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OFF-SITE MANUFACTURING FOR A NEW MODULAR WOODEN ARCHITECTURE MADE IN ITALY

Albino Angeli[1], Jacopo Bono[2], Guido Callegari[2], Adriano Francescotti[1], Massimiliano Lo Turco[2], Stefano Menapace[3], Jean Carlos Lapo Procel[2], Andrea Rossi[4], Benedetta Rossi[1], Paolo Simeone[2], Andrea Tomalini[2]

ABSTRACT: The industrial development project "SU.PRE.MO – from Super X-Lam To Prefabrication and 2D/3D Modularity", organised with the support of the Provincia Autonoma di Trento, focused on modular homes for self-build and emergency situations, using the prefabricated CLT products of the Trento-based company. XLAM Dolomiti was the project leader. This paper describes the design activities relating to the *modular house kits* designed in versions from 20m^2 to 100m^2 by the Polytechnic University of Turin, in cooperation with XLAM Dolomiti. A combination of off-site manufacturing and the standard products of XLAM Dolomiti was used to produce a digital catalogue of the various building concepts with a number of possible configurations for the modular homes.

KEYWORDS: off-site manufacturing, modularity, self-build houses, parametric design, computational design

1 – INTRODUCTION

The main objective of the multidisciplinary research project SU.PRE.MO was to develop a new generation of architecture in engineered wood from Super X-Lam to Prefabrication and 2D/3D Modularity. This paper presents the one-floor modular homes built using prefabricated components and off-site manufacturing systems with a wood-based CLT panel construction system. The product is destined for countries in which self-build homes are regulated and established, and included the analysis of social requirements for the development of a product capable of adapting to various international contexts and conditions.

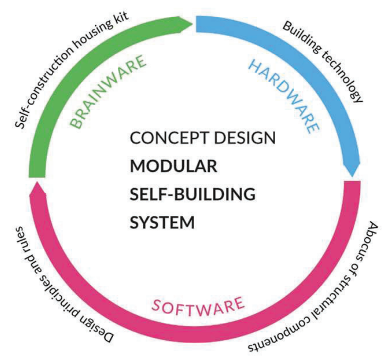

Figure 1. Concept design process according to the three fundamental components of technology for the SU.PRE.MO project

2 – BACKGROUND

The SU.PRE.MO. project takes up one of the challenges launched by the EU: to innovate the building sector through industrialised construction using bio-based materials in order to increase the diffusion of engineered timber construction systems as a decarbonisation strategy.

The project – a technological and production challenge – focuses on the theme Off-site Manufacturing Methods for Sustainable Building Systems.

Smart manufacturing is an important element of industry 5.0, the Collaborative Industry, a business model characterised by the goal of giving added value to production by creating highly customised products. In this specific case, the aim was to develop a design process capable of accompanying the most important Italian CLT manufacturer in the automation of the design stages of a self-build housing model, using a simplified and accessible construction process. The system includes the support of a user-friendly interface for end users, able to generate multiple housing solutions in a short time, while

[1] XLAM Dolomiti Spa, Castelnuovo, Trento, Italy, albino.angeli@xlamdolomiti.it

[2] Polytechnic University of Turin, Department of Architecture and Design, Torino, Italy, guido.callegari@polito.it

[3] ARM Process Srl, Trento, Italy, stefano@armprocess.com

[4] University of Kassel, Faculty of Architecture, Urban Planning and Landscape Architecture, Kassel, Germany, rossi@asl.uni-kassel.de

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respecting the rules and technical constraints present. The SU.PRE.MO. project was born in the context of the Autonomous Province of Trento (PAT), which is characterised by an industrial ecosystem of companies specialised in the sector of timber construction and research for eco-sustainable buildings. In Italy, this reality is one of the excellences in the reference sector that, in the last two decades, has generated added value with internationally recognisable contributions such as the SOFIE project conducted by CNR Ivalsa (now CNR Ibe) with the support of the Autonomous Province of Trento and ARCA, which is the certification system designed specifically for timber buildings by Habitech and Trentino Sviluppo. The acronym SU.PRE.MO identifies the three main focuses of the project:

- SU indicates the development of a Superlegno;
- PRE the theme of prefabrication systems and processes;
- MO the field of modular housing for self-construction and emergency.

In this framework, the skills of the Polytechnic University of Turin have been employed in developing the design of modular houses for self-construction, which is explored in depth in the context of this contribution. In addition to the Polytechnic University of Turin, the multidisciplinary research activity of the SU.PRE.MO project involved the Trentino technology district Habitech, the Bruno Kessler Foundation, the CNR IBE of San Michele all'Adige, the University of Trento, the University of Florence as well as several start-ups, innovative companies in the digital sector, and professional firms.

2.1 INTEGRATED CLT MANUFACTURING

XLAM Dolomiti is located in Trentino: founded in 2012 by the Paterno Group, it quickly gained an important position in the production of CLT panels and today represents one of the most authoritative and cutting-edge companies in the sector at an international level.

Figure 2. Photos from the manufacturing site in Castelnuovo (TN) – Italy. Photo: Paolo Simeone.

One of the distinctive features of XLAM Dolomiti is its integrated approach to the construction cycle; the company offers its customers a complete service, from the production of the panels to the design and construction of the buildings, guaranteeing perfect integration of the various phases up to the final realization.

Figure 3: Construction site of XLAM Dolomiti in Italy.

3 – PROJECT DESCRIPTION

The "SU.PRE.MO – from Super X-Lam To Prefabrication and 2D/3D Modularity" research project aims to develop innovative timber-based products. Initiated on September 5, 2022, the project has a three-year duration and is currently underway. SU.PRE.MO. includes a specific macro-deliverable on modularity (MO), which is divided into two branches:

- One investigates the design of emergency modules, created with the intention of providing shelter to those affected by natural disasters, where rapid response times are crucial.

- The other, which is the object of this paper, focuses on the creation of housing modules, with particular emphasis on those designed for self-construction.

The tasks related to self-construction modules include the creation of a series of standardized prefabricated modules intended for foreign markets (outside Italy) where self-construction is allowed. Starting from a limited number

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of basic CLT panels, it is possible to create a huge number of dwellings with these minimal production variations (see section 5). Furthermore, the project encompasses the study of architectural solutions, dwelling volumes, formal aspects, and performance.

Another key element of the project is the creation of a digital platform for non-professional clients, as consumers, managing the process from inquiry to delivery. Through an online configurator, users can customize their dwelling based on a series of feasible solutions adaptable to individual needs.

The objective is to offer a user-friendly, customizable self-construction system that guarantees high-quality standards. Flexibility and adaptability are fundamental components of this modular system relying on a set of realistic solutions.

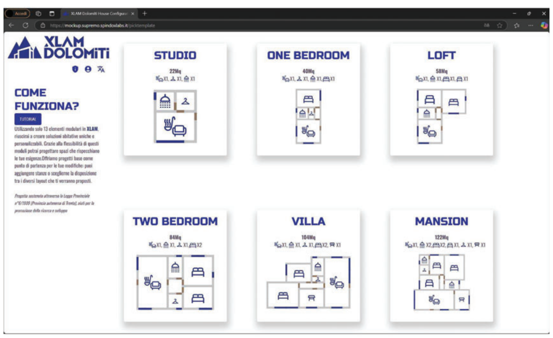

Figure 4. Digital platform's online configurator.

The digital platform plays a crucial role, allowing customers to configure the house, receive self-construction materials with precise assembly instructions, and exploit ancillary services from local partners. This platform will enable reaching customers worldwide, leveraging e-commerce systems and integrated logistics.

XLAM Dolomiti is in charge of the manufacturing of CLT panels, timber structure engineering and industrial use. Through regular meetings to review and share results, a project management approach facilitates collaboration between the organization and different entities, including research institutions, universities and specialists. Each organization provides specialized knowledge according to the various goals, collaborating to accomplish the project's objectives.

4 – DESIGN PROCESS

The research activity included an initial analysis of the benchmarks at international level with reference to the development of residential modules, and in particular to self-build solutions, both experimental and established. Subsequently, using a system of modular grids the design rules for the technological and construction system using load-bearing CLT panels and the organization of the rooms in the versions to be offered were identified. A handbook with a brief description of the main steps of the design process was written, which led to the charting of the design and process rules for the SU.PRE.MO modular system and the programming of an algorithm to generate the homes automatically using an online configurator.

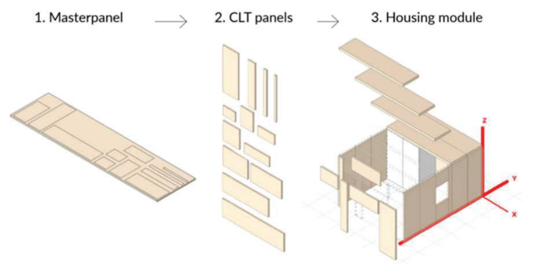

Figure 5. Production process: from the masterpanel of CLT (1) made in XLAM Dolomiti plant to typical panels (2) and housing module (3).

5 – MODULAR SELF-BUILD SYSTEM

5.1 A PROCESS FOR DESIGN IN SELF-BUILD PROJECTS

One of the primary goals of the SU.PRE.MO. project has been to establish a design and self-building process utilizing a limited number of structural components. The research led to the identification and definition of a system of fundamental design criteria — both architectural and constructive — developed by the research team at the Polytechnic University of Turin in collaboration with the expert team at XLAM Dolomiti.

This collaboration aimed to develop a new method for aggregating rooms and distributing functions in a one-floor house based on a simple grid using the measurement of the width of the CLT panel as a modular parameter: 1120 mm.

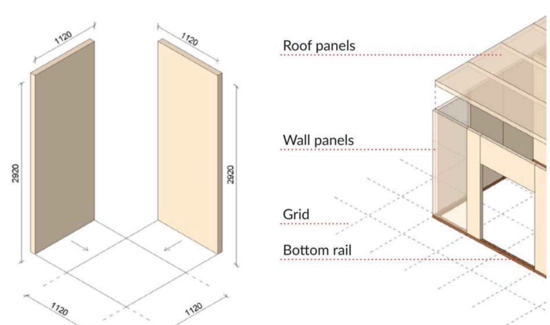

Figure 6. Modular grid based on the width of the CLT panel (112 cm); positioning of the main structural components on the grid.

An optimized self-construction process through a set of 10 basic rules constituted the design principles of the SU.PRE.MO. system that includes 4 "standard-kit" housing modules of various sizes, 26, 46, 67, and 84 (m^2).

The 10 basic rules are: 01-Modular grid; 02-Wall system positioning; 03-Floor system positioning; 04-Wall system; 05-Lintel system; 06-Door/window opening; 07-Floor system; 08-Connection system; 09-Rooms modular generation; 10-Self-construction kit.

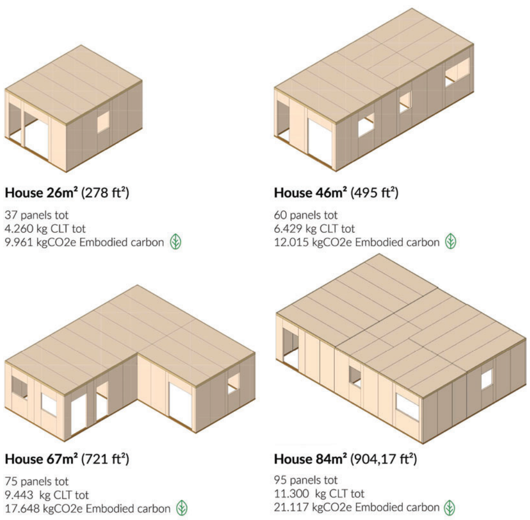

Figure 7. Four housing modules created using the panel kit in accordance with the 10 basic rules; the embodied carbon (KgCO2e) related to the mass of CLT utilized in each house.

In the design principles of SU.PRE.MO. system "Rule 09 – Rooms modular generation" is the fundamental rule that defines the criteria for the aggregation process of the rooms and the distribution functions for achieving the optimal configurations of the MO Self-construction. Starting from the 112x112 modular grid by applying the first 8 rules stated above, it was possible to define the scheme of all the rooms that can be generated to guarantee the main living functions of a house. (Figure XX). With an alphanumeric code, the scheme includes a set of 15 rooms, related to the typical functions, from A1.2 to A4.9 where the numbers refer to the modules of the grid; for instance: A2,4 means a room of dimensions (112 X 2) X (112 X 4) =224x448 cm² = a room of 10,00 m² of surface area.

TYPICAL FUNCTIONS	MODULAR GRID / ROOMS														
Corridor	1,2	1,3	1,4	2,2											
Storage/laundry	1,2			2,2											
Bathroom				2,2	2,3										
Kitchen					2,3	2,4	3,3	3,4	3,5	4,4	4,5				
Office					2,3	2,4	3,3	3,4							
Single bedroom						2,4	3,3	3,4							
Living room							3,3	3,4	3,5	4,4	4,5	4,6	4,7		
Twin/double bedroom								3,4	3,5	4,4	4,5	4,6			
Openspace								3,4	3,5	4,4	4,5	4,6	4,7	4,8	4,9

Figure 8. Abacus of 15 rooms generated by the modular grid, from A1,2 to A4,9, and their typical functions.

To show Rule-09, we will describe the 46 m² housing module (Figure XX), which is composed starting from the aggregation of 4 rooms: A1,2 (corridor), A2,3 (bathroom), A3,4 (double bedroom), and A4,4 (living room and kitchen). The following drawing illustrates the layout of the house with its 4 aggregated rooms.

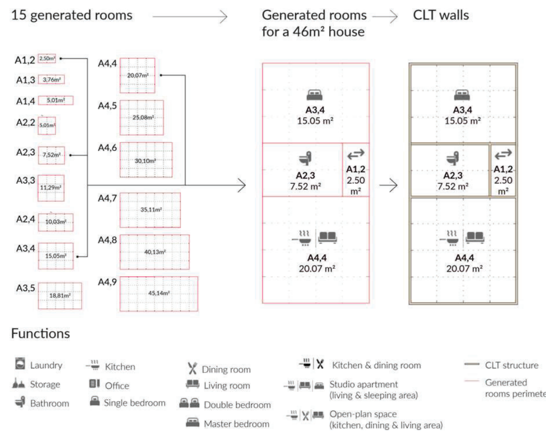

Figure 9. Abacus of the 15 generated rooms and the application of Rule-09 "Rooms modular generation" for the 46m² house.

This set of rules has been compiled into a manual titled "SU.PRE.MO.Sistema_Mo Autocostruzione Handbook" (SU.PRE.MO. Modular Self-build System Handbook) to provide a comprehensive tool for outlining the fundamental aspects of the design process. [1]

The research team at the Polytechnic University of Turin designed the manual with a detailed visual layout, where both text and illustrations (including 2D-3D schematics and architectural drawings) work together to clarify the complexity of the project's results.

The manual has been an essential tool for the subsequent development at the software level for advanced algorithmic solutions for the semi-automatic generation of housing modular layouts (see section 5.3).

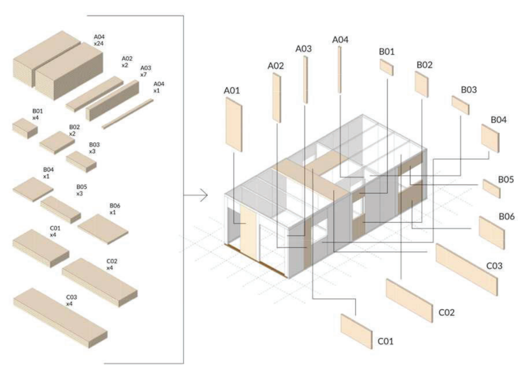

Figure 10. Self-construction kit made of 54 CLT panels ready for the assembly of a SU.PRE.MO. 46m² modular house.

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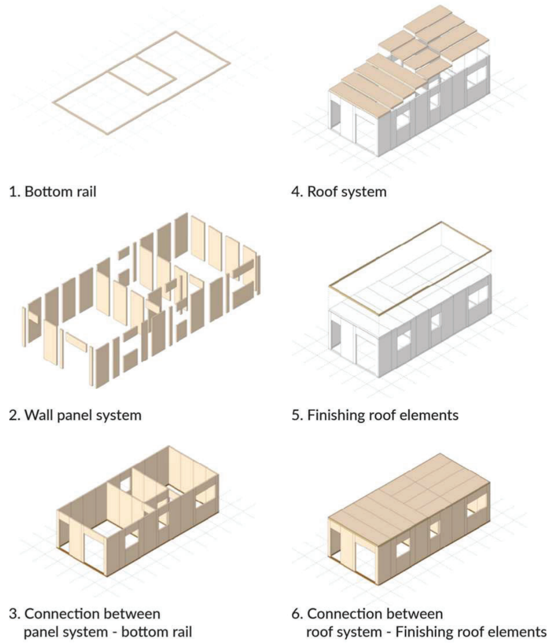


Figure 11. Assembly process of the self-construction housing kit for a SU.PRE.MO. 46m² modular house.

5.2 OFF-SITE MANUFACTURING PROCESS

Modular timber architecture is manufactured off-site using an organized and iterative process that begins with an initial concept design and continues through engineering and refinement stages until a final catalogue of elements ("Abaco") is defined. This approach fully exploits the advantages of industrialized timber construction by ensuring high precision, reduced material waste and improved assembly efficiency.

a) Modular design framework and concept development.

The design process starts with a parametric framework that defines modular constraints according to manufacturing, transport and on-site assembly requirements. The aim of the concept phase is to create spatial arrangements that optimize uniformity while maintaining architectural flexibility. At this stage, the following important factors are taken into account:

- Panel sizing based on transit logistics and production optimization;
- Evaluation of structural integrity to ensure seismic and load bearing specifications are met.

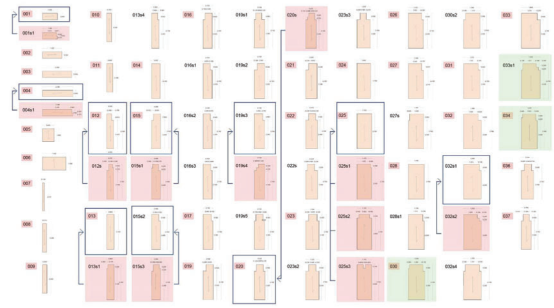


Figure 12. First step of optimization of the panel abacus.

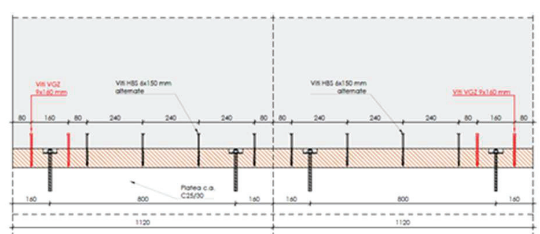
b) Design optimization and iterative refinement.

Once the modular principles have been established, each design element is evaluated for structural performance and manufacturability during an iterative refinement phase. During this phase,

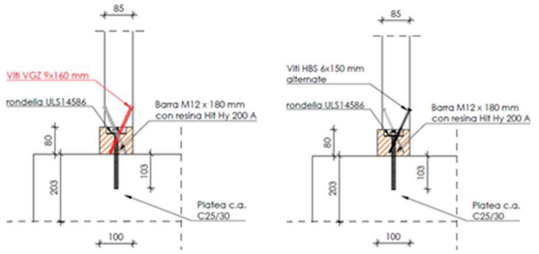
- *raw material consumption* is reduced and sustainability is improved through material optimization.

Figure 13. Further optimization of the panel abacus.

- *Connector system* engineering that ensures reliable and rapid on-site installation with minimal manpower.



Figures 14. Examples of connection details.



Figures 15. Examples of connection details.

- *Digital simulation* using Building Information Modelling (BIM) and Finite Element Analysis (FEA) to confirm the effectiveness of load-bearing components and structural nodes.

c) Abaco's final panel catalogue and standardization.

The final stage is to create a catalogue of the standardized components that make up the modular system. This "Abaco" will include:

- *Wall panels arranged according to their structural purpose.*
- *Roof components, optimized for spans, load distribution and thermal performance.*
- *Details of connections, such as mechanical fasteners.*

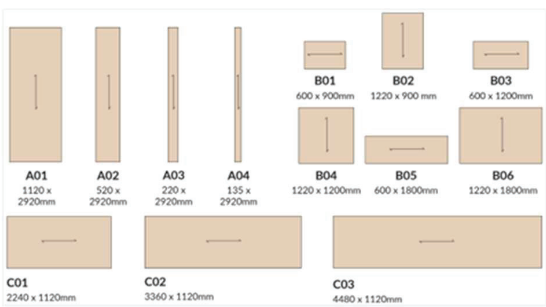


Figure 16. CLT panels KIT made of 13 structural elements organized into walls (from A01 to A04), lintel (from B01 to B06) and floor (C01, C02 and C03.

An industrialized production workflow is based on the refined panel catalogue, allowing mass customization while ensuring cost efficiency and consistent quality. Before being delivered to site, each component is prefabricated in a controlled factory environment, incorporating quality control procedures, precision CNC machining and bonding techniques.

d) Integration with logistics and digital manufacturing.

The modular components are easily integrated into a digital manufacturing process, where millimeter accuracy is guaranteed by CAD/CAM-controlled production. Optimize packaging and transportation strategies for volumetric efficiency.
Modular timber architecture achieves high levels of efficiency through this structured off-site manufacturing strategy, which also reduces construction times, improves sustainability and ensures compliance with engineering and performance standards.

5.3 ADVANCED ALGORITHMIC SOLUTIONS FOR SEMI-AUTOMATIC GENERATION OF LAYOUTS

The above mentioned web platform consists of a database of tested solutions and a filter interface to select the most appropriate one for the end user. Regarding the population of this database, a semi-automatic generative system was implemented to create different design configurations.[2]

This system consists of a sequential computational process divided into six interconnected phases. The definition of housing module aggregation standards required a preliminary analysis of the interrelationships between geometric, alphanumerical and topological information. This led to the definition of an abacus of rooms with typical functions, characterised by modular dimensions, typological and topological attributes. This abacus was converted into a structured data format for computational processing. The developed methodology exploits visual programming language through a dedicated environment and a specific plugin (Wasp) to implement combinatorial design algorithms and integrated data management.

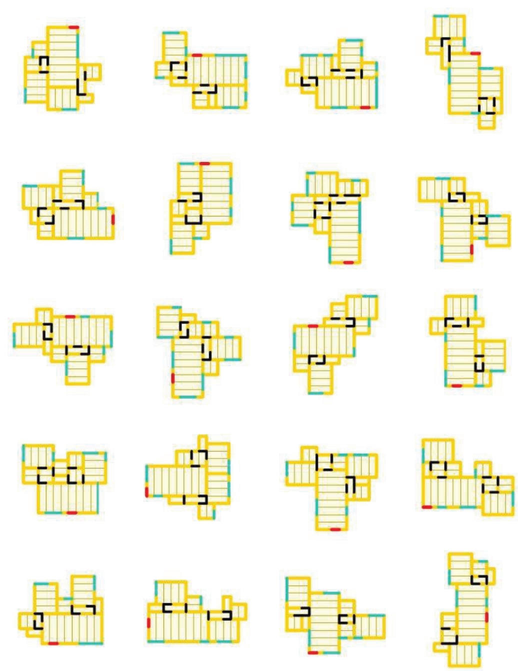


Figure 17. Generated solutions characterized by the same connection graph.

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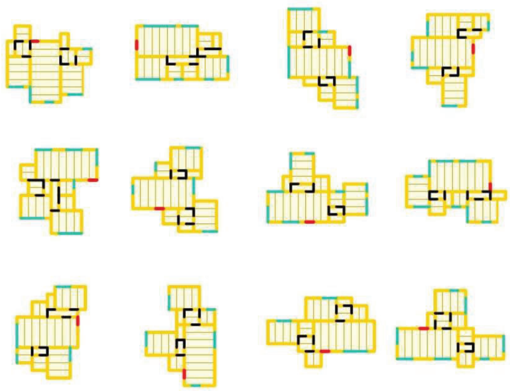

Figure 18. Generated solutions characterized by the same connection graph.

A visual interface allows the selection of desired functions and the definition of the total area. Dedicated scripts extract combinations of elements that satisfy the set constraints from the abacus. The plan generation phase uses a stochastic aggregation algorithm based on customisable adjacency rules to ensure distributional coherence and spatial connectivity between rooms.

The algorithm allows the variation of random parameters, producing a wide range of alternative solutions, while keeping the topological connection structure and the original constraints unchanged. The generated floor plans are then enriched with connection elements, such as doors and windows, then exported for further processing.

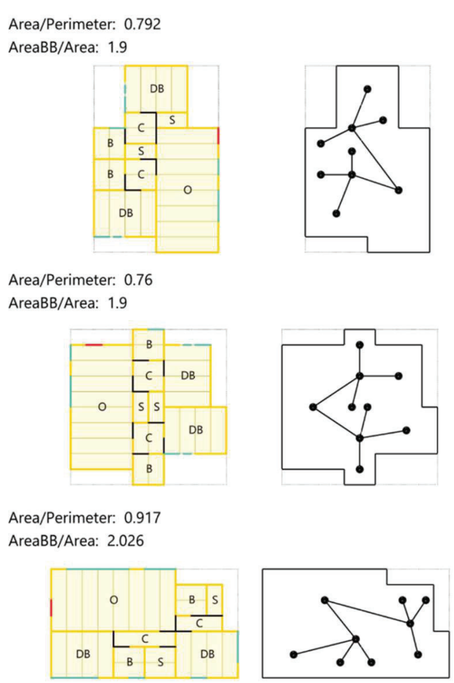

Figure 19. Three "compact" solutions with the same graph and same functions (O: Openspace; DB: DoubleBedroom; B: Bathroom; C: Corridor; S: Storage).

In order to ensure the quality and the consistency of the generated solutions, an algorithmic filtering phase was implemented to eliminate sub-optimal configurations. The filters adopted are based on geometric parameters, such as the area/perimeter ratio and the ratio between the plan area and the area of the minimum footprint rectangle. The selected floor plans are further processed with the automatic insertion of windows, in compliance with the regulations regarding air-to-light ratios. For this purpose, differentiated algorithms have been implemented to comply with specific regulatory frameworks, based on distinct calculation methodologies. The final stage of the process involves converting and exporting the data into a standardised textual format, including descriptive metadata such as the reference regulatory framework, the functional surface area, the spatial connectivity structure and a unique identification code, for subsequent integration into the web platform database.

Through the proposed methodology, starting from a syntetic abacus, more than one million configurations were generated.

Adopting open data formats and a fully automated computational workflow gives the system high adaptability and flexibility concerning changes in design parameters or modular dimensions.

5 – RESULTS

The project focuses on developing innovative modular self-build housing. Key aspects include:

Modular Housing: Designing prefabricated housing units for self-build scenarios using cross-laminated timber (CLT) through a digital platform easy to use for end-users.

Self-Build System: Creating an easy-to-assemble housing kit with a digital configurator to simplify design, reduce waste and optimize construction.

Design & Automation: Using computational design to generate efficient housing solutions with over a million possible configurations.

Sustainability: Prioritizing eco-friendly materials and circular economy principles.

Overall, the SU.PRE.MO project integrates material innovation, automation and sustainability to create efficient, scalable modular housing solutions.

6 – CONCLUSION

The SU.PRE.MO project has developed an automated design process for modular self-build housing, using engineered wood, emphasizing automation, adaptability and sustainability, simplifying and making construction more accessible. It features a user-friendly interface that generates multiple housing solutions while following technical constraints. The project established design and self-construction rules that minimize waste, optimize transport storage, reduce construction time and adapt to different markets.

A key innovation is the use of parametric and computational design, enabling high customization. By utilizing open data formats and an automated workflow, the system can generate over a million configurations, ensuring adaptability to design changes. The project also integrates off-site manufacturing for sustainable building systems and prioritizes bio-based materials, supporting the EU's decarbonization goals.

The use of the digital platform to drive the adoption of this solution in the self-build market, will require further development and implementation to enhance the end-user experience.

The system's flexibility allows for expansion beyond single-floor modular homes (multistorey buildings). Additionally, future research should focus on integrating plants and finishings using smart manufacturing, new materials, and partnerships to offer a turnkey building solution.

7 – REFERENCES

[1] "Su.Pre.Mo. Sistema_ MO Autocostruzione. Handbook" is an output of the "Deliverable 4.2.3 / Architectural design of self-construction modules" of SU.PRE.MO project, designed by the team of the Polytechnic University of Turin Department of Architecture and Design, Guido Callegari (scientific director) and Paolo Simeone, with the collaboration of Jean Carlos Lapo Procel, and the team of XLAM Dolomiti, Albino Angeli (CEO e President), Stefano Menapace (Project Manager - ARM Process Srl), Adriano Francescotti, Donato Fanti, Evgeny Borovin, Benedetta Rossi and Chiara Gonzo.

[2] The algorithmic platform for the automatic generation of project layouts is a partial product of the "Deliverable 4.3 / Software platform of self-construction modules". This specific Task, designed by the team of the Department of Architecture and Design of the Polytechnic University of Turin, Massimiliano Lo Turco (scientific manager) and Andrea Tomalini, with the collaboration of Andrea Rossi, and the team of XLAM Dolomiti, previously mentioned, and the team of Spindox, responsible for Deliverable 4.3.

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