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MERGING STANDARDIZATION AND ADAPTABILITY FOR EFFICIENT MODULAR CONSTRUCTION SOLUTIONS

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ABSTRACT: Modular timber construction represents a groundbreaking and eco-friendly advancement in the building sector. The constant evolution of construction methods, technologies and requirements, the concern of those who live architecture and, more recently, the climate crisis and social pressures, have made timber a viable alternative to conventional materials such as concrete, masonry and steel. The lightweight and versatile nature of timber, coupled with the efficiency of factory-based production, accelerates modular construction processes and meets the industry's growing sustainability demands. This study introduces a novel construction system that employs prefabricated two-dimensional (2D) and three-dimensional (3D) timber units as primary components of a modular system. By addressing contemporary needs for sustainability and efficiency, this project contributes to the evolution of building practices focused on resource conservation, waste reduction, and the promotion of a more sustainable and resilient built environment, while provides a solution for the current housing crisis.

KEYWORDS: industrialization; prefabrication; standardization; modular construction; timber

1 – INTRODUCTION

Prefabrication in construction offers key advantages. Conducted in a factory, it ensures strict quality control, enhancing predictability and precision. This efficiency shortens project timelines and cuts costs by improving schedules and productivity. Prefabrication also minimizes on-site activities, preserving component integrity and durability, and reduces labor, traffic, noise, and community disturbances. It enhances safety, reduces reliance on traditional equipment, and eliminates issues with wet processes, waste, and improper material handling, creating a more controlled indoor environment [1]. Modular construction embodies the principles of prefabrication, using a kit-of-parts approach to achieve design goals with minimal variation in building components, regardless of target programs [2]. This strategy supports the growing trend of modular construction and prefabrication, highlighting the benefits of standardized, repeatable elements in the built environment [3].

This study presents an innovative construction system within the "R2U Technologies" framework, balancing repetition and adaptability. The goal is to efficiently combine and reconfigure components to meet diverse architectural and functional needs, providing a fast, efficient, and sustainable solution to Portugal's housing crisis and urban development.

2 – BACKGROUND AND MOTIVATION

The use of timber in multi-story buildings has attracted significant attention over the past decade from researchers, construction professionals, and governments worldwide. Its sustainable profile, combined with structural properties such as a favourable strength-to-weight ratio, has made it an ideal material for modern structures. This growing interest has led to a rise in timber

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multi-story buildings, with increasing confidence in this typology [4]. Countries with a strong tradition of timber construction have quickly adopted new high-rise technologies, benefiting from their experience, trust in the material, and well-established market structures. In contrast, countries like Portugal have made slower progress.

Addressing market dynamics and overcoming negative perceptions are crucial for the broader adoption of timber construction. This understanding facilitates the development of solutions that challenge misconceptions and position timber as a viable alternative to traditional methods. However, beyond social perception, Portugal's timber construction market remains underdeveloped due to a lack of incentives, specific regulations, and specialized professionals [5]. The primary challenge now lies in the absence of solutions tailored to the Portuguese context. Research and innovation in colder-climate countries have focused on solutions suited to their specific conditions, which may not be directly applicable to Portugal.

To advance timber construction in Portugal, further research is needed to adapt this typology to local conditions. Key considerations include the temperate climate, which favours biological deterioration, temperature variations, urban regulations for new construction, national performance and fire safety requirements, the diversity of available timber species, the most widely used construction materials in terms of quality and cost, prefabrication technologies in the timber sector, transportation constraints, and prevailing architectural preferences. Addressing these factors will support the development of reliable, efficient, and durable solutions suited to the Portuguese context, fully leveraging timber's potential.

3 – PROJECT DESCRIPTION

The "R2U Technologies | modular system" initiative aims to develop and industrialize an innovative concept in modular construction, addressing the growing market demand and challenges, particularly in sustainability and environmental protection. This project seeks to equip businesses, academic institutions, and skilled professionals with the essential tools, knowledge, and competencies to establish a Portuguese hub for the global supply of modular construction solutions. Within this framework, the "Principles of Modular Construction" work package concentrates on creating sustainable, efficient, intelligent, and high-performance modular construction systems. These systems are based on a customizable and scalable matrix, designed to meet the specific requirements and challenges of various functional programs, offering a generic response to the particular features of each building.

4 – THE CONSTRUCTION SYSTEM

The construction system is centered around the development and innovation of prefabricated components, with timber as the primary material, including floor and wall panels, designed for both structural and non-structural applications, suitable for internal and external configurations (Figure 1).

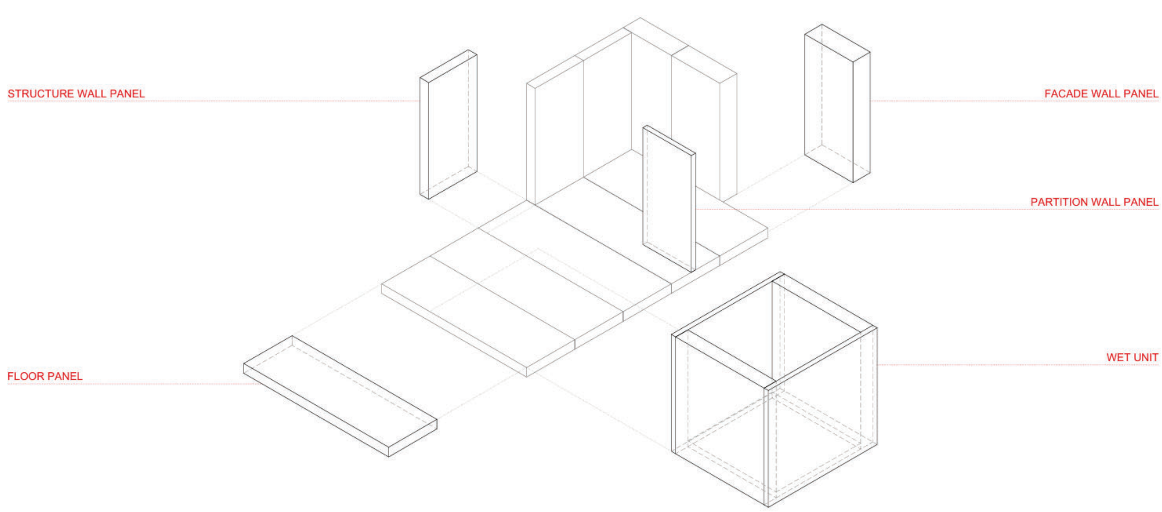

Figure 1. Axonometric view of the overall constituents of the system.

These panels integrate functional layers and accommodate MEP (mechanical, electrical, and plumbing) systems, ensuring efficient and streamlined installation. Fully pre-assembled 3D modules are created by integrating the previously developed 2D panels, addressing both the design requirements for the 3D elements and the specific programmatic needs. This approach simplifies the on-site construction process. In particular, wet modules have been developed for bathroom and kitchen facilities.

This system is engineered to meet both structural and functional requirements, while also addressing logistical constraints. Its development is facilitated through a Building Information Modeling (BIM) environment, which promotes interdisciplinary coordination, optimizes material use based on panel dimensions, and enables the automated integration of MEP systems. To ensure quality and compliance with industry standards, prefabricated panels undergo comprehensive experimental evaluation in line with European standardization testing protocols, assessing both mechanical and functional performance. The final goal is to develop a ETA (European Technical Assessment) for each of the proposed prefabricated component. Additionally, an Environmental Product Declaration (EPD) is generated for the final components, providing an in-depth analysis of their environmental impact and sustainability metrics.

5 – SCOPE, DESIGN CONSTRAINTS AND ASSUMPTIONS

5.1 MARKET TARGET

The timber modular construction system developed in this study is designed as a strategic solution for sustainable urban development in Portugal, enabling the rapid construction of dignified, energy-efficient, and affordable spaces. Given the geographical proximity and strong commercial ties between Portugal, France, and Spain, these last two countries have also been identified as key target markets for the implementation of the system. To ensure its feasibility and scalability, the system has been developed with careful consideration of several critical factors, including the availability and market acceptance of materials, the logistical requirements for manufacturing, transportation, and on-site assembly, as well as the specific regulatory requirements and constraints in each country.

5.1 BUILDING SCALE AND APPLICATIONS

The system is engineered to accommodate buildings of up to four stories (ground floor plus three additional levels), making it a versatile solution for various applications. Given the project's scope, timber-frame construction was chosen as the primary structural system for vertical and horizontal components. The intended uses of buildings constructed with this system encompass a diverse range of programs, including:

- Multi-family housing, addressing the growing demand for affordable and high-quality residential units in urban and suburban areas;
- Senior living facilities, offering safe and comfortable accommodations tailored to the needs of aging populations;
- Student residences, providing efficient and well-designed housing solutions for university and college students;
- Hotels, facilitating the development of modular, cost-effective, and rapidly deployable hospitality infrastructure;
- Hospitals, supporting the construction of adaptable and scalable healthcare facilities, particularly in response to urgent or evolving medical needs.

By integrating standardization with adaptability, this modular construction approach seeks to optimize efficiency while ensuring flexibility to meet the diverse requirements of different building types and regulatory frameworks.

5.3 TRANSPORTATION

Transportation constraints arise from both the type of vehicles used and the legal regulations governing safe circulation. Given the target market, road transport is prioritized, as it sets dimensional limits not only for accommodating prefabricated elements within trucks but also for ensuring compliance with road regulations in the designated regions. Throughout Europe, unescorted vehicles up to 2.55 meters in width are generally permitted. However, to avoid excessive restrictions on unit dimensions, the use of specialized transport for oversized loads is also considered. This requires meticulous logistics planning, including the selection of appropriate vehicles, lifting equipment, and, most importantly, the expertise necessary to ensure safe and efficient transportation throughout the entire route.

According to EU legislation 2015/719/EU [6], the maximum allowable dimensions and weights for national and international road transport within the EU are:

- 16.5 meters (m) in length (18.75 m for road trains);

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- 2.6 m in width;
- 4 m in height;
- 40 tonnes (t) in weight (44 t for combined transport, e.g., rail and water).

Oversized loads can also be transported, though specific requirements vary depending on the load's dimensions. Throughout Europe, Directive 96/53/EC [7] establishes a standardized framework for the movement of abnormal loads across the 28 European states, ensuring that such transport operations are conducted safely and efficiently.

For the proposed modular system, both standard and special-dimension transport are considered to avoid excessive constraints on unit size and architectural flexibility. This dual approach enhances design adaptability while maintaining logistical feasibility.

Beyond road transport, maritime shipping has also been accounted for, with dimensions compatible with standard 20-foot and 40-foot containers. This expands the system's scalability, facilitating future market expansion through international trade.

5.4 TECHNOLOGY AND EQUIPMENT AVAILABLE

The production phase of the panels is subject to constraints imposed by the available technological and material resources, which directly impact both manufacturing efficiency and the allowable panel dimensions. To optimize production speed and ensure precision, the system will be manufactured using an advanced automated production line, specifically designed to handle, cut, and assemble its components with minimal manual intervention. This automated production line integrates multiple processing stages, including material handling, CNC cutting, robotic assembly, and quality control mechanisms. The machinery is programmed to execute precise cuts, ensuring uniformity and reducing material waste. Additionally, automated fastening and bonding processes enhance structural integrity while increasing production efficiency. The entire workflow is optimized for speed and accuracy, significantly reducing lead times and minimizing human error.

As a result, the dimensions of the system's components must be compatible with the operational capacity of the machinery, which is limited to a maximum width of 3.5 meters and a length of 9 meters. These limitations define the modular configuration of the system, influencing both design decisions and logistical considerations for transport and assembly.

5.5 MATERIAL DIMENSIONS AND PROPERTIES

Beyond the constraints imposed by mechanized processing, the panels also incorporate engineered wood boards—specifically, OSB (Oriented Strand Board)—, which are commercially available in standardized dimensions. These predefined sizes played a key role in material selection, panel detailing, and the modular design strategy, ensuring that dimensions align with industry standards. By optimizing panel sizing to match standard board dimensions, the system minimizes the need for additional cutting, reducing material waste, lowering production costs, and streamlining the manufacturing process.

Working with standardized materials also enhances supply chain efficiency, ensuring greater availability and shorter lead times. Additionally, optimizing panel sizes to minimize off-cuts not only reduces waste but also decreases energy consumption during production and assembly, reinforcing a more sustainable construction approach. The use of widely available materials further increases the system's adaptability across different markets, simplifying sourcing and improving integration with regional supply chains.

For the structural linear elements, standard cross-sections were carefully selected to guarantee not only material availability and cost-effectiveness but also structural reliability and ease of assembly. Opting for readily available dimensions prevents the need for excessive wood processing, which could otherwise increase production complexity and costs. The chosen dimensions—45×95 mm, 45×145 mm, 45×170 mm, 45×195 mm, and 70×220 (solid wood); and 12×280 mm (glued laminated timber)—were selected to strike an optimal balance between structural integrity, efficient manufacturing, and logistical feasibility. These standardized sections contribute to a more sustainable and scalable production process while maintaining the adaptability required for diverse architectural applications.

In terms of strength, timber from the C24 strength class is utilized (EN 338 [8]), while the thicknesses of the OSB panels vary depending on the type of panel in which they are applied (e.g., wall, floor, etc.). Moreover, specialized components, such as CLT (cross-laminated timber)-based components and linear elements, can be applied for superior performance and reinforcement in targeted applications.

5.5 COMPLIMENTARY MATERIALS

The proposed construction system is based on the use of wood as the primary structural material. However, to meet functional requirements related to comfort and performance, additional materials must be incorporated. These materials, commonly used in timber construction, are selected to ensure the quality, safety, and durability of the buildings. Key components include insulation materials, membranes, coatings, and finishes, all of wich contribute to specific and multifunctional performance aspects such as thermal and acoustic insulation, fire resistance, and moisture protection. The selection of these materials is guided by their ability to enhance overall building performance while aligning with the system's core principles of sustainability, affordability, repeatability, and material efficiency.

Membranes: moisture protection and air sealing

A breathable membrane is integrated into the system to provide a protective layer against external weather conditions. This layer protects the panel while it is assembled on-site and, over the building's lifespan, the membrane acts as a secondary barrier against rainwater infiltration, enhancing airtightness and reducing uncontrolled heat loss due to air leakage. To effectively fulfill these functions, the membrane must strike a balance between high water and moisture resistance to prevent infiltration and low vapor resistance to allow for moisture diffusion, thereby preventing condensation within the wall assembly.

Additionally, a vapor barrier is installed to regulate the transfer of water vapor, preventing excessive condensation that could lead to mold growth, structural deterioration, and biological degradation of the timber.

An impermeable membrane is strategically applied in wet areas and on the roof to serve as a critical barrier against water infiltration, preventing moisture-related structural damage and ensuring the system's long-term durability.

Insulation: thermal, acoustic and fire protection performance

While primarily designed to reduce heat loss and enhance thermal comfort, insulation also plays a crucial role in soundproofing, by absorbing airborne noise, and in fire protection, by delaying flame spread and improving the fire resistance of external layers. An effective insulation strategy is essential to prevent thermal bridging and condensation, which, if uncontrolled, can lead to moisture accumulation, mold growth, structural degradation, and dimensional instability in wood, such as warping and cracking.

Various insulation materials, including cork, cellulose, wood fiber, and rock wool, were evaluated based on their performance, adaptability, and compatibility with the construction system. Among these, wood fiber was selected for its sustainability and superior thermal and acoustic properties, while rock wool was chosen for its fire resistance and durability, particularly due to its high resistance to moisture, ensuring an optimal balance between performance and environmental responsibility.

In addition to absorbent insulation materials, resilient materials in the form of mats and tapes are also incorporated to decouple rigid elements and reduce impact noise transmission, particularly improving sound insulation at low frequencies, which is a common weakness in wooden construction.

Cladding: water and fire protection and versatility

Exterior cladding plays a vital role in safeguarding the building against environmental factors while contributing to fire protection and aesthetic versatility. Although wood-based cladding is prioritized for its sustainability and aesthetic appeal, alternative materials are incorporated to enhance durability, fire resistance, and adaptability across different applications.

The interior wall cladding serves four key functions: i) providing an aesthetic finish, ii) enhancing water resistance, iii) improving acoustic insulation, and iv) ensuring fire safety by addressing both reaction to fire (flame spread) and fire resistance (encapsulation of the wooden structure for structural protection). Suitable materials include gypsum boards, ceramic tiles, vinyl finishes, alongside fire protection solutions such as intumescent paint and fire-resistant plaster. Additionally, the duplication of elements was employed as a strategy to enhance fire resistance by extending the protection period and to improve acoustic performance by increasing the system's layers and mass.

By integrating a range of materials, the system maintains adaptability to diverse climatic conditions, regulatory standards, and market demands.

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6 – DEFINITION OF THE CONSTRUCTION SYSTEM CONCEPT AND METRICS

The modular framework of the construction system was established through the definition of its fundamental unit. Accordingly, the system was primarily designed for 2D transportation and on-site assembly, streamlining logistics and handling. However, to ensure waterproofing, bathrooms are necessarily pre-assembled into 3D modules from 2D panels at the factory, enhancing quality control and finishing efficiency. The design also avoids horizontal pipe runs within PODs (Prefabricated Offsite Bathrooms) by concentrating plumbing within core units, which minimizes leak risks and simplifies maintenance. The system also permits individual components to be used independently, making it suitable for rehabilitation projects as well. This 2D-fundamental unit principle extends to the integration of linear structural reinforcement elements, which are also configured as flat components that align with the system's established metrics.

The development of the system's metric was driven by a comprehensive architectural analysis focused on the functional requirements of the spaces within the target programs. This analysis encompasses not only the required usable area but also the optimal spatial organization. By evaluating the dimensions of these spaces, a cross-dimensional logic emerged, forming the basis for the system's metric (Figure 2).

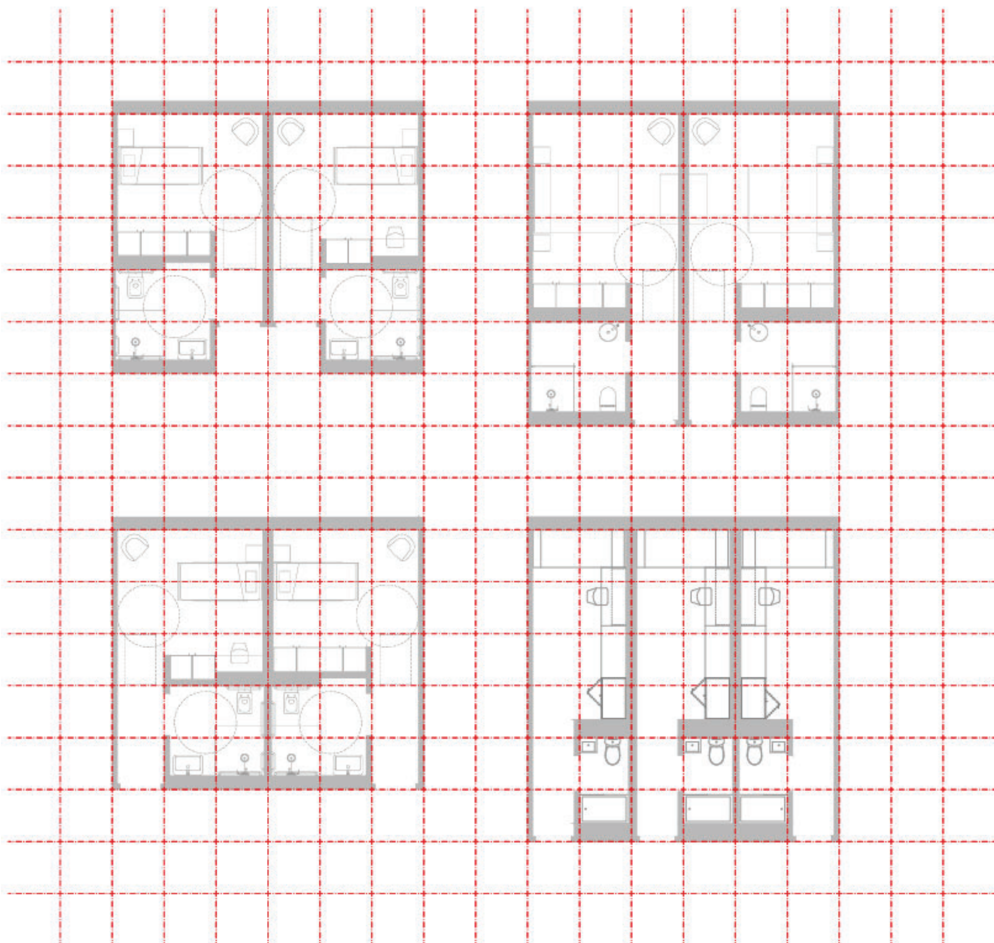

Figure 2. Elemental grid overlaying the rooms of different programs, illustrating the cross-dimensional logic behind the system's metric.

Moreover, the analysis was not confined solely to the spatial layout. It also incorporated factors related to the limitations of production, transportation, and installation, as well as the standardized dimensions of the materials that make up the system and their availability in the market. This integrated approach ensures the system's practical feasibility, enhances accessibility and replicability, and minimizes processing and waste. Through this process, the optimal dimension, which accommodates diverse spatial requirements while minimizing the need for cuts, was identified as the OSB panel size of 1250×2500 mm^2, which is used in the construction of wall and floor panels.

Based on this framework, the system allows for spaces to be combined in increments of 1.25 meters, creating areas with dimensions that are multiples of this value. Architectural design using exact multiples leads to industrialization, reaching a high level of prefabrication. This system has a maximum dimension of 7.5 meters of free span, dictated by the construction method, with the other dimensions being limited by the manufacturing equipment. This size is versatile enough to accommodate different spatial requirements, such as a classroom, two hotel rooms, or three student residences (Figure 3).

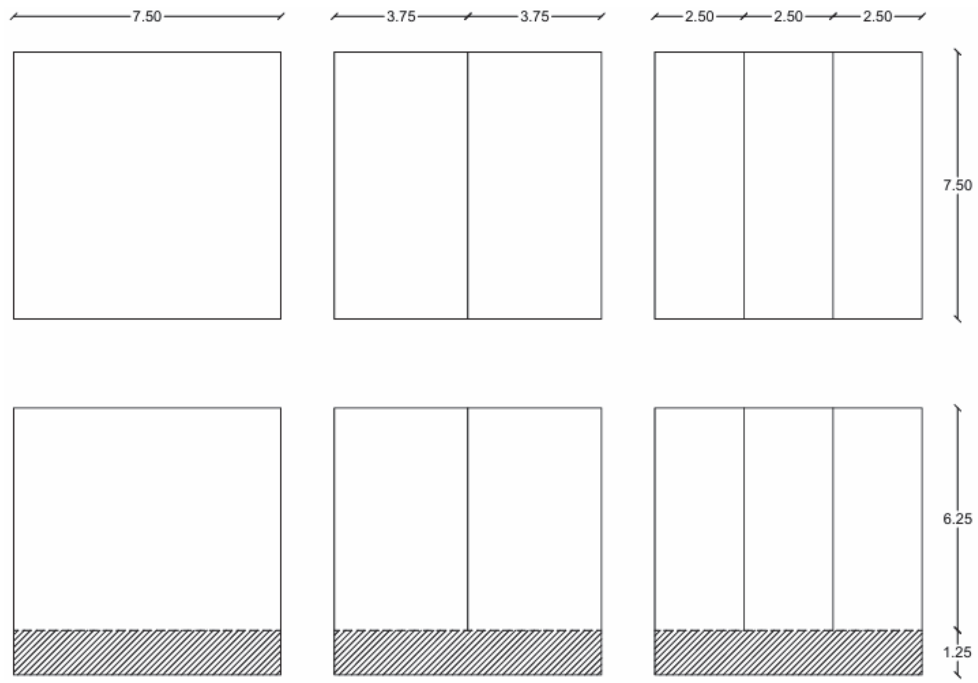

Figure 3. Space optimization solutions.

The base panel of the system is designed in accordance with the proportional metric of the spaces, ensuring its feasibility, regarding the automated production line and transportation, and compatibility across all target programs (Figure 4).

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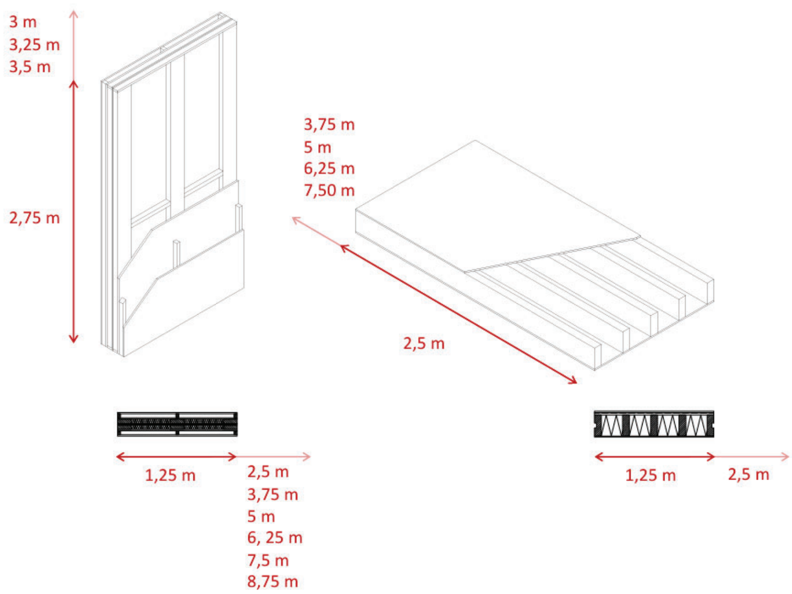

Figure 4. Range of base panel dimensions according to the system's metric.

7 – COMPONENTS OF THE CONSTRUCTION SYSTEM

The project developed specific modular components for both walls and flooring. For walls, the components include facade wall panels, structural and non-structural wall panels, and shafts. For flooring, three distinct options were created: a standard panel for dry areas, a specialized panel for wet areas, and a support panel designed specifically for wet areas. Each panel type is designed with a base composition that includes specific layering, material options, and dimensions tailored to its intended function.

Panels can be further enhanced with additional layers, allowing the system to adapt to various scenarios (e.g., climate, usage, protection requirements, maximization of prefabrication, quality control, and comfort). These reinforcements improve thermal, acoustic, fire protection, and aesthetic performance, while also enabling the integration of infrastructure.

It is important to highlight that the base panel already incorporates functional elements to meet minimum standards for thermal, acoustic, and fire protection. The ability to reinforce these elements ensures that the system can meet diverse performance and comfort needs, offering greater flexibility and versatility in its application.

6 – CONCLUSIONS

The aim of this construction solution is to contribute to the development of modular timber construction by introducing a kit-of-parts system using timber-frame wall and floor panels for four-storey buildings. It demonstrates the effective integration of 2D and 3D components, highlighting the efficiency of prefabricated timber systems.

Material selection and transportation strategies were pivotal to the project's outcomes. The research addressed logistical constraints by evaluating both road and maritime transport modalities, with maritime transport restricted to 2D modular components due to dimensional limitations. The EWP selected for the system is OSB, solid wood boards, and glulam in standardized dimensions. Furthermore, the automated production line was designed to accommodate components up to $3.50{\times}9\ m^2$. The spatial matrix was created through a thorough analysis of the needs for various building types, including hospitals, senior residences, student dormitories, hotels, and collective housing. By incorporating standard material dimensions and transportation constraints, a modular matrix of $7.5{\times}7.5\ m^2$ was defined.

Key findings include the successful use of pre-assembled bathroom modules for reliable waterproofing and quality control, as well as the benefits of a modular matrix system for optimizing space utilization and resource management. The deployment of EWP and modular design principles has led to significant gains in construction efficiency, materials optimization and use of renewable resources.

Future efforts should focus on performance validation through further testing, exploring design optimizations,

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material innovations, and advanced technologies to further enhance the sustainability, adaptability, and overall efficiency of modular construction. Currently, acoustic tests (airborne and impact sound) and mechanical tests (bending and rocking shear) on wall and floor panels are already being conducted.

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