied carbon within a product group but cannot be used to compare across materials (e.g., wood vs. concrete or steel). The end result of relying only on EPDs can be compared to rewarding a student from moving from a D- to a C-, while the A student is never considered or recognized.

Whole Building Lifecycle Assessments (WBLCA), conversely, are tools that do allow for comparisons across material categories and, when supported by robust data and a consistent and defensible methodology, can result in more significant reductions of embodied carbon than an EPD approach alone. Policy approaches for maximized carbon reductions will be explored in the presentation.

Finally, how wood is sourced is a common question that emerges, with an assertion that some wood is "good," and some is not. We will discuss a pilot project, soon to be broadly adopted, that collected data related to wood fiber sourcing. This data was compiled into a microsite to visually communicate the wood sourcing process to policymakers and architects, designers and builders (Figure 1).

Figure 1: *Wood Sourcing Transparency Microsite following the ASTM D7612 framework that will communicate a) mill-specific sustainability data in a framework that is practical (i.e., the information a mill already knows about its wood fiber sources) and b) forest certification data by region and landowner type. This website will be readily accessible through a smart phone by linking to a wood products grade stamp, each containing a unique mill identifier number.*

Today, the built environment is a climate liability. With robust and accurate data at the foundation, the built environment can emerge as a climate solution – speci-fying products with low embodied carbon and creating urban environments that act as carbon sinks. Transparency is essential. U.S. wood products are leading by ex-ample.

Keywords: carbon, climate change, build clean, data, visualization

Acknowledgment: The authors gratefully acknowledge that the fiber sourcing tool and microsite were funded by the Softwood Lumber Board and U.S. Endowment for Forests and Communities.

A Practical Approach to Developing and Sharing Advanced Mass Timber Solutions

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ABSTRACT: The United States (U.S.). market for mass timber has advanced at an accelerated pace rarely seen for new products or product categories. A number of factors have made this possible, including an unprecedented amount of research and product testing, standard development and code changes, growth in manufacturing capacity, and education/support for individuals involved in mass timber projects. With a growing number of completed buildings in the U.S., there is now a significant opportunity for technology transfer and outreach—i.e., to share best practices and lessons learned with the broader design community. As the U.S. wood industry's leading mass timber education organization, WoodWorks – Wood Products Council has developed a series of advanced design resources relevant to specific areas of mass timber design, engineering and construction. This approach, in contrast to developing an updated reference manual for mass timber design, allows flexibility to respond to issues and technological advances, while making it easier for design teams to access needed information. WoodWorks is proposing that this approach be formalized with a compilation document that includes these and other assets aimed at supporting the design and construction of mass timber projects in the U.S.

INTRODUCTION

The U.S. market for mass timber has advanced at an accelerated pace rarely seen for new products or product categories. Cross-laminated timber (CLT) was relatively new to the U.S. when the CLT Handbook (U.S. edition) was introduced in 2013 [1]. Since then, much of the information has been updated and/or made readily available through other sources. The number of mass timber buildings has also proliferated. WoodWorks – Wood Products Council, the industry's leading education organization for design and construction professionals, tracks the number of active mass timber projects and provides a quarterly update [2]. As of March 2022, 642 multi-family, commercial or institutional projects had been constructed out of mass timber in the U.S., and 742 were in design. (See Figure 1.)

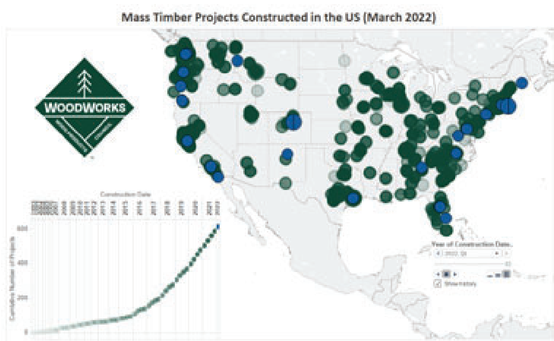

Figure 1: *Map of mass timber projects and ramp of project growth. Source: WoodWorks – Wood Products Council.*

Part of WoodWorks' role is to provide project support, and the organization has assisted on more than 75% of the built projects shown in Figure 1. WoodWorks has leveraged this familiarity to develop a series of papers, assembly inventories, design examples, and design guides with an emphasis on difficult or advanced topics that apply to the design and construction of U.S. mass timber buildings.

WoodWorks is proposing that a compilation document of individual papers replace the reference manual format in order to facilitate additions and changes as new information comes available. The nimbleness of this approach will make it easier for design teams to navigate current information, resolve technical issues, and complete successful mass timber projects.

COMPILATION STRUCTURE

The goal of this new design manual is to enable design and construction professionals looking for mass timber resources to access all of the necessary documents from within one download. This creates an e-book featuring an expanded table of contents with links to key documents. In addition to its role as a one-stop resource for information being sought, the e-book will serve as a guide to available materials. To this end, a stand-alone pictorial guide to the referenced publications will be made available as a separate download, making the e-book accessible to both beginners and those experienced with mass timber. This new "Mass Design Timber Manual" will be published by Think Wood and WoodWorks and focus primarily on content from these organizations. First released in 2021 and with a Volume 2 (Figure 2) release in April of 2022 this approach has proven successful with tens of thousands of downloads.

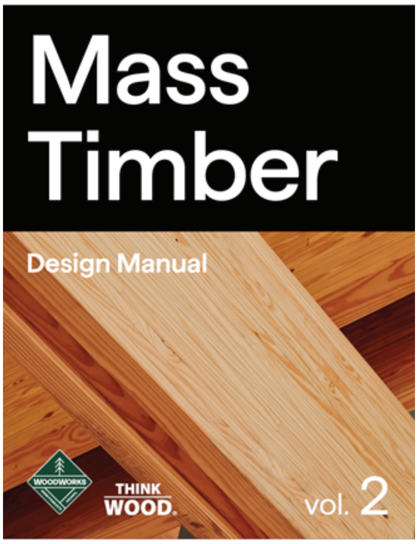

Figure 2: *Cover of Mass Timber Design Manual, Volume 2. Source: WoodWorks – Wood Products Council.*

Chapters in the document include:
1) Introduction
2) Mass Timber Products
3) Timber Design Applications
4) Timber Construction
5) Solutions for Building Taller
6) Mass Timber and Sustainability
7) Conclusion

High-level information is predominantly sourced from Think Wood Continuing Education Units (CEUs), and detailed technical information is provided by WoodWorks. Content includes product overviews, sustainability, forestry, green buildings, case studies, demonstration projects, connections, lateral design, vibration design, tall wood, installation, and other advanced design and detailing topics. The e-book serves as a comprehensive manual, while providing detailed technical content that allows experienced mass timber design professionals to resolve complex issues.

COMPILATION STRUCTURE

The WoodWorks mass timber design series currently includes the following resources:

Mass Timber Design & Cost Optimization Checklists – Guides coordination between designers and builders (general contractors, construction managers, estimators, fabricators, installers, etc.) as they estimate and make cost-related decisions on mass timber projects [3]

Fire Design of Mass Timber Members: Code Applications, Construction Types and Fire Ratings – Focuses on how to meet fire-resistance requirements in compliance with the International Building Code (IBC), including calculation and testing-based methods [4]
Inventory of Fire Resistance-Tested Mass Timber Assemblies – Evolving list of mass timber assemblies and penetration fire stopping systems in mass timber assemblies that have been tested for fire resistance [5]
Acoustics and Mass Timber: Room-to-Room Noise Control – Covers mass timber acoustical design with an emphasis on room-to-room noise control [6]

Inventory of Mass Timber Acoustic Assemblies – Evolving list of mass timber assemblies that have been acoustically tested [7]

Concealed Spaces in Mass Timber and Heavy Timber Structures – Covers the choice of construction type and other implications for concealed spaces [8]
Tall Wood Buildings in the 2021 IBC: Up to 18 Stories of Mass Timber – Summarizes changes to the 2021 IBC as well as the background and technical research that led to their adoption [9]
Shaft Wall Requirements in Tall Mass Timber Buildings – Takes an in-depth look at the requirements for shaft walls under the 2021 IBC, including when and where wood can be used [10]

Demonstrating Fire-Resistance Ratings for Mass Timber Elements in Tall Wood Structures – Examines how to achieve FRRs under the new tall wood construction types in the 2021 IBC [11]

Breaking Convention with Wood Offices – Features a variety of mass timber wood offices in the U.S. [12]

The following CEUs have been created by Think Wood:

Mass Timber in North America – Examines the trend toward mass timber in the context of carbon footprint, construction efficiency, fire and life safety, occupant well-being and other potential advantages [13]

The Impact of Wood Use on North American Forests – Considers the use of wood as a construction material in the context of long-term forest sustainability and attributes such as embodied energy and carbon footprint [14]

Additional items are included in the MTDM but not in this paper due to space.

CONCLUSION

WoodWorks' role as a provider of education and project support has created an opportunity to leverage lessons learned on the growing number of U.S. mass timber buildings for the benefit

of the broader design and construction community. This paper demonstrates an approach to creating and maintaining a suite of resources that is both nimble, allowing quick response to issues and technological advances, and easy to navigate by design and construction professionals. Although focused on the U.S. market, this approach and the resulting documents could easily be replicated in other countries.

Keywords: timber, wind, wind tunnel test, pedestrian comfort, structural loading

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Moisture Management Strategy Using Sensor Technology in Mass Timber Construction

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ABSTRACT: To monitor the use of timber and how it is affected by moisture in the construction phase, sensor technology by Woodsense has been incorporated in the moisture management strategy and construction of the mass timber construction of Sophie Radich in Lillestrøm. By taking a preventive approach to moisture management in the construction phase, it is possible to reduce resource waste, as damages can be found earlier in the process and before the building is put into use. After having used sensors on the Sophie Radich project, increases in moisture levels were detected. The preventive approach of the sensors made it possible to correct the cause of the moisture increase, avoiding further damage to the construction while illustrating the advantages of sensor-based technology.

INTRODUCTION

More sustainable construction calls for solutions that reduce resource consumption and CO2 emissions through an increased use of sustainable building materials such as timber. Although timber is a better alternative resource for the climate than conventional materials such as concrete and steel, many in the industry have concerns about using it in construction due to challenges associated with moisture protection and management.

Some of the main barriers preventing the use of timber as a building material is fear of moisture damage and, as a result thereof, a waste of resources. To document the moisture management of the Sophie Radich project, which is made of cross laminated timer (CLT), the intelligent sensor solution by Woodsense has been incorporated into the project. Through constant monitoring and automatic alarms, the sensors assist in carrying out an effective moisture content strategy with documentation of correct moisture management throughout the entire construction process.

The sensors are effectively used e.g. to document that there is no excessive moisture in the elements, and share said data between construction actors in the project. Additionally, the sensors contribute to the reduction of resource waste and a responsible use of building materials. Furthermore, by preventively monitoring the growth of mold, the sensors promote a healthy indoor climate to benefit the health and well-being of the building's users.

SOPHIE RADICH PROJECT AND MOISTURE MANAGEMENT STRATEGY

Sophie Radich school in Lillestrøm is an 8-parallel youth school with room for 720 students. The project has been developed in collaboration with contractor Kruse Smith and Lillestrøm municipality. Arkitema is involved as an architect and landscape architect. The building is a CLT construction and has a very high environmental ambition with a blue-green focus.

The school has a distinctive architecture shaped as a four-leaf clover, and with a strong focus on the surrounding nature, students will experience an interaction between the indoor and outdoor environment.

Timber has been chosen as part of the main construction for the entire building, primarily from an environmental point of view. However, it is also a choice based on the theory that the use of wood has a positive impact on physical and mental health (tsenetsugu, Miyazaki, Sato. 2005). Findings from another study regarding use of wood in buildings show a massive decrease of systolic and diastolic blood pressure (Rice et al. 2007). This is, in addition to aesthetic considerations, the basis for choosing visible wood in the building's interior.

2.1 The moisture management strategy

During the construction process, it was a challenge how to handle rain and moisture in the Norwegian climate, where ice formation and snow can also be a major problem. It was considered using a tent during construction, but this would mean additional costs which is a disadvantage compared to traditional construction methods. It was therefore decided not to cover the building during the construction period. It was expected that repair of any damage would be less than the cost of a tent / superstructure. Unfortunately, the autumn of 2021 was particularly rainy and windy, and there was some concern related to moisture, especially on the roof. An agreement was therefore made with Woodsense, to uncover any leaks and moisture problems.

USE OF SENSOR TECHNOLOGY TO AVOID DAMAGES CAUSED BY WOOD MOISTURE

One of the main issues of working with timber in construction is related to moisture damage, and as a result thereof, a waste of resources. The sensor solution by Woodsense seeks to address that issue by measuring wood moisture, temperature and humidity, and comparing the data with local weather data. By analysing the collected data, it is possible to detect leaks and conditions that can lead to mold and rotting of the wood. Through constant monitoring, moisture damage can be prevented, thus reducing resource waste when using timber in construction projects.

The digital platform of the sensors has integrated the so-called mold curves, derived from mathematical models from research in the field. These are used, among other things, to visualize the environment of a given sensor and determine the risk of mold growth. By preventively monitoring the growth of mold, the sensors promote a healthy indoor climate to benefit the health and well-being of the building's users.

Sensors was placed on various locations in the Sophie Radich-construction to monitor particularly exposed areas, detect moisture damage before it occurred, and document moisture management throughout the construction. Developers have expressed their satisfaction when working with the sensors and digital platform, due to the ability to constantly monitor the moisture level, which leads to a higher sense of control with the moisture content of the construction materials.

In one of the selected areas, sensors were placed towards the edge of the roof to ensure proper roofing, under windows on roofs, and on different facades to monitor the difference in north-, south-, east-, or west-facing facades. Additionally, a sensor was placed on a cornice to monitor the cover towards the edge. Here, the sensor found a mistake made by the roofer, as the covering had not been completed, which had resulted in water entering the construction and rising to more than 30 %. Had the sensor not detected the damage in the cornice, it could have led to a substantially more expensive repair, as the water could have been in the construction for several months, and potentially developed mold growth. This exemplifies the advantages of sensor-based technology, as it is possible to capture situations such as these immediately.

CONCLUSIONS

Using the sensor solution, several increases in moisture levels were detected, which could have developed into more extensive moisture damages. The damages found by the sensors exemplifies the advantages of sensor-based technology, as it is possible to immediately capture situations that can be damaging to the construction.

Furthermore, developers and other participants of the project expressed their satisfaction with the product due to a higher sense of moisture control. Going forward, several sensors will remain on the roof of the construction to ensure that the green roof laid on top lasts as expected, and that the drains likewise work as intended.

Further research can be done to investigate how different coating affect the moisture storage in wood-based materials, for example fire painting. This can be done by using Woodsense sensor technology.

Keywords: CLT, moisture management, sensor technology

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Lightweight Floors Vibrational Comfort: First Experimental Results of the GIVILIF Project

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One of the main issues of high-rise timber buildings is the large floor height compared with steel or concrete construction. Then, to make a more spacious building, it may be desirable to expand the joist spans. However, by doing so, the stiffness of the wooden floor will decrease and vibrational discomfort could appear. Then the regulatory texts to define and give critical values of floor parameters to ensure comfort remains to be improved. The parameters and the thresholds of perception and intolerance to evaluate and predict the vibrational discomfort for other contexts (e.g. Canada) are known (Ussher et al., 2022). In Europe and particularly in France where lightweight floors are not so commons, it is always required to carry out more empirical experiments on the relation between physical characteristics of vibrations (frequency, displacement, velocity, acceleration) and psycho-physiological sensations.

The GIVILIF project (Group Induced vibrations on Light floors) aims to improve and complete the existing standards concerning vibrations on light floors induced by group activities, especially ISO 2631 and ISO 10137 (Hu et al., 2018). In particular, the problem related to floors with a fundamental frequency lower than 8 Hz, which are not taken into account in the Eurocodes, and require specific studies for each project.

The methodology of the study aimed, in a first step, to evaluate the perception of subjects for different vertical displacements. The proposed experimental protocol allowed the testing of 59 signals by stimulating frequencies from 1Hz to 16Hz for different displacements (0.01mm, 0.05mm, 0.1mm, 0.5mm, and 1mm). Using a shaking table, 36 subjects underwent vertical vibrations in different positions (1) sitting without activity needing concentration, (2) sitting with an activity needing concentration, and (3) lying position (See Figure 1).

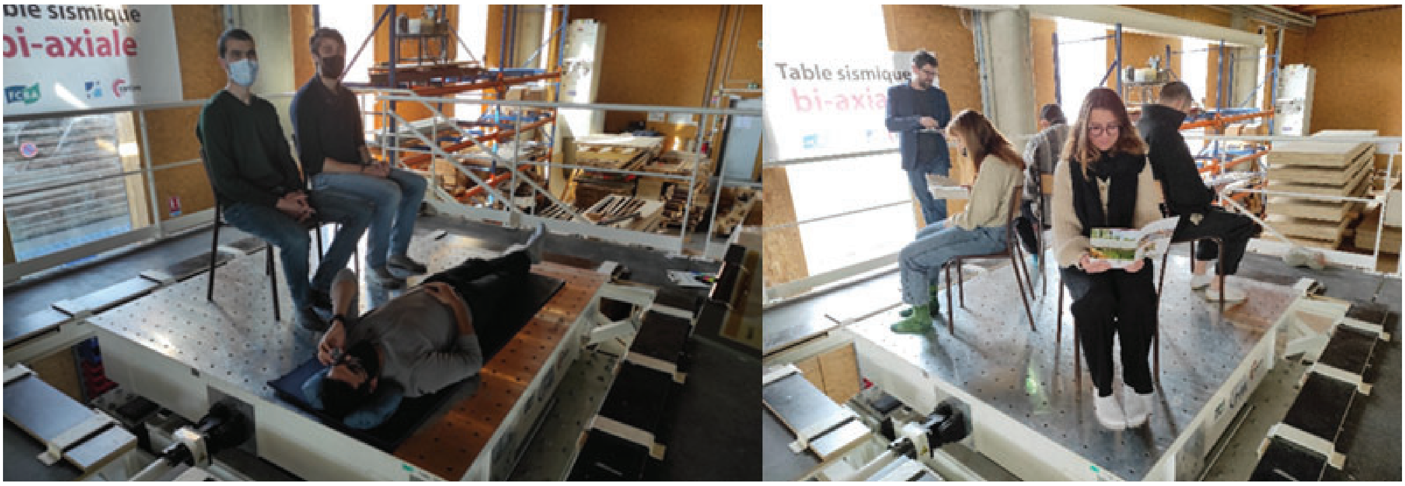

Figure 1: *Experimental tests of vibrational comfort using a shaking table.*

After an exposition time to vibrations of 60 seconds by signal, subject evaluations were recorded on a four-level scale from "imperceptible" to "intolerable". Furthermore, physiological measurements related to the stress conditions of the subjects were done before, during, and after the experiments.

Experimental tests showed that the thresholds of perception, discomfort, and intolerance vary from one person to another depending on gender, age, body morphology, sensitivity to vibrations in everyday life, etc. Furthermore, the thresholds of perception differed importantly according to the characteristics of vibrations. Thus, low frequencies of vibration (1Hz to 2Hz) are perceptible when the displacement is high (0.5mm to 1mm). Whereas for a low displacement (0.01mm), the frequency must be 3Hz to 4Hz for the vibration to be perceived. Regarding position, subjects in a lying position are more sensitive to vibrations than seated subjects. Moreover, the displacement, frequency, and time of exposure affected the part of the body through which the vibrations are perceived. Feet, for example, are sensitive to vibrations from 0.05mm, 1Hz, and 15s while the head is sensitive from 0.01mm, 5Hz, and less than 15s (See Figure 2).

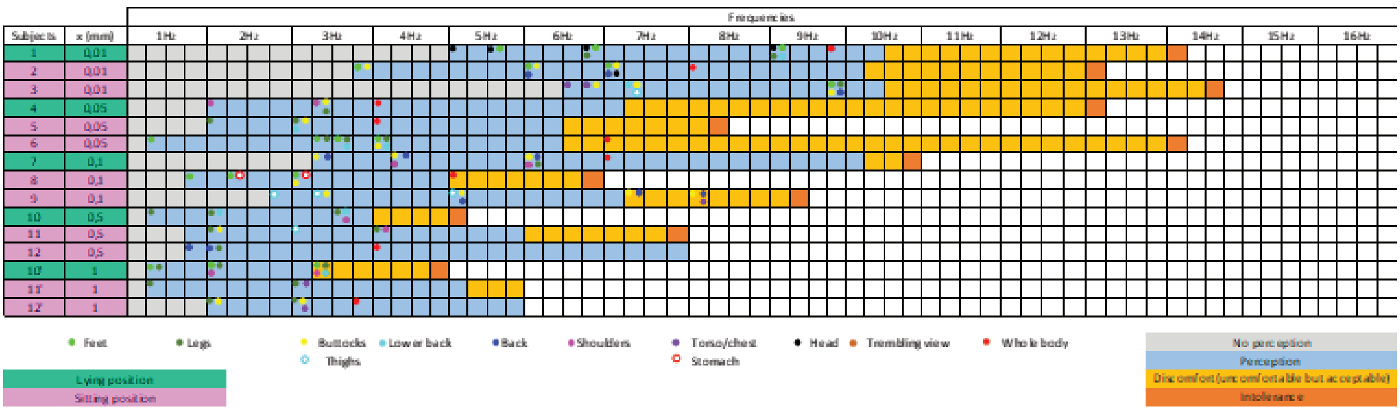

Figure 2: *Examples of vibration evaluation.*

This first experimental phase enabled both the validation of a protocol for evaluating perceptions of vibration comfort and the release of initial results on the impact of the various physical characteristics of vibrations on the subject's perceptions. The next phases will consist of evaluating comfort first on an experimental wooden floor, then on a real site in occupied housing. The main objective of the project is to determine the physical characteristics that affect comfort and to define a method to evaluate the comfort threshold for a given population since comfort seems to be linked with the experience of users. The tests will be conducted for realistic load, as walking, running, and shock, and not only with harmonic sinusoids. The project will contribute to the improvement of existing standards around vibrations of lightweight floors and will lead to better-designed floors, especially for new medium and high-rise timber buildings.

Keywords: timber construction, vibrations, standards, experimentation, perception

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Specific Systemization of Timber Building to Promote Urban Redensification of Housing Stock

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Especially in urban areas, the demand for housing space is higher than the supply. This problem is partly addressed with new suburban building areas on the greenfield sites. In the alpine urban areas, however, there's almost no sustainably usable building land, because all potential area for new building have already been in use by infrastructure, agriculture as well as flood prevention and nature preservation. (Glinka, 2017, p. 49) (Voigtländer, 2017, p. 108)
A better approach is the redensification of the housing stock by adding stories. Especially, timber construction building systems are perfectly suitable for this task, because of their low weight, low building moisture as well its fast construction process and finally its carbon footprint. Unfortunately, in the timber building branch, most of the companies (SME) cannot realize big projects in this special field yet due to their low production capacity and the level of complexity. On the one hand, there are plenty of standardized and publicly available timber panel constructions for multi-story buildings, though their suitability for loft conversion projects is questionable. On the other hand, individual effortful planning and proof of building physics is necessary to consider the structural conditions of the multi-story housing stock.

The project aims at providing a certified timber construction building system for redensification, which offers secure application, cost certainty and flexible planning. Besides, cooperation of companies, especially SME, will be promoted by the company-independent and freely available standard construction system (including construction components and construction details). Furthermore, the degree of prefabrication is as high as possible to benefit from above mentioned advantages of the construction method.

Different methods were used to achieve these aims. The issue of compatibility was addressed by preselection, modification of available components and development of junction details. Specifically, construction components were optimized for loft conversion as well as resource efficiency by minimalizing material effort, using biogenic materials and maximizing prefabrication. In parallel, the individual share of planning effort was minimized through company-independent choice of material, generally valid construction rules and limitations of application for typical residentials buildings of the 1950s to 1970s. By reducing the variety of building components, a specialized building system is created and thus cost security is achieved. Furthermore, several external experts were called in to ensure a proofed wood building system. Beside this, different analysis methods were conducted to provide a base for development. Initially, 33 existing objects were analyzed to be able to construct three abstract and representative building floor plans for added stories (see figure 1). In addition, the occurring structural system types were identified and listed.

This information was used as a planning draft for consulting by an external structural engineer. For the walls and floor panels, adverse structural system types were chosen and combined with the data of the abstract design to assess the range of dimensions of the panel constructions.

Figure 1: *Representative floor plan with planned addition of stories, based on 33 real buildings*

In parallel, the most adverse exterior noise level for the central city of Salzburg was identified and assessed by the sound protection expert. Starting from the night level of 55 dB, relevant levels for the sound reduction index Rw for the opaque construction elements were determined considering a 45 percent share of window area and the real sound transmission. Eventually, the different panel constructions were assessed and modified where needed.

Regarding fire protection, the analysis revealed that the relevant building stock has a number of 4 to 5 stories. Above 6 full stories, a fire protection concept is necessary, which has a very building-specific character. Therefore, the system is designed for 1 to 2-story additions up to 6 full stories. There are strong national requirements in the resulting building class 5 (GK5), which makes drywall encapsulating of the bearing wood structures, in the case of fire resistance rating of REI90, necessary. The system provides an optional adding of a gypsum fibre board layer to reach different REI ratings. The calculations for thermal and humidity protection were performed internally.

The result is a resource-efficient, environmentally sustainable and flexible timber construction building system specialized for urban redensification and especially tailored for SME and their cooperation freely available by autumn 2022.

Keywords: urban redensification, SME, timber construction system, story addition, loft conversion

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Bioinspired Living Coating System for High-Rise Buildings

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Several tall buildings have achieved greater heights and their designs have become more attractive and complex. Consequently, access and maintenance of building façade has become more demanding in terms of efficiency, coordination, and customisation. Architectonic coatings enhance the functional and aesthetical durability of degradable materials by protecting their surface against environmental and biotic degradation. Therefore, paint and coating applied on the exterior of a residence, or a commercial building, not only add to the aesthetics of the building but also protect it against heat, UV, harsh winters, soaking rain, and other adverse weather conditions. Hence, the service life of architectural coatings significantly impacts the overall building maintenance costs.

The deterioration process of bio-based building materials (timber, engineered wood products) exposed to weathering mainly affects aesthetical properties. In most cases, weathering is caused by abiotic factors and manifests as an alteration in color, surface cracking, change in glossiness, and increased surface roughness. The intensity and extent of weathering depend on the local macro-, meso-, and microclimate conditions, weather history, material type, architectural details, and specific surface properties. The most important factors that affect weathering kinetics are solar radiation and stresses imposed by the cyclical wetting (moisture), together with changes in temperature, environmental pollutants, and the actions of certain microorganisms. In general, unprotected raw bio-based materials weather faster on the subsurface, leaving the bulk intact. Differences in discoloration may be very noticeable on the same façade, especially on buildings where water and solar radiation are not spread uniformly across the surface (Sandak et al. 2019).

To broaden their applicability, an overall improvement of several properties of bio-based materials, such as dimensional stability, thermal stability, fire resistance, biotic and abiotic degradation resistance, and mechanical properties, is required. Protection methods include environmentally friendly bulk treatments, such as thermal treatments, densification, impregnation, and chemical modifications as well as surface treatments, including innovative coatings, impregnations, or integration of developments in nanotechnology to protect biomaterials. The latest trends are driven by the biomimicry approach of capturing and exploiting properties that have evolved in nature, which is also the inspiration for ARCHI-SKIN. This project will implement biomimetic principles for the development of Smart Living Surfaces (SLS), where a living coating system will be designed and implemented for the protection of various building materials. Such an approach allows for the derivation of optimal designs that benefit from improvements made during the evolution of living organisms and efficient use of natural resources in a more sustainable and environmentally friendly manner.

The coating formulation will be optimized for three types of substrates: bio-based porous, inorganic porous, and non-porous (Fig.1). Both organic and inorganic (wood, modified wood, concrete, stone, and bricks) porous materials, will be filled with various carbon sources that will serve as nutrients, and selective bio-additives that will stimulate microbial growth, control cell morphology, and Extracellular Polymeric Substances (EPS) matrix production. Additionally, biological materials will be impregnated with environmentally friendly fire and flame retardants. For non-porous materials (metal, plastic), the coating system formulation will contain a higher content of modified lignin. Thanks to various natural additives as well as the presence of living fungal cells, the ARCHI-SKIN coating system will possess several innovative properties such as self-regeneration and bioremediation.

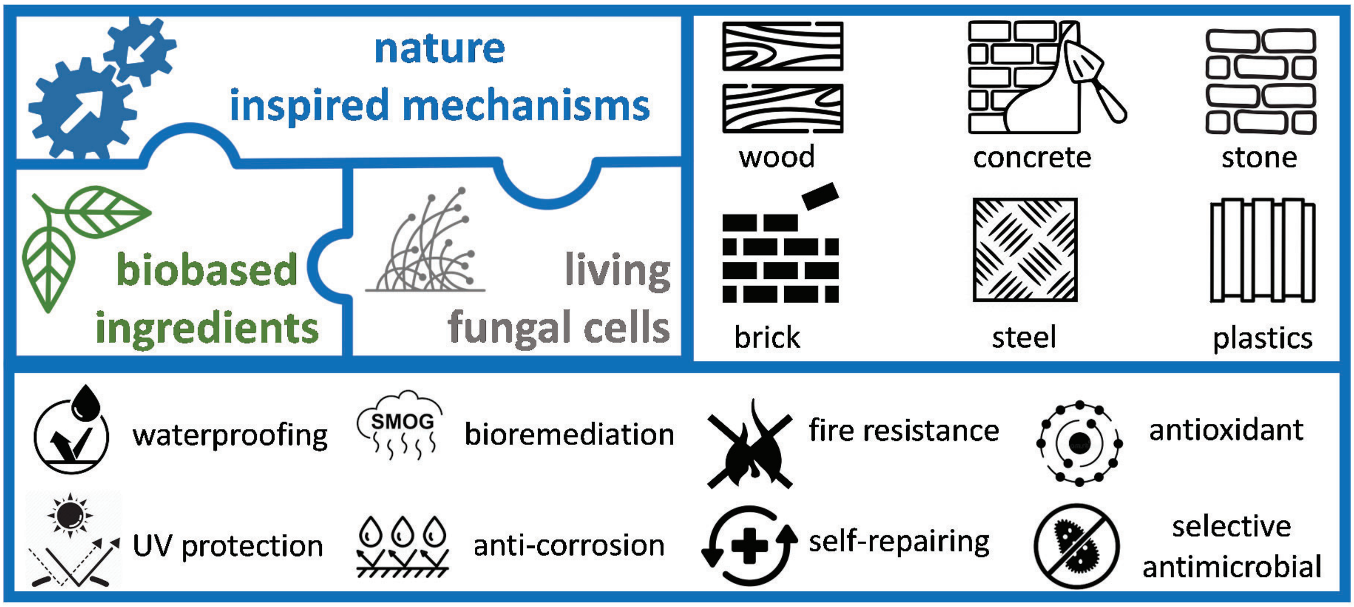

Figure 1: *ARCHI-SKIN project concept*

Application of ARCHI-SKIN coating in big cities will potentially contribute to lowering air pollution, a major global urban challenge resulting in an estimated extra 800,000 deaths a year in Europe (Lelieveld et al. 2019). The enhancement in performance due to self-repair functionality will improve the environmental impact and reduce the cost burden of premature failure in service and maintenance activity. Superior service life performance is particularly relevant in tall structures, where regular maintenance and renovation are more time consuming and costly. Improvements in quality of materials that reduce the cost of recoating over decades should, therefore, be economically attractive for architects, building owners, and ultimate users.

Keywords: architectonic coatings, durability, smart living surfaces, engineered living materials, building façade

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Sustainable Development of Wood-based Products for the Construction Sector: The NewWave Project Approach

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Twenty-first-century manufacturing requires new materials and new techniques to produce sustainable products made from bio-based materials that are easy to reuse and recycle. The construction sector is one of the main candidates to make bigger and more transformative changes, due to its centrality in a variety of value chains and their large potential contribution to emissions reductions. The EU aims to achieve climate neutrality by 2050 by accelerating the twin green and digital transitions according to the European Green Deal objectives. This requires the development of new technologies fundamental to creating new products, services, and business models.

The research project, newly funded by the Horizon Europe NewWave is building a circular economy by adapting existing manufacturing lines to substitute traditional fossil-based materials with bio-based resources that are sustainable, non-toxic, and fully recyclable. The NewWave consortium is a unique combination of European companies and institutes covering different value chains from biomass resources to valuable end products. It consists of seven innovative SMEs, two academic partners, and two large industrial companies representing four different but interlinked manufacturing lines. The four manufacturing lines are polyols and polyurethane, hydroxymethyl furfural (HMF) and derivatives, engineered wood panels, and modified wood. The NewWave produces wood-based products for the construction industry, including Cross Laminated Timber (CLT) to replace steel and concrete, Medium Density Fiberboard (MDF), plywood for interior usage, and modified wood for a durable, maintenance-free, outer skin. After extensive laboratory tests, new construction products will be manufactured at an industrial scale and used at a demonstration site. Modified wood boards, plywood, and CLT produced in the NewWave manufacturing lines will be used as cladding and construction materials that will be a part of the new InnoRenew building.

Building information modeling (BIM) will be implemented as an essential mock-up simulation tool to simulate full coordination of various design details before physical construction.

Geometrically complex façade elements will be first generated by parametric modeling techniques, allowing coordination and optimization of various design details. Consequently, the virtual mock-up will be used for the improvement of construction operations and the implementation of new materials in the building envelope.

The performance of the materials, moisture content, and temperature in envelope layers will be monitored in situ, allowing for observing the deterioration of materials, and estimating service life regarding functionality and aesthetics (Fig.1). This information will be used for future optimization of the formulation and modification process as well as scheduling of recommended maintenance actions. The demo site mock-up will provide practical experience in terms of material machinability, application, and behavior during service life.

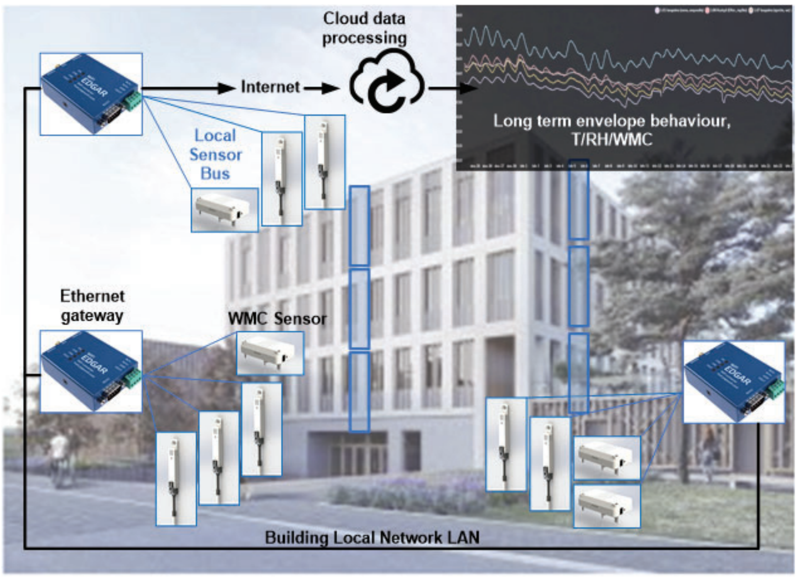

Figure 1: *Schema of the building envelope monitoring system that will be implemented on the InnoRenew CoE building.*

An important aspect of the NewWave project is the end-of-life and circularity of developed modified/engineered materials. Therefore, flexibility and behavior of feedstock at the target value chains will be studied. For the first step, different reused and recycled biomass resources, including the ones from the recycling of end-of-life wood products, will be identified and analyzed. As a second step, the recycling/reuse of the by-products generated by the manufacturing lines will be assessed. Then, the recycling/reuse of the selected end-products (at their end-of-life) will be studied. Finally, a life cycle assessment (LCA) and life cycle costing (LCC) will be carried out to evaluate the environmental and economic impact of the production of biobased products.

Keywords: natural resources, circularity, bio-based products, sustainability, digitalisation

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Enabling Robust and Precise Life-Cycle-Costing in Wood Construction by Novel Methods for Service Planning: An Outline of the 'WoodLCC' Project

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The overall objective of the ForestValue project WoodLCC is to enable robust and precise Life-Cycle-Costing (LCC) based on input from novel models for detailed service life performance specification for wooden components and buildings.

It was hypothesized that (1) improved service life input data will enable more precise and robust LCC for wood-based products, resulting in significantly improved economic and environmental impact, and (2) LCC finds common acceptance only if reliable input data are available and complemented with knowledge about user expectations. Therefore, a holistic approach is used to integrate service life data in LCC analysis instruments.

The key scientific and technological objectives of WoodLCC defined to provide optimised input data to LCC for wood-based materials are to (1) Utilize novel service life prediction models to provide reliable service life estimates for LCC of wooden components and buildings, (2) Quantify the effect of different maintenance, repair and replacement schedules on service life and the effect on LCC of buildings, (3) Survey service life and cost acceptance of stakeholders at a European scale, (4) Determine LCC of wooden components and buildings in comparison with competing alternatives, (5) Analyse cost benefits of moisture safety measures during the construction phase, (6) Quantify the impact of imperfect design details on LCC, (7) Identify and analyse potential risks related to the use of mass timber in the climate envelope as well as the costs associated with damage and mitigating measures, and (8) Validate service life and LCC estimates based on real-structure inspections.

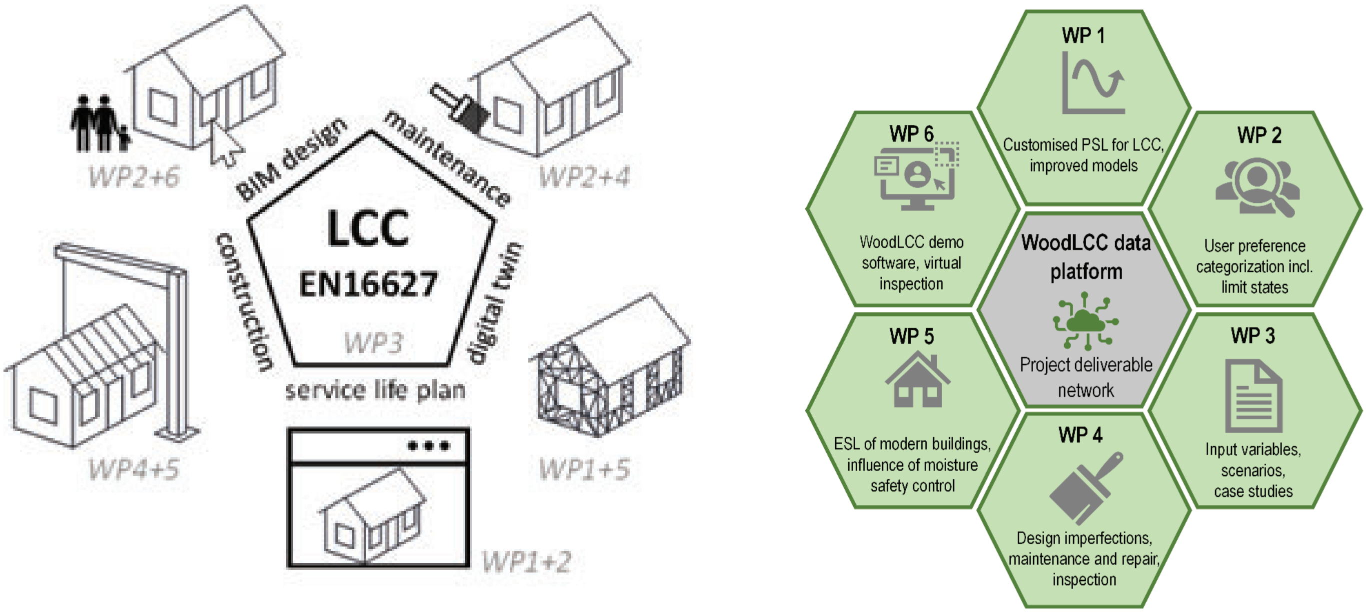

Figure 1: *Core elements of WoodLCC and their link to work packages (WP).*

WoodLCC will take full advantage of results from novel methods for detailed service life performance specification established through extensive research over the last years on dose/ response functions for exterior wood elements. The novelty of WoodLCC is to optimise the input data for LCC for wood-based building products. Instead of generic data, the service life of wooden materials and building components will be assessed with novel methods including performance models that account for fungal, insect and weathering 'damage' and considering climate, design and use conditions. Service life estimates will be linked to consumer acceptance thresholds of planers, house builders and owners.

Six research institutions and 12 partners from industry representing Norway, Sweden, Estonia, Slovenia and Germany teamed up in WoodLCC. The work is allocated to eight work packages as illustrated in Figure 1, i.e. WP 1 – Service life prediction and performance specification, WP 2 – Service life and cost expectations, WP 3 – Life-Cycle-Costing and case studies, WP 4 – Impact of design detailing on LCC, WP 5 – Adaptation of methods to modern building techniques, WP 6 – Software development and validation studies, WP 7 – Project management and monitoring, and WP 8 – Transnational dissemination.

Keywords: aesthetical appearance, fungal decay, life-cycle-costing, performance, service life prediction

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Factory-bonded Gypsum on CLT: A Quest to Improve Quality and Efficiency

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The development of cross laminated timber has increased possibilities for the construction of timber. Gypsum board protection is often implemented to meet acoustic and fire safety requirements. These boards are commonly fastened to the protected construction on site. However, mostly the labor involved for gypsum board protection adds a very significant share to construction costs of CLT buildings (Chaggaris, 2021). The study presented in this abstract considers an alternative method: factory bonding.

Factory bonding of gypsum boards on CLT is expected to involve significantly reduced costs, as they potentially could be bonded as an extended procedure of the CLT production. This process could use the same adhesive and press as is used for the CLT production.
In addition to improved cost-effectiveness, it is expected that factory bonding gypsum boards has advantages regarding fire safety during the construction phase and quality control.

This abstract discusses assessments of the fire protective ability of bonded-on gypsum boards in a series of small-scale fire tests and a full-scale fire resistance test. The gypsum board failure time is compared to the failure time provided in the final Draft of the upcoming Eurocode 5, EN 1995-1-2:2020 (E).

Materials
As its fire protective ability is one of the main reasons to apply gypsum boards to CLT, fire performance of the adhesive allowing a long enough duration of protection is essential. In this study, Loctite HB X, a recently certified 1-component polyurethane CLT adhesive is used, which is so far the only 1-component PUR adhesive that showed resistance against CLT glue line integrity failure according to current North American standards and proposed European testing methods.

Different types of gypsum boards are included in the small-scale study. The tests included gypsum fibre boards (Knauf Vidiwall), a gypsum plasterboard (Knauf Diamant) and a fire rated fleece-lined plasterboard (Knauf Fireboard). The full-scale test was conducted with one layer of bonded-on Vidiwall boards.

Fire testing

Four small-scale tests and one full-scale test were conducted. The small-scale tests aimed to give an initial indication of the performance at full scale. These tests were conducted on a furnace that exposed an area of 400 x 500 mm. The specimens, which consisted of CLT and bonded-on gypsum boards, were positioned on top of the furnace in a way that the exposed gypsum board element was not supported by furnace walls and could freely fall from the CLT into the furnace. Three thermocouples were positioned at the CLT-gypsum interface to indicate fall-off using assessments in line with EN 13381-7 (2020). However, due to the smaller scale for these four tests, a stricter failure criterion was chosen, where only one thermocouple reading over the given limits was identified as failure.

The loaded full-scale test was performed on an industrially produced specimen in accordance with EN1365-2 (2014) and the test duration was 100 min. A large amount of temperature measurements was included in line with EN13381-7 (2020) at the unexposed side of the gypsum fibre boards and in the CLT.

Results in Table 1, indicate that the failure times of the factory-glued CLT-gypsum specimens were higher than calculated in accordance with the final draft of the upcoming Eurocode 5. For the full-scale test, this indicates that the performance is at least within the range of the performance expected for traditionally fastened gypsum boards.

Table 1: *Gypsum board failure times of CLT specimens with glued-on gypsum boards set against values in the final draft of the upcoming Eurocode 5, EN 1995-1-2:2020 (E).*

		Failure time (min)		
Scale	**Board**	**Experiment**	**Final draft of upcoming Eurocode 5**	**Experimental failure time > upcoming EC 5 failure time**
	Vidiwall 12.5 mm	35	23	Yes*
	Vidiwall 12.5 mm (2 layers)	36 (1st) 53 (2nd)	23 (1st) 46 (2nd)	Yes*
	Fireboard 12.5 mm	42	25	Yes*
	Diamant Board 12.5 mm	28	17	Yes*
Full	Vidiwall 15 mm	33	26	Yes

** According to EN13381-7 (2020) the fall-off time needs to be determined using full-scale testing. These results only serve as an indication*

Conclusions

The full-scale test showed that bonded-on Vidiwall board using Loctite HB X has a fire performance that is at least as good as the performance expected for mechanically fastened gypsum boards. The four small scale tests gave an indication of good performance, but due possible scaling effects cannot directly be used to determine failure times.

Expectations and future work

Gluing-on gypsum boards as an extension of the CLT production process shows a potential to improve the cost-effectiveness of timber structures with fire protection, which would increase its competitiveness against other materials. However, a number of production details including: cutting; waste management of residual gypsum material and; on-site water protection similar to timber framing, need analyses to get a complete picture of pros and cons.

Keywords: gypsum fibre board, cost-effectiveness, fire protection, CLT, fire resistance

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Copenhagen's Largest Timber Building: A full LCA Comparison

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The current climate crisis and the major part cause by the construction sector has led to an increase in complex and ambitious timber projects around the world. One such project is currently under construction in Denmark as the capital, Copenhagen, aims to become the world's first carbon-neutral city by 2025.

To rise to the challenge of the Paris Agreement, Denmark has published a new legislation limiting the allowable carbon footprint of new buildings, which will take effect in January 2023. As part of the 2023 Building Regulation not only are all new buildings required to undergo a full life-cycle assessment but also new buildings larger than 1000 sqm are required to have a carbon footprint smaller than 12kgCO2e/sqm/year. These two requirements are complemented by a "voluntary" sustainability class with a limit of 8 kgCO2e/sqm/year.

With its completion in 2024, Marmormolen is going to be Copenhagen's largest mass tim-ber building embedding tons of carbon into its structure.

Marmormolen consists of ten rectangular cubes that differ in height from 4 and 8 stories, stepping up and down in response to its surroundings. The building will combine parking basement, retail, public spaces, offices, roof gardens and a courtyard, which combined sums up to 34,000 sqm.

The superstructure is comprised of prefabricated concrete cores, CLT slabs, steel and glulam beams, and glulam columns. Steel beams are used where necessary to accommodate installation routes below the ceiling. The building contains around 7700 m3 of mass timber.

Ramboll is supporting the climate conscious and ambitious client, AP Pension, and the architects, Henning Larsen Architecture, in the design of the building which intends to become a prototype for future timber structures.

Considering that buildings in Denmark traditionally are built using prefabricated concrete elements and since timber structures are slightly more expensive than concrete structures, Ramboll undertook a full one-to-one LCA comparison between the timber building and a corresponding concrete building to highlight the environmental benefits of mass timber buildings and to support the client's decision to build using this alternative material.

The analysis results are reported for the following stages: upfront carbon (A1-A3), usage (B4, B6), end of life (C3, C4) and beyond life opportunity (D) in order to provide maximum transparency.

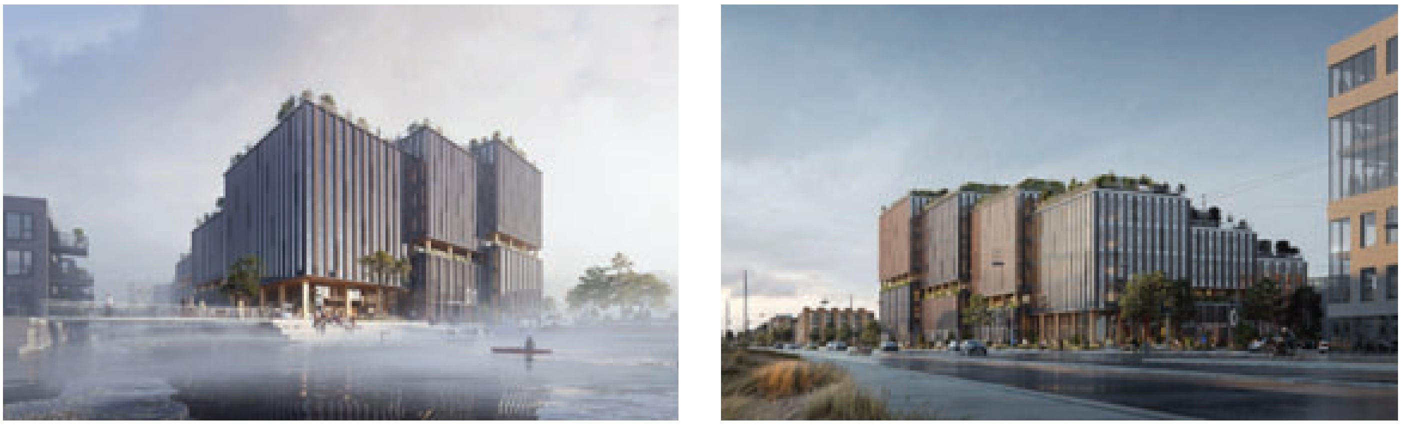

Figure 1: *Marmormolen – Architectural render*

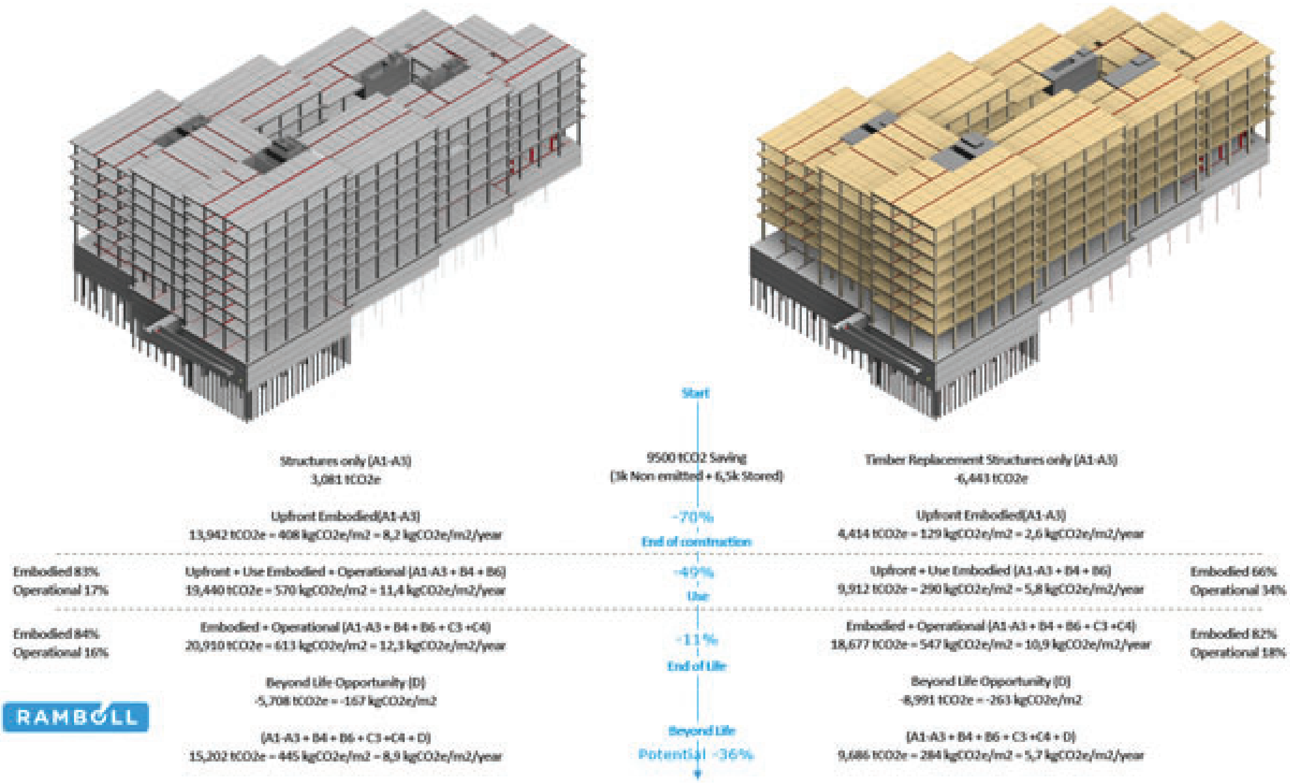

Figure 2: *Marmormolen – LCA Comparison*

Table 1: *Government strategy for reducing CO2*

2020	Testing phase of the voluntary sustainability class, which requires LCA-calculation		
	New builds larger than 1000 sqm	**New builds smaller than 1000 sqm**	**Voluntary CO2-class**
2023	Requirement of LCA-calculations Requirement of CO2-limit corresponding to 12 kgCO2e/sqm/year	Requirement of LCA-calculations	Requirement of LCA-calculations Requirement of CO2-limit corresponding to 8 kgCO2e/sqm/year
Ultimo 2023	Contracting parties meet to determine limits from 2025 based on latest knowledge and data		

	New builds larger than 1000 sqm	New builds smaller than 1000 sqm	Voluntary CO2-class
2025	Requirement of CO2-limit based on latest knowledge and data		Requirement of CO2-limit corre-sponding to 7 kgCO2e/sqm/year
Ultimo 2025	Contracting parties meet to determine limits from 2027 based on latest knowledge and data		
2027	Requirement of CO2-limit based on latest knowledge and data		Requirement of CO2-limit corre-sponding to 6 kgCO2e/sqm/year
Ultimo 2027	Contracting parties meet to determine limits from 2027 based on latest knowledge and data		
2029	Requirement of CO2-limit based on latest knowledge and data		Requirement of CO2-limit corre-sponding to 5 kgCO2e/sqm/year

Keywords: timber, sustainability, LCA, embodied carbon, carbon footprint

Decarbonization and Circularity Potential of Prefab Building Envelope Components

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Radical decarbonization of the building sector is an urgent need to mitigate climate change (European Commission 2021). This will back the EU renovation wave (European Commis-sion 2020) program and empowers clean energy systems, because buildings' operational heat energy demand will be lowered close to nearly Zero Energy Building (nZEB) level with an improved building envelope. Therefore, new environmentally sound passive technologies based on renewable materials and decarbonized supply chains must be developed and ap-plied for deep energy renovation of buildings to allow them to be used for a second life cy-cle. Passive measures on the envelope serve to prolong the use of the entire building and avoid its demolition, a reuse case at is best, providing ultimate circularity index results for existing assets. The previous innovation steps in the field of deep renovation have mainly been concerned with the development of solutions for process optimization with simultane-ously mastering thermal performance, because expansion of the renovation rate, higher ac-ceptance by the residents and, in sum, a higher overall economic efficiency was seen as op-portunities (Roux le S. and Ott S. 2014). The acceleration of the renovation process is main-ly determined by relocating the manufacturing to the factory, minimizing the duration of site processes, and this is achieved mainly by changing the size of the renovation elements.

Deep renovation intervention consumes new resources to implement renovation and requires intervention in existing buildings for replacement of worn-out, low performing components as windows or even adaptation of floor plans to today's needs. Thus, the following question arises: "Where does decarbonization have to tackle the environmental burden of retrofit products?" It is currently seen in the selection and production of materials for these products and systems and construction phase related emission from transport and building activities. (Göswein et al. 2021; Zhong et al. 2021) This demands a higher proportion of materials from renewable resources, because they have a carbon sequestration potential and change reno-vated buildings into a carbon sink. In addition to this seen improvement potential, reduction of environmental impacts in production by including secondary material from previous use cycles must be established, because this reduces the need for primary resources and increas-es decarbonization effects in the manufacturing phase. Service life issues are important for decarbonization as well, but not analyzed in this article. Two hypotheses can be taken from the research goals. First, lightweight and material saving options for renovation products help to decrease environmental impact of production phase. Second, environmentally disad-vantageous raw material consumption in production phase can be lowered by adding more secondary material to the prefab product.

In this article, LCA methodology is used to compare environmental performance of a base-line fossil foam ETIC façade renovation product to a timber-framed, wood fiber insulated element, with varying frame structure insulation ratio. Additionally, prefabricated alterna-tives made mainly of renewables are evaluated, and environmental impact is analyzed. The calculation scheme follows EN 15978:2011 and EN 15804:2012 rules. The life cycle of the product is analyzed for two life cycle modules A1-3 (Production stage) and C (End of Life stage, EoL). Module B is excluded because service life is not part of this article's hypothe-sis. Circularity in production is measured by input indicators of the data available in data-base ÖKOBAUDAT (BMWSB 2021). For this purpose, the quantities of secondary material contained in the background data are reported and included in the analysis.

Compared to baseline ETIC, a prefab façade element has on average 60% lower GWP emis-sions. A sensitivity analysis shows the influence of environmental impact indicators of the load-bearing structure in relation to the insulation layer. Figure 1a reveals that more struc-tural share leads to a higher share of GWP, although insulation and structure are both made of renewable resources. For the carbon sink balance, only A1-3 is considered in Figure 1b and here it results that more solid wood increases the biogenic carbon content. Proportion of renewable materials increases with change of the structure-insulation ratio. The low volume fraction of structure is more sensitive to the thickness changes. The circularity indicators in Figure 1c decrease slightly with increase of structural fraction, for the insulation they stag-nate.

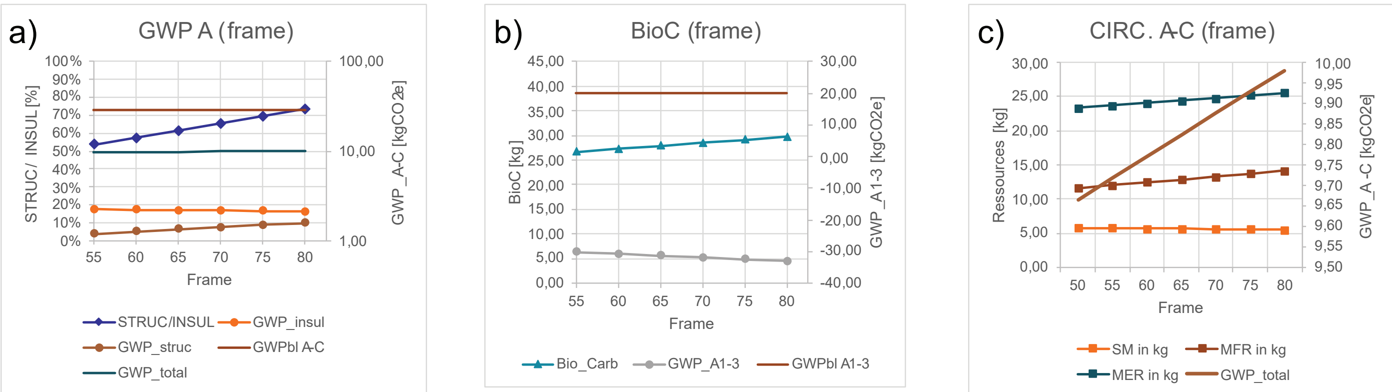

Figure 1: *GWP a), Biogenic Carbon b), Circularity c) indicators of different structure-insulation ratio*

Discussion and conclusion shown that decarbonization effects have been revealed by the calculation of LCA indicators for timber-based external retrofit envelope components that are assembled onto existing buildings for insulation purposes. Circularity indicators illus-trated that prefab elements should contain more secondary material (SM) and hence in-creased the decarbonization effect (GWP_total) as well. The carbon sink effect would only have an advantage if reuse with functional preservation of the facade element or cascade use with secondary material use would be practiced at EoL. Today widespread practice of energy utilization of timber (MER) will diminish carbon sink gains at EoL and must be avoided in future.

Keywords: decarbonization, prefabrication, facade panel, deep renovation, life cycle assessment, circularity

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Life Cycle Assessment (LCA) of the Largest Wooden Building in Slovenia: The InnoRenew Centre of Excellence, Izola

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The construction industry accounts for around 15 % of all greenhouse gas emissions. During their use phase, buildings use 40 % of the total energy consumption, which contributes significantly to resource consumption and air pollution. This has an impact on availability of resources for current and future generation. The use of non-renewable energy sources like oil, natural gas and coal emits large amount of greenhouse gases that leads to climate change and threatens the fulfilment of intergovernmental progress to curb climate change (UNFCCC, 2015). Energy consumption during the use phase is predicted to decrease as efficient buildings, like zero and near zero energy buildings, become more common. However, climate change and other environmental problems from the production or raw materials, construction and end of life remain serious concerns that need to be solved urgently.

End of year 2021, the InnoRenew CoE research building in Izola, Slovenia was finished. This is the largest wooden frame building in the country and hosts offices and laboratories for up to 90 researchers on a total area of 8200 m2, where roof terraces constitute 1400 m2 and inner closed space 6 800 m2. The predicted service life of the building is 60 years. The building in Izola consists of a garage, reception, research and meeting areas in addition to offices. In the middle of the main building there is a atrium with a large wooden staircase. The lower part of the building is made of concrete and reinforced concrete, while the upper part of the building is mainly made of wood. There is a green roof where there is not a terrace.

One of the main features of LCA is the inclusion of the supply chain upstream (raw material extraction, transport and preproduction) of the building component. This holistic view brings opportunities as the main environmental impact often is at the beginning of the life cycle or at the end outside the direct operational control. This is now more and more also the case for buildings, where better insulation and improved heating and cooling system leads to less energy consumption in the use phase.

In this contribution, LCA is applied to the InnoRenew CoE building in Izola, Slovenia and the results with hot spots are presented. The system boundaries include the concrete foundation, the façade of natural stones and wood laths and the wooden structure from cradle to gate (module A1-A3 in EN 15804-terminology) and the operational energy use for heating and cooling (B6) in addition to water use (B7).

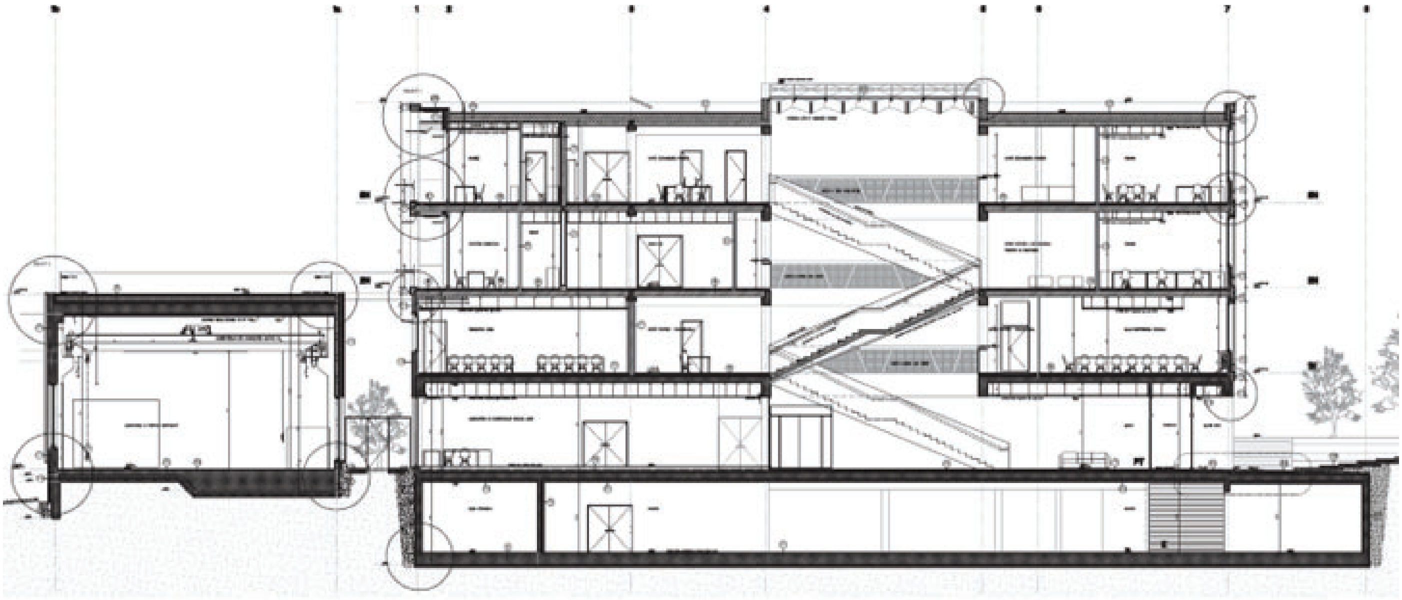

Figure 1: *Section drawing of the building*

Regarding the results for the climate change global warming potential indicator (carbon footprint), the large contribution from the concrete foundation (almost 2300 t CO2-equivalent) leads to a total cradle to gate impact roughly equally to the mitigation potential of 3000 newly planted oak trees.

This contribution focus on the carbon footprint results and the influence of biogenic carbon and recycling options in the end of building life stage. Contrary to most other existing build-ings, the use stage operational energy and water use (B5-B7) is of minor importance com-pared to the cradle-to-gate (A1-A3) impacts. This shows that material choice is the most important factor for the building's carbon and environmental footprint.

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Keywords: research building, life cycle assessment (LCA), sustainability, carbon footprint

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Towards a Sustainable Built Environment Based on Fire-safe Design with Timber and Wooden Products

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INTRODUCTION

Climate change and environmental deterioration stress the necessity to adopt more sustainable and renewable solutions in all human activities, including the construction industry. The energy use in the built environment (heating, cooling, and servicing) accounts for 60% of the worldwide global energy consumption and 40% of the carbon emissions (IFSS, 2021). These use-phase emissions should be considered along with the emissions arising from the manufacturing and processing of building materials, namely embodied carbon (Carcassi et al., 2022). In attempts to address the climate crisis, supranational, national, and local governments have established sustainability goals for the near (2030) and somewhat more distant future (2050). Sustainability can be evaluated based on balancing economic growth, social development, environmental protection, and conservation. For example, the UN has established 17 Sustainable Development Goals (SDGs). Similarly, the EU has ambitious goals to achieve carbon-neutrality by 2050, mainly through implementing the European Green Deal, which focuses on energy consumption, research, and innovation actions (EC, 2019).

THE WOODEN RENAISSANCE

Due to the international focus on sustainability, the construction industry, traditionally dominated by high-carbon-demand materials like cement- and metal-based (e.g., concrete and steel), is experiencing new, extensive use and application of wood and wooden products. These bio-based, renewable materials significantly decrease the embodied carbon, as wood acts as a carbon sequester. This revolution has affected many materials in the construction industry, from bio-based insulation materials to load-bearing structural elements. In particular, technological advances have enabled the development of engineered wood products for the construction of tall timber buildings, which is now the fastest growing sector in the construction industry (Ramage et al., 2017). These products are made of wooden planks or veneers glued together to create structural elements of virtually any dimension with improved physical and mechanical properties. Moreover, modular construction and prefabrication make timber buildings cost-effective solutions with considerable advantages: high quality control, rapid construction, "clean" construction environments, low waste, and enhanced occupational health and safety. Also, the aesthetics of visible timber construction have been shown to improve the life quality of occupants and increase client profits (Ramage et al., 2017).

FIRE SAFETY OF WOODEN PRODUCTS

However, bio-based construction assemblies have simultaneously generated new and critical challenges, with fire safety being the most critical, because, as opposed to traditional construction materials (e.g., concrete, steel, masonry, and plaster), wooden products are combustible. From a fire safety point of view, wooden products can increase the fuel load within buildings and facilitate the fire spread between separate compartments, hence leading to a higher building fire risk (probability times consequence). On the other hand, from a structural engineering perspective, wood combustion reduces the load-bearing capacity, and it could compromise integrity and stability of the structural system during and after a fire. In addition, the safety associated with novel wood and timber solutions has not been explicitly assessed, which calls for increased research on the fire behaviour of wood and timber (Bartlett, 2019).

COUPLING SUSTAINABILITY AND FIRE SAFETY

Furthermore, the impact of fire events has not been included in sustainability assessment methods (Roberts et al., 2016). One reason could be that fire safety engineering in building codes primarily focuses on life safety, while a key measure in established methods is carbon emissions. In fact, there are currently explicit goals for CO2 emissions per m2 of buildings on the way in several countries. The current situation is that most sustainable solutions have not yet been tested regarding fire incidents and a fundamental question arises in relation to the quantification of fire in the sustainable built environment (Adrubali et al., 2015). An example of an effort to combine fire safety and sustainability is the Fire-LCA model proposed by Andersson et al. (2007), which used case studies focused primarily on carbon emissions but did not quantify the fire impact on society (toxicity, monetary costs, emissions, and life cost). Therefore, it is still a long way to go to include fire-related aspects in sustainability measures. Still, such inclusion is absolutely necessary to claim that sustainability has been properly addressed for the full life-cycle analysis in the built environment. This is particularly important for the new wave of wooden and timber buildings, as they introduce an even more fire risk analysis than is the case for buildings with non-combustible (load-bearing) materials. It is important to emphasize that it can be done, but that research is needed for successful inclusion in current schemes or the development of new ones. The current work maps the challenges associated with quantitatively including fire safety of wooden products and timber buildings in sustainability schemes and investigates various approaches to overcome this problem.

Keywords: wood, timber, fire safety, fire, sustainability, built environment

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Towards Architectural Design Freedom in Multi-Storey Timber Buildings: Applications of a Novel, Adaptive Building System

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Current wood building systems are defined by their modular nature. Even though engineered wood processes enable the fabrication of modules of almost unlimited size and shape, transport and assembly requirements greatly limit the complexity and scale of these systems and the resulting buildings. The anisotropic nature of timber limits most structures to be unidirectional, creating mostly rigid grid structures and designs (Svatoš-Ražnjević et al. 2022). Recent developments in computational design methods, material science, and fabri-cation techniques open new possibilities to overcome these technical limitations.

This research is based on the previous development of a novel point supported hollow multi-directional timber building slab system capable of expanding the design possibilities in tim-ber construction (Orozco et al. 2021; Krtschil et al. 2022). This research presents the results of four building design case studies developed during the ITECH 20/21 Design Studio at ICD/ITKE, University of Stuttgart. Each case study expanded the development timber plate building system with building services integration, lateral bracing, and façade integration considerations (Figure 1). The case studies were validated by testing the designs in different program states (Figure 2). of occupants and increase client profits (Ramage et al., 2017).

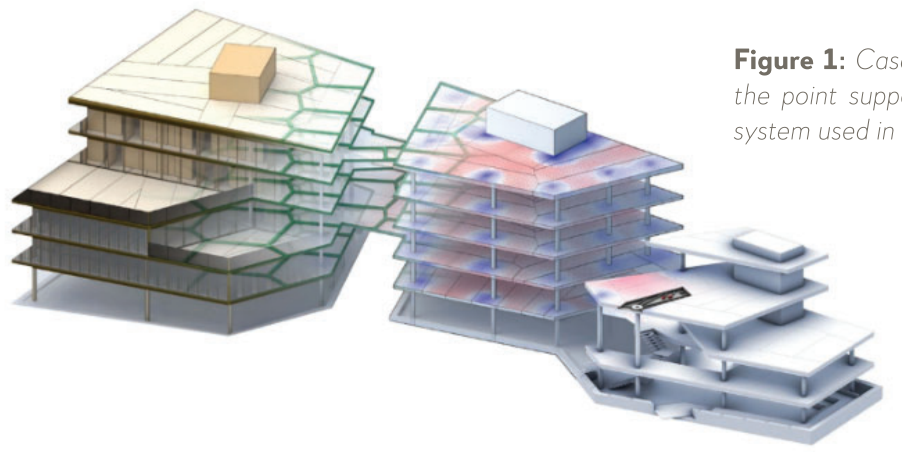

Figure 1: *Case Study 1 showing different aspects of the point supported multi-directional timber building system used in the building design*

In this research we ask the following questions: (I) how digital fabrication and computation-al design methods can enable novel multi-storey timber building typologies, including inno-vative building service integration and (II) what overarching and timber specific design strategies are needed for a building that will change its program over a 100-year building life span.
The methods are based on an integrated co-development of the building design, its building system, and the details that constitute it, with a focus on their fabricability and architectural implications for a robust non-programmed building design.

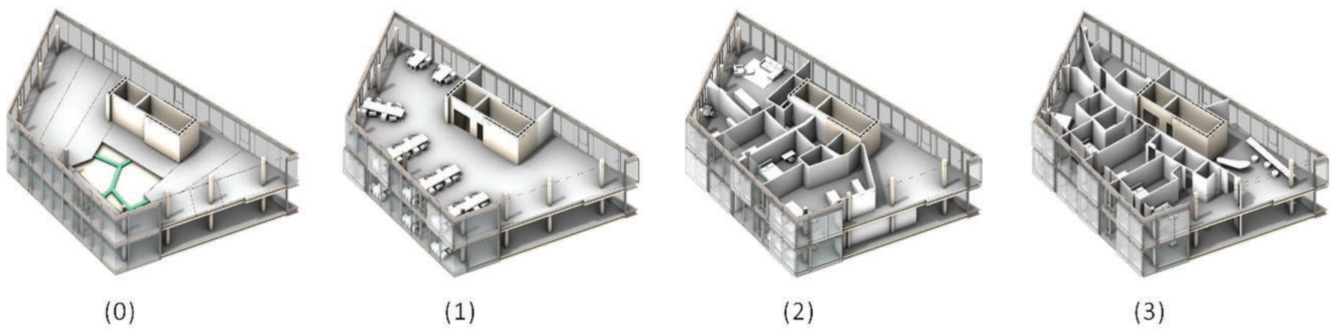

Figure 2: *Case Study 1, flexibility and change of use in four states with timber plate panelization, service distri-bution, and temporary wall placement: (0) non-programmed state, (1) state 1- open office use, (2) state 2 – residential use, (3) state 3 –hotel use*

Keywords: multi-storey timber building design, flexible building use, building service integration, timber building system, computational design, integrative design

Subtopic: digitalization

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Weather Protection and Moisture Content of Large Mass Timber Buildings During Construction

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Although mass timber buildings with cross laminated timber (CLT) or glue laminated tim-ber (glulam) are erected rapidly in comparison to other systems of construction, they are al-ways exposed to weathering if not completely covered with temporary roofing. Still, tempo-rary roofing can be applicable only if the building is not too large or tall. When exposed to accidental weathering, short term moisture or high relative humidity can lead to mold growth, that can be potentially hazardous for health in living spaces of the building after completion.

Trapped moisture inside joints between different structural elements can cause long term decay of timber and can affect its physical and mechanical properties. Besides, weathering can cause visual damage of the surfaces of visible timber walls and ceilings which decreases the attractiveness of mass timber buildings.

To understand the moisture performance and danger of accidental weathering during con-struction, we extensively monitored the moisture content (MC) in CLT during construction of InnoRenew CoE building complex in Izola, Slovenia. The upper parts of the complex (1st-3rd floors) made completely of mass timber were erected during the period of 6 weeks be-tween September 25 and November 11, 2020. The gross floor surface of the timber part of the building complex was 2.550 m2, using 850 m3 of mass timber. Since the complete cover-ing of the structure with temporary roofing was not possible due to its large spans (23,5 m x 38,6 m), we used alternative ways of timber protection. These were a combination of struc-tural and architectural details and their local waterproofing, weather protection on façade scaffolding and monitoring of the drying.

The monitoring was performed with thermal camera, handheld pin-type moisture meter (with measuring depth of 2cm) and pin-less moisture meter. We measured 289 points on the floor plates during the period of 4 months - from the beginning of the timber construction until the complete closure of the building with roof and covering of floors with further per-manent layers. With examination of these large number of points we prevented extensive moisture penetration and unwanted trapping of water inside and between wooden elements, future decay of wood and undesired deformation. Besides, we performed also continuous on-site improvements of waterproofing.

The highest MC were observed at the spots of longer leakage from unfinished roof and fa-çade towards south and west, where the weathering influence was the strongest. Exposure to sun and wind showed that trapped water was dried out rapidly, decreasing MC level by 20% within two days, despite lower temperatures (below + 10oC) in wintertime. Interestingly, measuring deeper than 2cm into CLT did not show any significant difference of MC. At fi-nal monitoring we reached average value of moisture content of 21,3%, with all points be-low fibre saturation point and no new leaking spots. Knowing these data helps to further de-velop details and end grain protection of CLT for future construction projects.

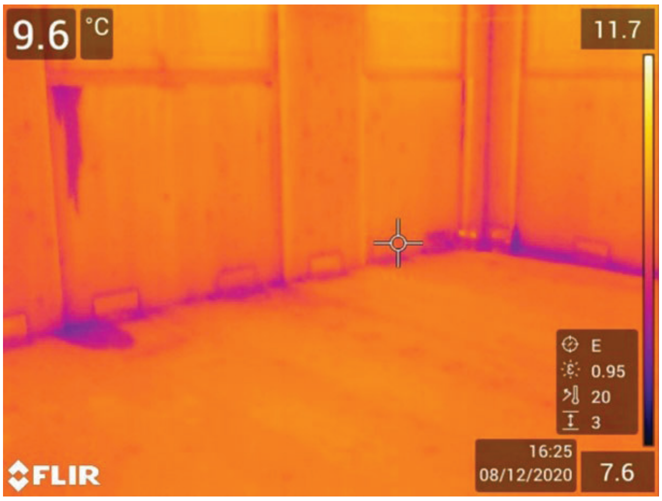

Figure 1 and 2: *Monitoring with thermal camera*

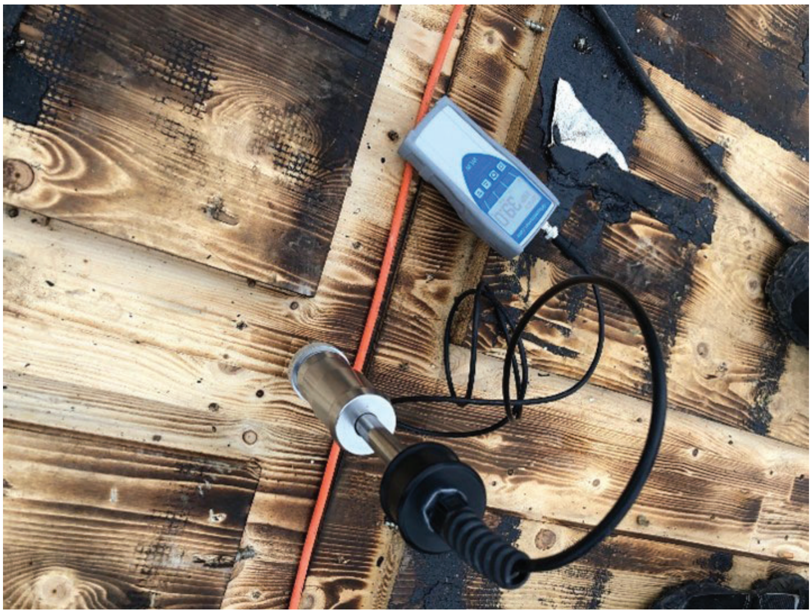

Figure 3 and 4: *Monitoring with pin -type moisture meter*

Keywords: sustainable architecture, mass timber buildings, CLT, hygrothermal monitoring, moisture performance, weather protection

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Restrained Swelling Deformation of Densified Wood Dowel in Dowel-Laminated-Timber (DLT)

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Engineered wood products (EWPs) have been implemented in timber construction to overcome some of the weaknesses of wood as a construction material. EWPs are, however, most cases assembled by adhesives, which reduce their machinability, sustainability, and complicate recyclability. Therefore, there is a gap in timber construction for an ecofriendly, recy-clable, and nonbrittle substitute to replace adhesive. Assembling timber by hardwood dowels without using metal fasteners or adhesives has been invented and applied in furniture mak-ing and timber construction like dowel-laminated-timber (DLT) already in the ancient time. However, the environment climate change and stress relaxation could result in imperfect connection between the dowels and the lamellae, which finally leads to degrade performance and be a safety risk during its service life. The set-recovery of densified wood dowels could be a remedy for such issue by providing additional frictional force along the dowel-hole in-terface to maintain tightness of the joint (Mehra et al., 2021). However, the restrained swell-ing deformation of densified wood dowel and the influence on the DLT performance re-quires further investigation.

In this study, industrial kiln-dried Norway spruce (Picea abies (L.) Karst.) timber was used for lamellae, and Scots pine (Pinus sylvestris L.) and European beech (Fagus sylvatica L.) timber were used to manufacture densified wood dowels. The timber was conditioned at 20°C and 65% RH to achieve an equilibrium moisture content of approx. 12%.

The components for dowel were thermo-hydro-mechanical (THM) densified in the radial direction from 30 to 15 mm thickness (50% compression ratio) in an open-system hydraulic hot press, and thereafter immediately processed into dowels with a circular cross section of 10 mm in diameter by using a lathe. The dowels were placed in air-tight plastic bags to pre-vent moisture uptake which may induce set-recovery.

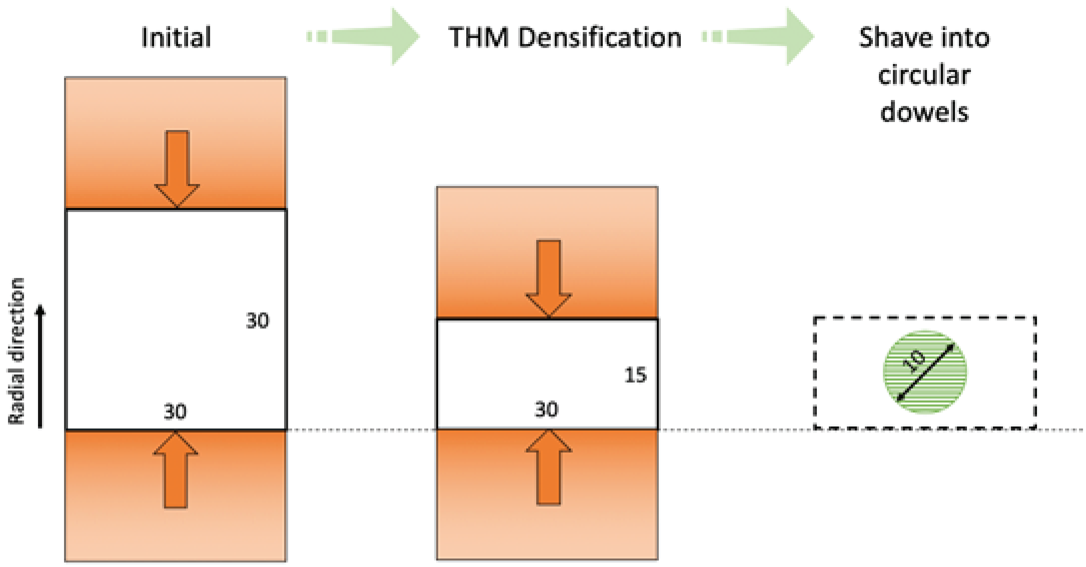

Figure 1: *Manufacturing flow of densified wood dowels.*

A three-layer DLT beam with dimension of 1500 x 75 x 75 mm (Length x Width x Thick-ness) were fabricated by inserting the densified wood dowels into two rows of pre-drilled holes (Fig.2). The diameter of pre-drilled holes was 10.1 mm to create a tight connection with the 10 mm wood dowels. The distances between the dowels along the length and across the width of the beam were 50 mm and 25 mm, respectively. The 58 dowels were evenly distributed over the DLT beam.

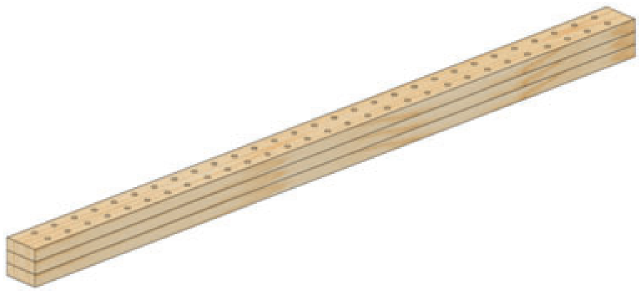

Figure 2: *Design of three-layer DLT beam.*

The swelling deformation of dowels inserted in the DLT beam was measured by X-ray CT scanner (Siemens). A specially designed drying kiln that fits within the gantry of the scanner was used moisten the DLT at 20°C and 65% RH. A CT scan with 3 mm scanning thickness was made on each dowel before the start of test and then every hour during the following one week.

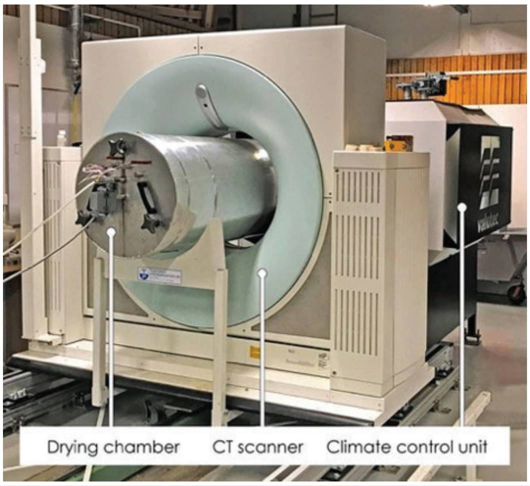

Figure 3: *X-ray CT scanner and drying kiln fitted in the gantry of the scanner*

Keywords: thermo-hydro-mechanical densification, Norway spruce, Scots pine, European beech

Acknowledgment: The authors acknowledge the European Commission for funding the InnoRenew project (Grant Agreement #739574) under the Horizon 2020 Widespread-Teaming program and the Republic of Slovenia (investment funding of the Republic of Slovenia and the European Regional Development Fund) and the Slovenian Research Agency ARRS for funding project J4-3087. The support of CT WOOD is also gratefully acknowledged.

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Long-Term Statistical Assessment of Conditions in Timber Buildings Construction

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EU Green Deal forces investors in member states to use more natural sustainable materials in new constructions as well as during renovation process. Family houses and commercial buildings are built nowadays from timber and data from the timber structures are available for further processing and evaluation to assess if the conditions are safe for wood in case of long-term exposure. Wood susceptibility to moisture, risk of mould fungi growth in timber constructions are common threads which need to be taken into account during project and construction phase of the timber buildings. When monitoring data records are available it is possible to evaluate periods where the conditions were favourable for mould fungi growth and assess the percentage of time where the timber construction was exposed to dangerous conditions.

Mathematical models describing the risk of mould fungi infestation in timber construction were published and verified during laboratory tests. Lepage and Schumacher 2019 describe mathematical models estimating the conditions for mould growth and model usability including the advantages and limitations. In order to apply the models for long term evaluation of conditions it is necessary to consider both, periods of favourable conditions as well as dry periods when the condition are not favourable for mould growth. Some of the models (Sedlbauer 2001) do not take into account dry periods and thus cannot be used for long term evaluation. Models published by Isaksson 2013 and Viitanen 2010 are widely used to predict the risk of mould growth inside the timber structures. Both models define a critical humidity/dose above which, the condition become risky in terms of mould growth.

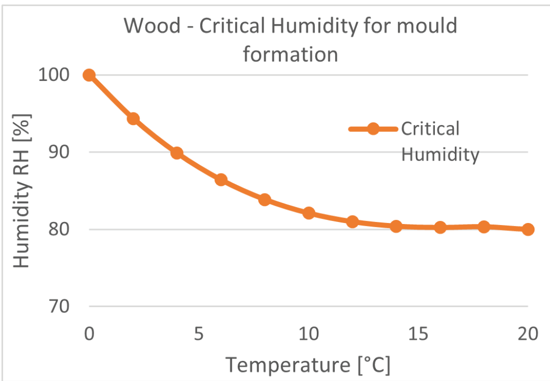

Figure 1: *Wood critical humidity as a function of temperature, Viitanen 2010*

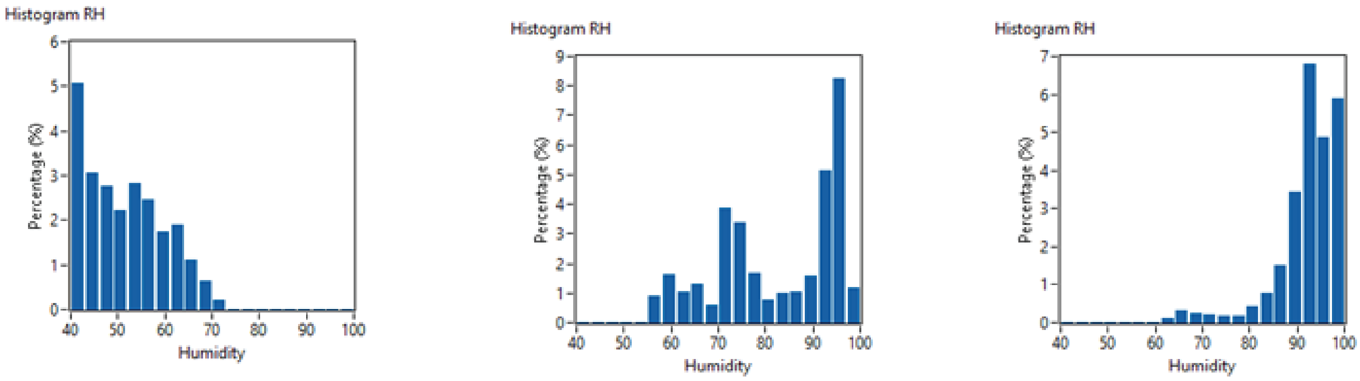

Figure 2a, b, c: *7-years humidity histograms from 3 different parts of timber frame construction of the same house (moistureguard.cz)*

Keywords: timber construction, monitoring, mould growth

Acknowledgement: Jan Vcelak gratefully acknowledges the European Commission for funding the InnoRenew CoE project (Grant Agreement no. 739574) under the Horizon2020 Widespread-Teaming program, and the Republic of Slovenia (Investment funding of the Republic of Slovenia and the European Union of the European Regional Development Fund).

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Maquette Acoustique AdivBois: The In-situ Flanking Transmissions Measurements Facility for High-rise Wooden Buildings

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Abstract: AdivBois has been carrying out the "Build in Wood for livings" project since 2015. Its goal is to support and facilitate the construction of demonstrators combining a me-dium and high-rise wooden structure and an evolving or reversible living environment, using wood. To accelerate these innovations, a set of thematic committees have been working since 2016 on various facilitating axes including acoustics. In France, the new environmen-tal regulation for construction, RE2020, has been enforced since January 1st, 2022, it pro-motes the use of renewable materials, including wood, that can store carbon. In 2019, under AdivBois founding, FCBA, CSTB and CERQUAL created an acoustic test facility composed of 12 rooms arranged in 3 floors building, representing a high-rise building structure.

Acoustic measurements are presented for different structure configurations: airborne sound insulation, impact noise behavior and heavy impact noise, through partitions and floors. Flanking transmissions were evaluated with measured vibration reduction levels. And theory of estimation of acoustic performance of buildings from the performance of elements is discussed.

In recent years, new questions have arisen regarding the possibility of having visible wood surfaces for aesthetic and occupant well-being aspects. The article reviews the acoustic studies carried out on the acoustic facility; on the one hand, numerous laboratory tests on CLT floors and, on the other hand, measurements and predictions of the acoustic performance of CLT walls and floors buildups. The results concerning the visible wood surfaces (wall, col-umn and beam) are mainly detailed and discussed.

Concerning acoustic performances for building sector, it is now integrated that the criterion of impact noise level must take into account low frequencies and respect L'nT,w+CI50-2500 ≤ 55 dB to improve the comfort of occupants, which goes beyond the current acoustic regulations for residential buildings.

Figure 1: *In-situ flanking transmissions measurements facility for high-rise wooden buildings*

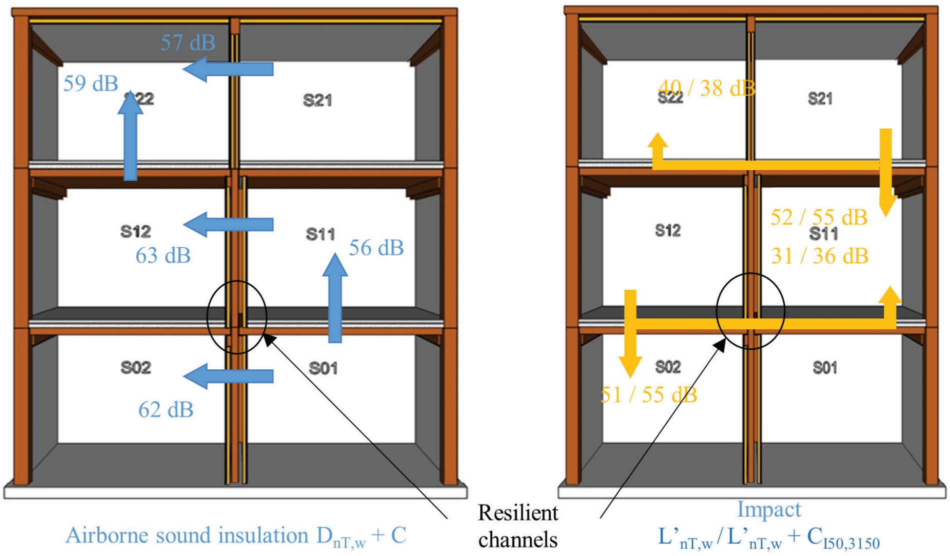

Figure 2: *Insulation between rooms Sx1 and Sx2, airborne sound and impact sound*

Keywords: airborne and impact in situ measurements, flanking transmissions, apparent wood

Acknowledgement: The authors would like to acknowledge the financial support of AdivBois, CODIFAB and the Nouvelle-Aquitaine region. In addition, the authors would like to thank the various partici-pants who contributed to this study, who carried out complementary acoustic measurements, and finally the members of the AdivBois acoustic workshop for their contributions and con-structive exchanges.

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Renovation – Improvement of Sound Insulation of Wooden Ceilings in Historical Residential Buildings

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About one third of residential buildings in Austria were built before 1960, and a lot of them have wood-based ceilings combined with walls made of bricks. Considering the number of residential units in Austria about 1.200.000 dwellings date from this time. Typical ceilings are the "Holztramdecke" (wooden beam ceiling), sometimes with a recessed lintel formwork, the "Fehltramdecke" (double beam ceiling) and the "Dippelbaumdecke", a ceiling with a layer of tree trunks trimmed on three sides.

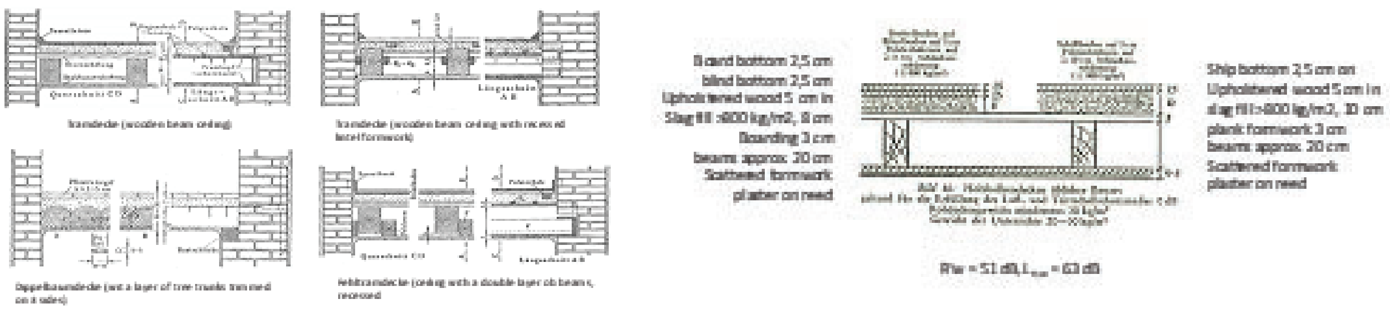

Figure 1: *Left: Typical wood-based ceilings of historical multistory residential buildings; right: results of an unrenovated ceiling (Source: Bruckmayer, 1962)*

Most of these ceilings have a wood-based floor, which is mounted on a separated lathing and not fixed in contact with the beams. This brings an advantage for impact noise compared to constructions, where the floor is directly connected to the beams. If the boards of the subfloor are fixed to the beams, the Ln,w can be estimated around 72 dB, with a CI, 50-2500 of -2 dB; with a ceiling insert with weighting of 100 kg/m2 the construction will have a Ln,w of 69 dB and a CI of -3 dB, which are not very satisfying results.

If the subfloor is not fixed to the beams, the transmission of impact noise is reduced, depending on the type of gravel (> 800 kg/m2) to about 57 dB to 63 dB. The second transmission path of sound energy is airborne sound, and this part depends on the type of Floor, subfloor, and the ceiling. In some cases, the cavity resonances can be worse. A big mistake is it to change the old slag material to mineral wool. The lack of weight the impact sound increases the impact sound level especially in the low frequency range.
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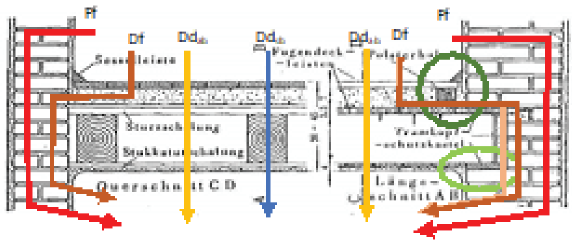

Figure 2: *Sound transmission paths through an historical ceiling*

The "Fehltramdecke" reduces the Path Ddsb significantly. Especially for airborne noise the flanking transmission must be taken into account, it depends on the bulk density of the masonry and therefore limits the possibilities of improving the sound insulation if just renovation of the ceiling is done. But in every case, it is would have a lot of advantages to change a simple wooden beam ceiling to one with double layer beams, because this helps to reduce the impact sound also in the low frequency range. There is just one limitation for not doing that: There is some additional space necessary, of about 1 cm plus deflection from permanent and live loads between the between the top edge of the existing beam supporting the floor and the top edge of the new beam supporting the floor. Another possibility to reduce this second part of deflection would be to use a beam superelevation. More space would be needed, if the deflection is higher than 6 mm and the Eigenfrequenz of the beams is too low (< 8 Hz), than it is necessary to enhance the stiffness. If you do this with using wooden beams, then to increase the height is the measure of first choice. But this needs more space and therefore the level of the upper floor will change. It could be a challenge to avoid this e.g., using beams with Carbon or steel strips. The second advantage of such a construction is the possibility to reduce the low frequency impact sound, because in this case the low frequency vibration of the floor is not directly connected with the ceiling.

In most cases the rooms in such rooms are quite high, so this opens the possibility to use a suspended ceiling. This can be helpful to reduce airborne sound.

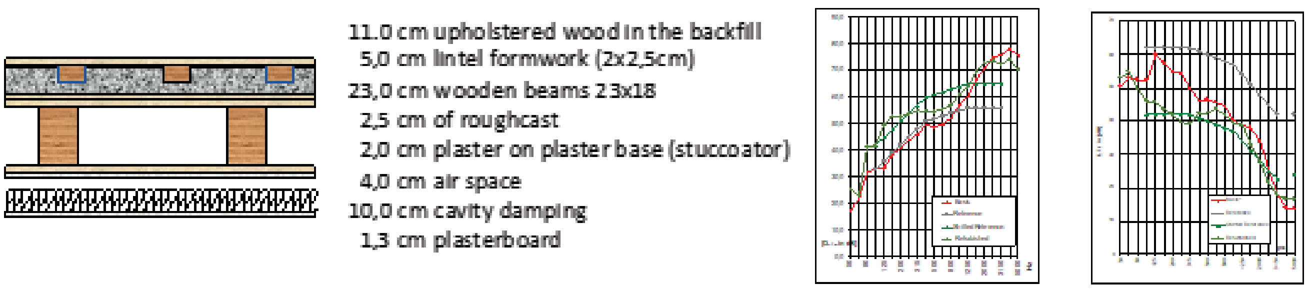

Figure 3: *Left: Example Floor with improvements; right: measurement results DnT,w and LnT,*

A significant improvement of the impact sound can also be achieved, if sufficient additional board height is available, e.g., by a floating screed with an impact sound insulation board made of rock wool and a Cementous or anhydrite screed.

The ceiling above could be improved with such an additional floating screed to a weighted impact sound level of 32 dB – but with a bad impact sound level of more than 60 dB at a Terzband center frequency of 63 Hz. To reduce this, additional weight or other measures as "Tilger" (vibration absorbers) should be considered.

Conclusion

The refurbishment of existing wood-based partition ceilings will be a big theme in future. There exist a lot of possible measures to improve the airborne sound and impact sound as a single number value.

The same problem arises in urban densification, when attic is developed for additional apartments. In order to achieve a noticeable improvement and not only to improve the respective single-number statement, additional research is important for future development.

Research Program for Addressing the Fire Safety Challenges of Timber Buildings

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A fundamental difference between timber and many other conventional building materials is that timber is combustible and will contribute to the fire as it burns. Therefore, fire safety is one of the main limiting factors when designing timber buildings. Use of timber may invalidate current fire safety design approaches, based on traditional building materials such as concrete or steel, especially for medium and high-rise buildings, for which the timescales of egress and fire service intervention are longer. The traditional layers of fire safety are a) prevention, b) detection and alarm, c) compartmentation of fire, d) evacuation, e) suppression (incl. fire services), e) structural resilience. Fire safety traditionally relies on strict rules for how these layers of protection can be fulfilled. In Denmark, deviations from these standards are allowed through a fire safety engineering approach, by certified fire safety engineers and additional revisions from a third-party reviewer. Considering that use of timber in many cases results in deviations from standard requirements, Danish Institute of Fire and Security Technology (DBI) has recently started a number of research activities to support fire safety engineering in design of timber buildings. Some of the examples are provided in this presentation.

Compartmentation

The fire dynamics of compartment fires was extensively investigated in the 1970s and 1980s and this allowed the development of contemporary designs. However, timber compartments were not included in these studies. It has been reported that the fire load due to the burning of timber compartment linings could be at least twice (Su et al., 2018) as much as the mova-ble load (such as furniture). Timber buildings may also not be able to maintain structural integrity until complete burnout (Wiesner et al., 2017), which is an inherent assumption in the fire resistance approach. Project Assessment of design fires for timber buildings will aim to quantify and describe the phenomena related to the burning behavior of exposed timber surfaces.

The fire can also spread between the fire compartments through the building façade. The requirements for the façade cladding and external wall material use are traditionally based on the reaction-to-fire classes, obtained through small scale testing. Timber shows relatively poor reaction to fire performance and use of it on external walls and façade cladding is effectively limited. Alternatively, large-scale façade mock-up (height 6 m and more) are allowed in some cases to demonstrate the façade fire performance. Such tests are expensive to perform and, considering the combustible nature of timber, they are prone to failure. Project Enabling use of biobased facades through fire safety assessment will investigate the use of numerical simulations with software Fire Dynamics Simulator for predicting the fire spread external to the buildings. The outcome would support the optimization of the façade construction hence reducing the costs and time associated with the large-scale testing. Furthermore, due to the additional fuel load in the compartment, the external flaming from exposed timber compartments may be more severe compared to standard tests. The evaluation of different fire loads (compared to standard façade tests) may be of growing interest in the future and require some flexibility in façade construction assessment.

Evacuation

Introducing large amounts of combustible materials into buildings will compromise their ability to withstand the full duration of a fire. Hence people are potentially more likely to be exposed to harmful situations and structural measures alone cannot completely mitigate these risks. A holistic approach to evacuation safety for buildings including combustible materials is currently missing, as most of the research emphasis in the field has been put on ensuring that tenable conditions are extended rather than systematically identifying solu-tions aimed at reducing evacuation times. The project Safe biobased buildings through evacuation training will aim to evaluate novel evacuation training methods and developing engineering methods for effective fire safety strategies in biobased buildings.

Structural resilience

According to standard fire resistance testing, constructions are exposed to one single standard fire curve. Timber loses much of its mechanical strength at relatively low temperatures, with a negligible capacity at around 300 °C, while progressively developing a char layer that effectively isolates the inner parts of the timber element. While timber charring is relatively easy to predict during the standard fire tests, it resembles little the potential actual fires. For example, the standard fire curve does not include the cooling phase. Nevertheless it may have an impact to the structural performance as the thermal wave continues to penetrate the construction also while the fire compartment cools down. The aim of the project Thermal behavior of engineered timber structures under natural design fire scenarios is developing an experimental validation of a heat transfer model in engineered timber products exposed to different fire conditions, including the decay phase of the fire. This will also involve a parametric study of moisture migration and interaction with adhesive layers.

Conclusion

Understanding the impact of timber begins with understanding the heat transfer processes inside wood. Heat transfer drives creation of combustible pyrolysis gases through thermal decomposition and thermal degradation of material properties. Decomposition and degradation, together with fuel load, fuel orientation and ventilation factors contribute to fire dynamics inside the exposed timber compartment. Fire dynamics thereafter influence the external flames from the window and external fire spread as well as the response of structural elements. Finally, the building response to the fire will determine the evacuation strategies. DBI aims to develop a broad range of expertise as well as to contribute to new knowledge through the above listed projects and future research activities.

Keywords: fire, heat transfer, flame spread, evacuation, timber

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Additive Manufacturing of Fully Recyclable Walls Made of a Renewable Secondary-resource Composite

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To counteract the low material efficiency, low productivity and comparatively high volumes of non-renewable resources used within the construction industry, the University of Natural Resources and Life Sciences Vienna (Universität für Bodenkultur Wien, short BOKU) developed a new strategy for additive manufacturing (3D printing) of fully recyclable walls called 3DP Biowall, as presented in Figure 1 (Kromoser et al., 2022). As the construction sector counts to the most energy and natural resource consuming sectors and wood construction shows great potential when looking for possible ways to push forward a more sustainable building mentality, 3DP Biowalls is a step in the right direction towards a more resource friendly construction environment. The presented construction method uses only renewables coming mainly from waste/side streams, i.e. from the sawing and paper industry contributing to increase the material utilization and enabling to increase the total possible share of wood structures and therefore the CO2 storage. Simultaneously the productivity of the production process itself can be increased and a real circular economy in wood construction can be realized.

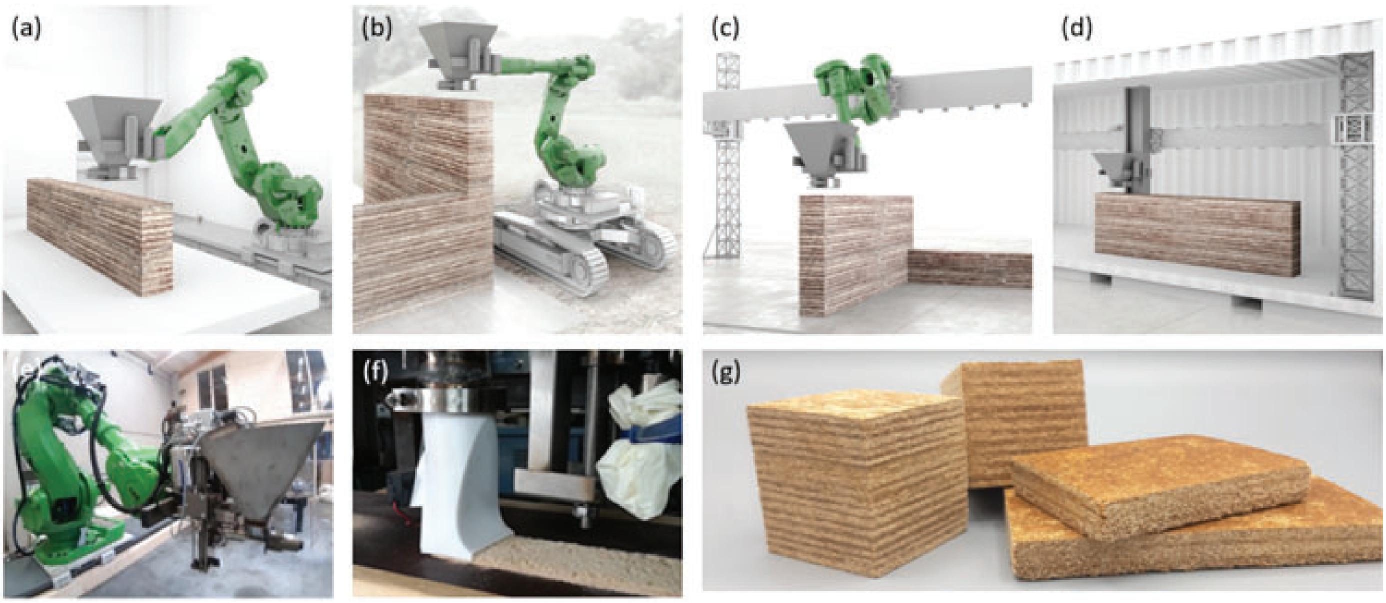

Figure 1: *(a)-(d) Possible carrier systems and construction strategies; (e) First prototype of the print head mounted on the 6-axis ABB robot at BOKU; (f)Printing nozzle allowing for a continuous and constant layer of the printing material; (g) Specimens produced and formatted for the material tests.*

Four different concepts (material, production, application and recycling) are currently being investigated focusing on in the development of the new construction approach. The main idea was to have a completely bio-degradable product which is printable yet completely recyclable. As far as the printing of raw materials is concerned, the experiments to find the perfect blend regarded lignosulfonate and industrial starch as a bio-based binder called Biomix (Hellmayr et al., 2022) in combination with wood particles of all shapes and sizes. The conducted test showed that a triboelectric charging can be favourable for a homogenous distribution of the particulate mixture. The developed powdery adhesive allows for the mixture to be extruded in a dry state. Subsequently water is added, and the printed layer is pressed and heated to a temperature between 150°-200°C.

To facilitate the printing process two different material preparation concepts are investigated, one considering a fully integrated production where all materials can be added separately, the second considering a granulate based production with the printing material being added to the printing head as a granulate. The printing head itself is a merger of all needed modules for the production process (preparation module, water dispersion unit, printing nozzle, compression and heating module) and can be mounted on various bases as visualised in Figure 1(a)-(d). With the material of 3DP Biowall being 100% bio-based the recycling scenario is implemented in the material design, addressing the circular economy principle. The idea is to recycle the printed walls using an optimised shredder process aiming for the wood particles to stay widely unchanged in size and form and therefore allowing the material to be 100% recycled without the addition of any further adhesives.

To show that the presented concepts are possible selected preliminary tests (DVS measurements, compressive strength testing, flexural strength testing, microscopic investigations, single flame source test) in combination with a Life Cycle Assessment - LCA (cradle-to-gate) were conducted (Hellmayr et al., 2022; Kromoser et al., 2022). The data derived from investigations prove the competitiveness of the material mix in regard to an application for wall elements and the potential of the closed material loop approach. Within the LCA the product was looked into on a material basis as well as in an evaluation as a wall system with multiple recycling cycles.
Investigations focusing on the improvement of the mechanical properties as well as the water resistance and biological degradation, by testing various mixing ratios and additives, are currently being pursued. Furthermore, a more detailed LCA, including the whole life-cycle is being carried out in order to evaluate the impact of the printing process on the environmental indicators.

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Additive Manufacturing of Fully Recyclable Walls Made of a Renewable Secondary-resource Composite

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Abstract: Artificial neural networks approach is employed to predict airborne sound insulation curves of various lightweight façades. The prediction model is developed using 100 Lab-based measurements for façade systems in one-third-octave bands (50 Hz – 5 kHz). Geometric and physical information of each wall (structural materials, dimensions, thicknesses, and more) are utilized as input parameters. The model demonstrated satisfactory results in predicting airborne curves, especially at middle frequencies (250 Hz – 1 kHz). However, higher deviations are remarked in lower and higher ranges due to effects of fundamental and critical frequencies, which influence the predictive precision. The weighted airborne sound reduction index (Rw) of façades is forecasted with a maximum error of 3 dB. A sensitivity analysis is carried out to investigate the effect of structural parameters on the sound insulation estimations. Results highlight the importance of the total thickness and density of the clustered exterior structural layers of walls.

Introduction

In North America, wood-frame structure systems have been the dominant in the building construction sector in the 20th century (Popovski, 2015). Although lightweight structures reduce the construction time and cost, the main challenge in some types of those structures is that the subjective sound insulation quality is considered as lower than that of a heavy structure with the same sound insulation data (Rasmussen, 2014). An accurate forecasting of sound insulation performance of double structures has been and still a challenge (Vigran, 2014). The applications of machine learning have been widely used to solve complex problems in various fields, such as: image classification, speech recognition (Abdel-Hamid, 2013), but few studies in building acoustics (Bader Eddin, 2022). The scope of this study is to develop a prediction tool based on artificial neural networks for airborne sound insulation estimation of façade structures. Finally, a feature attribution analysis is carried out to explore the influence and the significance of parameters on the prediction of airborne sound insulation.

Methods

Artificial neural networks approach is a mathematical model which is motivated by the structure of a real human brain to simulate its biological behavior (Svozil, 1997). It uses very simple computational operations to solve complex and mathematically ill-defined problems (Graupe, 2013). The database is developed based on 100 standardized laboratory measurements received from Lund University in Sweden and CNRC (Bradley, 2000) in Canada. The measurements consist of airborne sound insulation tests performed on 100 different façades in one-third octave frequency bands (50 – 5000 Hz).

Results and Discussion

Figure 1 shows a comparison between measured and predicted curves of different façade configurations for airborne sound insulation. It is significant that the predicted curves are close to measured ones with some deviations in certain cases. Those deviations increase in some samples in low and/or high frequency bands. The smallest deviation is notable for façade #3 with a RMSE value of 2.19 dB, while the largest is 5.73 dB for façade #10.

A classification is carried out on the database to explore the influence of thickness and density of exterior, main and interior parts of façade structures on the estimations. Results yield that the density and the thickness played an important role in the estimations across all frequencies, especially for exterior part of walls.

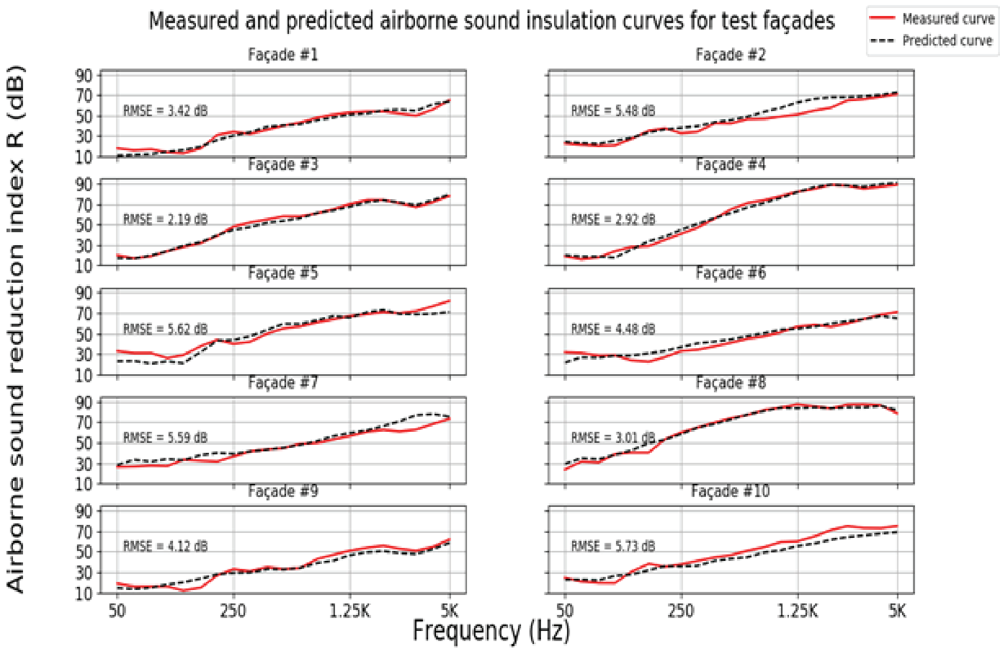

Figure 1: *Predicted and measured airborne sound reduction index curves of test walls*

Conclusion

The present paper illustrates the potential of artificial neural networks in prediction of airborne sound reduction index R based on 100 Lab-based measurements of different lightweight façades. In general, the prediction accuracy demonstrates a better accuracy in the middle frequency bands of 250-1000 Hz. A sensitivity analysis is performed to estimate the most significant parameters on estimation of airborne sound insulation curves. The total thickness and total density of the exterior part of façades have significant effects in all frequencies. Further research would be expected on optimization of certain parameters to control and improve the prediction of sound insulation curves.

Keywords: airborne sound insulation, façade, prediction model, artificial neural networks

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