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ALL-IN-ONE INDUSTRIALIZED ACTIVE FAÇADE FOR DEEP BUILDING RETROFIT: TIMBER ENGINEERING PROCESS AND PERFORMANCES ANALYSIS

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ABSTRACT: The present paper illustrates the development and validation of an innovative all-in-one timber-based envelope solution for deep building renovation, designated as the "energy and air-fresh distribution kit." This research encompasses the comprehensive engineering process of integrating HVAC systems into prefabricated timber façades and presents the results of numerical and experimental analyses. The façade kit incorporates the innovative HVAC concept that completely replaces the traditional energy infrastructure, including the previous methods of generation, distribution, and heat emission. This integrated approach requires carefully dimensioned components, including the HVAC machinery and associated ductwork into the timber prefabricated façade. One of the main research objective was to embed these elements within the prefabricated timber based elements normally used for the industrialized renovation. Two viable configurations were developed and validated: a façade-integrated system and a parapet-mounted solution. Performance assessment through numerical simulations and laboratory testing on full-scale prototypes demonstrated that the integrated system maintains an equivalent thermal transmittance, comparable to reference façades without integration. While preliminary simulations indicated potential condensation risks under critical boundary conditions, laboratory tests confirmed no condensation formation, with relative humidity remaining below ninety percent at minimum supply air temperatures of fifteen degrees celsius. Several insulation configuration on the VMU (Ventilation Machine Unit) has been evaluated and for instance the addition of a ten millimiters aerogel insulation layer further enhanced hygrothermal performance. The successful integration of HVAC components, despite increasing manufacturing time, demonstrates the feasibility of this solution for real-case implementation. The thermo-igrometrical simulation and testing activities influenced the prefabricated facade element design and engineering, especially in the airducts passage though the timber mullions, and in the localization and integration of the VMU and the distribution elements (Plenum). This research establishes a foundation for future developments in integrated HVAC systems within prefabricated timber façades, suggesting opportunities for optimization in manufacturing processes and material selection while maintaining performance standards.

KEYWORDS: active timber, timber façade, deep renovation, multifunctional façade, All-in-one industrialized façade

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1 – INTRODUCTION

Most of European buildings are poorly insulated and consume a considerable amount of energy for heating and cooling. According to the European Parliament's Committee on Industry[1], Research and Energy, we should renovate at least 3% of the building stock each year in order to mitigate the effects of climate change on our cities and reach the decarbonisation targets for 2050. The building sector is one of the main contributors to Greenhouse Gas (GHG) emissions, being 40% of the energy consumption in the EU associated with building needs, mainly for heating, cooling and domestic hot water purposes[1]. In order to achieve 2050 decarbonisation goals, significant increase in the low renovation rates is needed. The building envelope is a fundamental element since typically at least 75% of heat losses occur through the envelope comprising façade, roof and windows[2]. Therefore, improving the envelope represents the basic requirement when undergoing a renovation project and, to achieve NZEB targets, advanced functionalities are required for this element that should go beyond current passive thermal barrier to become an active element (integrating energy harvesting, energy generation, energy distribution, storage and active technologies). Prefabricated multifunctional envelopes offer a promising approach to enhance the speed and quality of deep building renovations. Despite their technical viability, widespread adoption faces challenges, primarily due to the complexity and high costs[3] of customized solutions.

This research employs a multidisciplinary approach to develop innovative facade solutions that (i) incorporate renewable technologies, (ii) improve building quality and occupant comfort, (iii) are structurally robust and pre-industrialized, (iv) simplify installation with minimal resident disruption, (v) transform houses into low-energy reaching the nZEB target (vi) enhance aesthetics, economic value, and sustainability. The study adapts advanced prefabrication methods from the timber construction sector, integrating both passive components (e.g., windows, shading systems) and active technologies for heating, cooling, air renewal and energy production (Thermal and Electrical). The development of these industrialized prefabricated technologies was done within the INFINITE project. The project introduces a "Renovation 4.0" approach that leverages digitalization and industrialization to overcome these barriers. At its core is a multi-user, interdisciplinary BIM-based platform enabling all stakeholders to contribute effectively throughout the renovation process. The project develops process-optimized, all-in-one industrialized envelope kits incorporating passive eco-compatible green systems, Energy and Fresh Air distribution modules, smart window integration, building-integrated photovoltaics (BIPV), and building-integrated solar thermal systems (BIST). Focusing on the Energy and Fresh Air Kit, differently from other innovative approaches [4]–[5] where the HVAC system is integrated punctually or as a "support system," the developed Kit substitutes the entire existing building HVAC system to be renovated.

This comprehensive approach is supported by smart control systems ensuring optimal performance during operation, all underpinned by a comprehensive online repository of technical solutions and best practices. Prefabricated façade fabrication follows a well-developed and established production line, which includes specific checkpoints. One of the major challenges is modifing and adapting the line to incorporate all additional technological components while maintaining the façade module fabrication process within a "lean engineering" framework. Ensuring the durability and long-term performance of these complex systems and the increased upfront costs of prefabricated, multifunctionaly façade with the potential long-term benefits in terms of energy savings and reduced installation time is a crucial design step.

2 – BACKGROUND

Traditional prefabricated wood-based façade solutions for building retrofits are well-established in the timber industry. However, emerging sustainability requirements and renovation challenges are driving the evolution of these systems. The push to achieve nearly Zero Energy Building (nZEB) standards, coupled with the need to accelerate deep retrofit rates while minimizing disturbance to inhabitants, has led to the development of multifunctional envelope solutions[6]. Deep renovation of existing buildings presents multiple challenges. There is limited standardization across renovation solutions, along with insufficient technical flexibility and scalability. The market suffers from a lack massive activation on the demand side, while value chains remain sub-optimized and based on traditional renovation approaches. The integration of energy systems and their related distributions directly into the façade makes these advanced envelope systems particularly complex. This integration presents new challenges across various aspects of the process, extending beyond simple thermal performance to include structural integrity, accessibility, and maintenance considerations. The development of efficient solutions that meet both energy needs and increased comfort requirements for existing buildings has become a global challenge. In recent years, the development of prefabricated, multifunctional façades

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has seen a significant upward trend, driven by multiple factors. There is an increasing demand for energy-efficient and sustainable building solutions, which can be fulfilled by integrated functions in façade elements. Multifunctional façades offer opportunities to improve energy efficiency, thermal insulation, and energy generation through technologies such as integrated photovoltaics[7]-[8]. Additionally, the prefabrication of façade elements enables a more efficient and cost-effective construction process, as elements can be manufactured under controlled conditions and quickly assembled on-site[9]. Multifunctional prefabricated timber walls represent an innovative solution for improving building energy performance while minimizing renovation impact on both the existing structure and its occupants. The integrated design approach, incorporating various components at an early stage, ensures reduced construction time and enhanced overall performance.

3 – PROJECT DESCRIPTION

The H2020 INFINITE project introduces an innovative approach to building renovation by leveraging prefabrication and digital technologies. The project promotes the Renovation4.0 concept, which integrates industrialization and digitalization to deliver eco-friendly, cost-effective retrofit solutions with a comprehensive life-cycle perspective. Through this initiative, five all-in-one industrialized envelope kits have been developed to address nearly Zero Energy Building (nZEB) retrofit requirements. These kits comprise modular timber frames designed for external installation on existing buildings, achieving high energy efficiency and indoor comfort while reducing renovation time and costs. Each module can integrate multiple technological components to provide customized solutions, including: passive eco-compatible and green envelope solutions, energy and fresh air distribution systems, smart windows with intelligent glazing, building-integrated photovoltaic systems (BIPV), and solar-thermal generation systems (BIST).

This paper focuses on the development, timber engineering, and performance evaluation of the energy and fresh air distribution system, which presents the most significant integration challenges. To do so, the engineering of a modified timber-framework has been done, the 3D thermal calculation of the resulting façade layers has been modelled and a detailed thermal-hygrometrical evaluation of a mockup installed in an outdoor laboratory has been carried on for about two months. The kit is designed to provide fresh air, heating, and cooling to dwellings through the integration of several technical components into the façade modules: a) Mechanical Ventilation Unit (MVU) with heat recovery and water coil for air heating and cooling (dimensions: 900x1300x300mm); b) Air ducts with connection points for fresh and exhaust air (diameters: ducts from machine to plenum: 125mm ; distribution ducts from plenum to inlets: 90mm); c) Water pipes connected to the heat pump; d)Electric wires, sensing and control unit

The ventilation unit connects to different apartment areas through air ducts integrated within the prefabricated façade modules (Figure 1). A centralized heat pump, which can be installed on the rooftop, in a technical room, or other suitable spaces, generates the energy required for heating and cooling. This heat pump connects to each decentralized ventilation unit through façade-integrated water pipes, with the system regulating air and energy distribution based on apartment indoor conditions. Except for the centralized generator (Heat Pump), the facade-integrated energy solution completely replaces traditional heating, ventilation, and air conditioning infrastructure through a groundbreaking approach. By embedding the entire mechanical system (machine, pipes, ducts, and plenums) directly into the building's prefabricated envelope, the research specifically targeted the comprehensive integration of mechanical components and ductwork within precise dimensional constraints into a timber-based façade. This approach transforms the facade from a mere building envelope into an active, dynamic energy system, setting it apart from more conventional HVAC implementations.

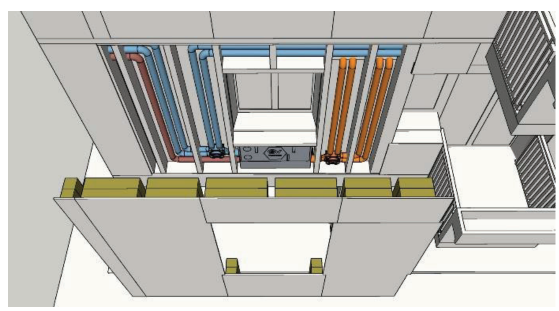

Figure 1 - VMU and related distribution façade integration concept

In detail, the kit is a prefabricated wood-based façade integrating a ventilated façade, insulation layers, load-bearing timber frame, air ducts, and an innovative HVAC unit with a post-heating/cooling heat exchanger. Two versions of this prefabricated façade concept have been developed: one with the machine detached into a balcony parapet and another with the machine fully integrated into the façade plane. The distribution networks, consisting of flexible pipes and plenums, are embedded within the façade modules. The design prioritizes

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minimal manufacturing impact, ease of installation, replicability, and system performance and maintenance. The distribution system utilizes market-available components, with frame notches accommodating duct passage. A specific detail was developed for inter-element duct connections, and full-size mock-ups validated the design solutions, considering perspectives from manufacturers, installers, facility managers, and end-users. The project methodology encompasses three main steps: timber engineering and mock-up detailed design, façade numerical modeling for performance characterization, and laboratory measurements. This development and assessment process aims to create a timber-based facade that satisfies performance requirements for statics, hygrothermal properties, installation functionality, and prefabrication efficiency.

Figure 2. The three full-scale mock-ups, functional mock-up on the left, FSIL with two configurations in the middle and right.

4 – METHODS AND EXPERIMENTS

The analysis addressed the behaviour of a prefabricated wood-based façade with integrated ventilation machine and air-distribution, focusing on critical points in overall performance. To do so, three real-scale mock-ups were designed, engineered and manufactured (see *Figure 2*). A first one was undergoing a functional test campaign to verify the onsite installation of a façade corner as the most critical building renovation geometry. This functional mock-up was a 16 sqm prefabricated façade with three different ventilated façade claddings (BIPV, BIST and GREEN) including the corner details for the distribution system installation. The two other specimens (9 sqm each) have been designed, manufactured and tested in the Façade System Interactions Lab (FSIL) of Eurac Research. The integration design of the energy and fresh air distribution system was supported by a set of detailed numerical performance simulations. All the results of the analysis performed was used for the timber façade structure engineering.

4.1 MODELLING AND SIMULATION

Prior to the realization of the prototypes and the experimental campaign, a set of numerical simulations were conducted using the Finite Element Method (FEM) based software COMSOL Multiphysics. These simulations were essential because, in both installations (balcony parapet and façade), the energy and fresh air distribution kit is in close contact with outdoor ambient conditions. The primary goal of these simulations was to determine the optimal insulation for the distribution kit to minimize thermal losses and prevent condensation risk. The appropriate insulation layer was selected to ensure that the heat losses of the new installation configuration are equivalent to those from a typical installation of the kit in a technical room. Furthermore, for the identified insulation layer, a series of simulations under summer design conditions were conducted to verify that the minimum temperatures on the external surface of the energy and fresh air distribution kit remain above the dew point temperature.

4.1.1 INTEGRATION INTO THE FACADE

A parametric simulation was conducted with insulation thicknesses varying from 0 to 50 mm and a constant thermal conductivity of 0.035 W/(mK) to identify the optimal insulation layer for integrating the ventilation unit into the façade. Under specific winter conditions (-5.2 °C outside, 21° C inside, 38.7 °C supply air temperature), heat losses varied from 33 W to 14 W with external insulation between 0 mm and 50 mm. From this analysis resulted that an external insulation thickness of 30 mm would provide similar performance to a technical room installation.
Another series of simulations were performed in summer design conditions (33.6 °C outside, 26 °C inside, 15.5 °C supply air temperature and 60% inside relative humidity) in order to evaluate possible condensation risk. The simulation under critical summer conditions showed that, regardless of insulation thickness (within technically feasible limits), the temperature of the ventilation unit's external surface near the supply air zone is slightly below

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the dew point (0.4 °C below the dew point temperature). Nevertheless, it was decided to use an external insulation of 30 mm, based on the evaluations in winter conditions, and to assess its performance during the experimental campaign. Figure 3 shows the temperature distribution around the supply air zone of the ventilation machine.

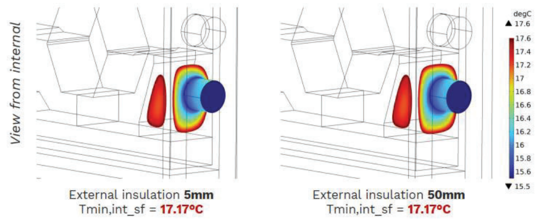

Figure 3. Surface temperature distribution from numerical simulation, focus on supply air zone, critical summer condition (33.6°C outside, 26°C inside, 15.5°C supply air temperature and 60% RH), dew point temperature = 17.6°C

4.1.2 INTEGRATION INTO THE PARAPET

A parametric simulation with insulation thicknesses ranging from 0 to 150 mm and a constant thermal conductivity of 0.035 W/(mK) was used to determine the optimal insulation layer for integrating the ventilation unit into the façade. Under winter conditions (-5.2 °C outside, 21 °C inside), heat losses varied from 15 W to 29 W with external insulation between 150 mm and 50 mm. From this analysis resulted that an optimal insulation thickness of 100-150 mm would provide similar performance to a technical room installation. Additionally, the impact of the insulation of the recirculation duct was analyzed, revealing that insulating the air circulation duct offered minimal thermal benefits. For summer, the same boundary conditions as the façade integration were used, except that relative humidity was adjusted to 45% based on outdoor ambient conditions according to standard UNI/TR 10349-2:2016. In this configuration, the impact of the insulation layer was not negligible. Indeed, the minimum surface temperature decreased at increasing insulation layer thickness. With an external insulation layer measuring 50 mm in thickness and a thermal conductivity of 0.035 W/(mK), the minimum surface temperature remained above the dew point temperature. Based on the requirements for winter and summer conditions, an intermediate insulation layer was chosen. The insulation was divided into two layers: a 10mm insulation layer with high thermal resistance (e.g., aerogel with thermal conductivity of 0.016 W/(mK)) was glued to the ventilation machine casing to keep the external surface temperature above the dew point, and an 80 mm external layer of mineral wool was applied to provide adequate thermal insulation during winter conditions.

4.2 EXPERIMENTAL SETUP

The two façade specimens have been tested in the FSIL Lab (*Figure 2 middle and right façade*). Specifically, two façade prototypes were manufactured: one with the integration of the energy and fresh air distribution kit, and another without any integration, serving as a reference façade. For the integrated kit, it was initially installed inside the façade and tested for a significant period both in summer and winter conditions. Subsequently, the ventilation kit was relocated and integrated into an external structure simulating a balcony parapet. The laboratory consists of two identical test chambers (8 x 4 x 3m) mounted on a rotating platform to reproduce the orientation of any real structure. For this test, the orientation was South. In each test chamber, one of the face is designed to house a façade sample with a maximum size of 3.7 m x 2.8 m x 0.5 m. The laboratory is equipped with an energy generation system that can be used to maintain indoor conditions but that can be also exploited at need by active systems. The entire test campaign lasted from October 2022 to August 2023 and was done on the two different kind of integrations: (1) ventilation unit integrated in the façade and (2) ventilation unit integrated in the balcony parapet.

4.2.1 INTEGRATION INTO THE FACADE

The test campaign with the energy and fresh air distribution kit integrated into the façade under the window covered various aspects. These included: functional tests on (i) installation of the air vents, (ii) maintenance procedures, (iii) ventilation unit control strategy, and performance tests on (i) ventilation unit leakages, (ii) air flow rate and uniformity, (iii) façade airtightness, (iv) thermal performance, (v) condensation risk, (vi) acoustics. This paper discusses performance tests related to airtightness, thermal performance, and condensation risk due to their significance in affecting façade timber engineering and their relevance to the topics of the WCTE conference.

For the air tightness assessment, a blower-door test was performed in order to measure the overall air tightness of the façade with integrated ventilation unit compared to the reference façade without any integration. The test was done in under-pressure following standard UNI EN ISO 9972:2015 method 2 (closed windows, openings, vents). For the thermal performance assessment, various measurements using temperature and heat flux sensors were conducted. This data was used to calibrate a numerical 3D model of the entire façade using COMSOL Multiphysics. Using this calibrated model, the equivalent thermal transmittance of the façade could be calculated

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under various operational conditions, along with that of the reference façade for comparison.
The condensation risk was assessed by monitoring the relative humidity and temperature in specific, most critical, positions and inducing critical internal conditions in terms of temperature and relative humidity. A first test series was carried out during winter/spring with relatively cool outdoor temperatures but using the HVAC system of the FSIL laboratory to keep the interior temperature and relative humidity condition at 26°C / 24°C and 60% RH, typical for summer conditions. The ventilation unit integrated in the façade (under the window) was operating in cooling mode. The supply air temperature was set to 15°C. Moreover, thanks to the mock-ups realized for the experimental tests, the timber engineering process, which includes all the distribution components and the main ventilation machine, was applied and tested on the real factory production line

4.2.2 INTEGRATION INTO THE PARAPET

The test campaign for the energy and fresh air distribution kit, integrated into a structure simulating a balcony parapet, primarily focused on assessing the risk of condensation, as the tests were conducted during the summer season. This season allowed to exploit more realistic conditions for the condensation risk assessment in terms of temperature and relative humidity. This test series evaluated different operating parameters, including two internal ambient air setpoints (23°C and 25°C) and three supply water temperatures (11°C, 15°C, 17°C). Temperature and relative humidity around the unit, particularly near the supply air zone (illustrated in *Figure 3*), were continuously monitored, with daily trends recorded for specific days.

4.3 TIMBER ENGINEENING AND MOCK-UP DESIGN

To integrate the HVAC system, a standard timber frame façade underwent an advanced engineering process to detail all necessary technical adjustments for feasible and functional integration. Five critical challenges were addressed to develop viable mock-ups:

1. The timber frame was calculated to accommodate the placement of the ventilation unit beneath the window opening and to incorporate all other HVAC system components. This necessitated a redesign of the minimum structural cross-section of the frame's studs and sill trimmer.

2. Certain vertical studs required drilling to allow for the passage of air-ducts. Structurally, the ideal position for these holes was along the stud axis (hp.2). However, this assumption conflicted with the need for optimal insulation of the ducts from external conditions as shown by the preliminary hygrothermal tests. Consequently, the studs were structurally designed to permit 100mm asymmetric holes, shifted inward (hp.1).

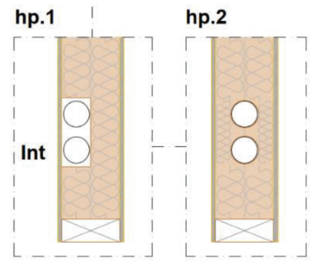

Figure 4 - Ventilation ducts positioning hypotesys into timber frame

3. All HVAC system components had to be securely fixed within the frame to prevent movement and potential damage during handling, transportation and installation as all-in-one element. To achieve this, specific supports were incorporated into the frame.

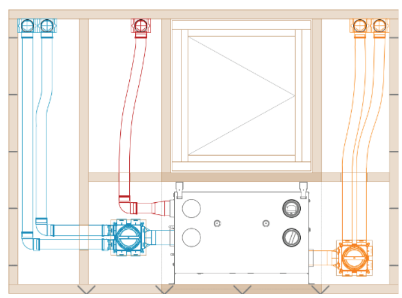

Figure 5 - Mock-up design with the integration of the VMU into the timber frame (integration into the façade)

4. For the corner configuration mock-up, a removable panel section was incorporated into the outer side of the timber frame to facilitate the connection of the ventilation ducts (*Figure 6*). Plug-in connectors were utilized to streamline this process.

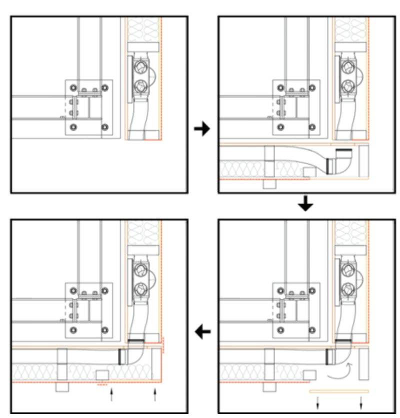

Figure 6. Facade corner detail for ventilation ducts connection

5. For the mock-up containing the ventilation unit, a re-sealable airtight system was developed. The unit compartment needed to be accessible from the inside for maintenance purposes. Thus, the unit was housed in an openable box protruding from the frame's thickness, which could be sealed on all sides after maintenance.

The final prototype's material layers were selected based on simulation results, material availability, and structural requirements. In particular, the stratigraphy of the final configuration for the façade integration is reported in Figure 7, while for the balcony parapet integration in Figure 8.

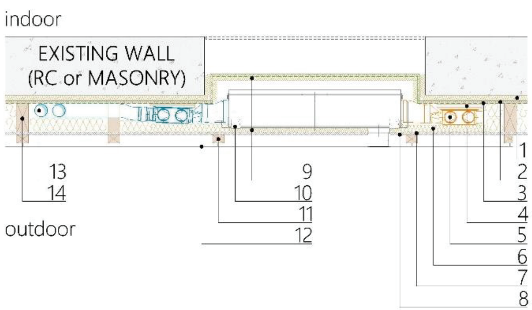

Figure 7. Façade integrated ventilation unit, stratigraphy and material specification: 1) 6) and 9) mineral insulation; 2) OSB panels; 3) Vapour membrane; 4) Plenum support; 5)Plenum; 7) Gypsum fiber board; 8) Watertight membrane; 10) HVAC unit; 11) Wooden stud; 12) Cladding; 13) Ducts and 14) Timber studs.

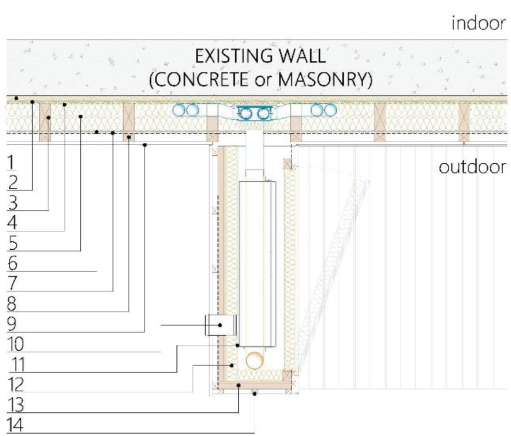

Figure 8. Balcony parapet integrated ventilation unit, stratigraphy and material specification: 1) 5) and 12) mineral insulation; 2) OSB panels; 3) Timber studs; 4)Vapour membrane; 6) Gypsum fiber board; 8) Watertight membrane; 9) Cladding; 10) HVAC unit; 11) Aerogel insulation; 13) CLT elements and 14) Wooden stud

5 – RESULTS

The primary results of the timber engineering process and the main findings of the performance tests for the energy and fresh air distribution kit integrated into the façade and balcony parapet are reported.

5.1 TIMBER ENGINEERING RESULTS

The integration of HVAC systems into prefabricated timber frame façades presented several technical challenges and design considerations. The main achievements and findings are summarized in the following areas:

Structural integration and design requirements: the integration of HVAC components into the timber frame façade required specific design adaptations. An inspectable compartment of approximately 400 mm thickness was created to embeded the HVAC unit (*Figure 9*). The air distribution system necessitated a minimum frame thickness of 140 mm, with 100 mm notches in the timber frame to accommodate air ducts (*Figure 10*). Special attention was given to maintaining façade functionality, particularly regarding airtightness and vapor barriers, which required additional taping and sealing around air circulation and hydraulic connections.

Figure 9. Mock-up realization, VMU and ventilation ducts integration

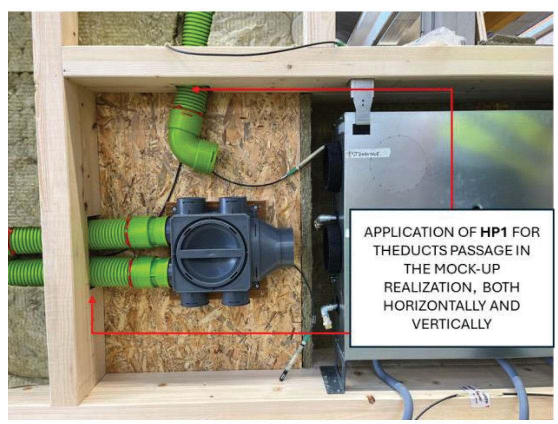

Figure 10. Detail of the ducts passage into the timber mullion

Manufacturing and installation implications: The incorporation of the air distribution system significantly impacted manufacturing times, nearly doubling the standard assembly duration in mock-up production. However, on-site installation time remained unaffected

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due to the implementation of efficient plug-in joints for connecting air ducts between façade elements (*Figure 11*). Manufacturing efficiency is expected to improve as expertise in HVAC component integration within timber frames develops. Alternative approaches, such as using granular or blown-in insulation materials instead of rock wool panels, could potentially reduce assembly times by better accommodating the complex geometries of ducts and plenums.

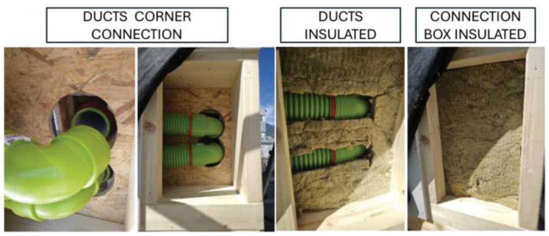

Figure 11. Details of the ventilation ducts connection in corrispondence of the facade corner

Numerical simulations and experimental activities during the two-year development period revealed several key performance aspects that was transferred into the timber enginnering:

1. Thermal Performance: Mineral wool insulation of 100-150 mm thickness in the façade kit proved necessary to maintain heat losses within acceptable limits. This allow to keep the vertical timber mullion above these limits allowing the air ducts ventilation integration while keeping the thermal performnaces of the façade compliant with the renovation requirements (nZEB standards)

2. Moisture Management: No condensation risks were detected in either summer or winter conditions around the ventilation unit, ducts, plenum, or inlets in both configuration (parapet and under the window). This allow to keep a feasible façade thickness to be accepted in a renovation project and to guarantee no condensations into it.

3. System Integration: The incorporation of the HVAC unit with respectively for the parapet integration and façade ones, 30 and 100 mm mineral wool insulation maintained the overall façade performance requirements (*Figure 12* and *Figure 13*). These results were used to define the final stratigraphy of the façade kit.

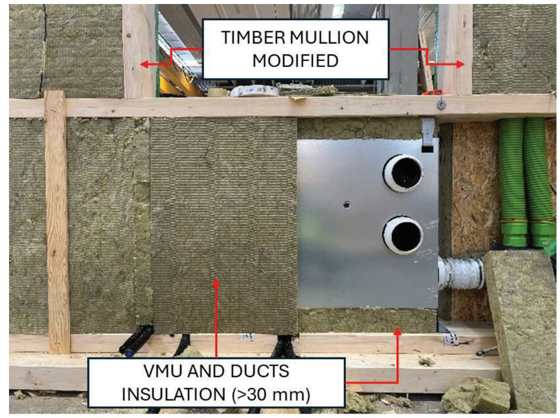

Figure 12. Detail of the VMU integration with insulation layers and timber mullion modification

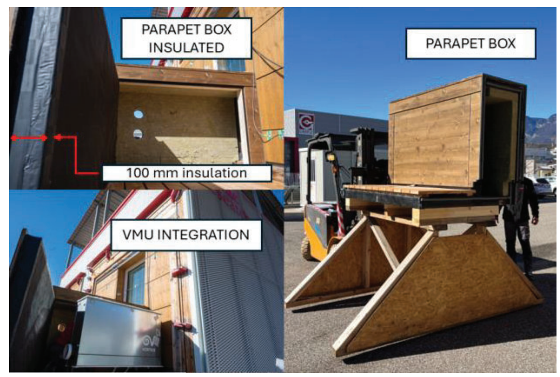

Figure 13. VMU parapet insulated timber structure solution

These findings demonstrate the technical viability of integrating HVAC systems into prefabricated timber façades while maintaining essential performance characteristics. The results provide valuable insights for future developments and real implementation in prefabricated multifunctional façade systems.

5.2 TEST RESULTS ON FAÇADE INTEGRATION SOLUTION

The tests on the energy and fresh air distribution system integrated into the façade provided useful insights into the overall façade performance. Regarding the air tightness tests, a comparison was conducted between the reference façade and the façade with an integrated energy and fresh air distribution system. The results indicated that the reference façade achieved a value of 0.051 ach (air changes per hour) at a 50 Pa pressure difference, while the façade with integration reached a higher value of 0.171 ach at the same pressure difference. These increased value is attributed to the integration of elements such as the ventilation machine and ducts; however, it remains within acceptable limits.

The collected temperature and heat flux measurement data were used to calibrate and validate a numerical model done in COMSOL Multiphysics. This model was used to conduct different simulations to calculate the equivalent thermal transmittance of the entire façade, with different ventilation machine states: active at supply air temperatures of 30°C, 35°C, and 40°C, inactive, and a reference façade without ducts. The results indicated that the thermal transmittance is 0.22 W/(m²K) when the ventilation machine is inactive and 0.21 W/(m²K) in the reference façade case, suggesting no additional losses due to passive ducts. During the operation of the ventilation system, the equivalent thermal transmittance of the façade decreases to 0.11 W/(m²K) at a supply temperature of 30°C, and further reduces to 0.07 W/(m²K) at 40°C. These findings show that ventilation units and ducts do not compromise the thermal performance of the façade. Moreover, when the ventilation machine is active, the warm air inside the ducts further increases the façade’s thermal performance.

The condensation risk assessment focused on the most critical zones, identified during the preliminary simulations. These zones include the external case of the ventilation unit in the supply air zone. The surface temperature of the ventilation unit case was assessed in the supply air zone, which was anticipated to be the most critical area. This measurement was then compared with the dew point temperature, as illustrated in *Figure 14*. The surface temperature in the supply air zone was near or slightly below the dew point, but no condensation was observed during the test days.

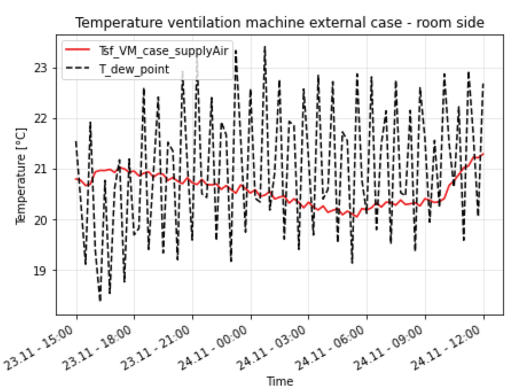

Figure 14. Assessment of Condensation Risk: Surface Temperature on Ventilation Unit and Dew Point Temperature During Test Days

5.3 TEST RESULTS ON PARAPET INTEGRATION SOLUTION

The test series on the balcony's parapet integration included various operating parameters: two internal ambient air setpoints (23°C and 25°C) and three supply water temperatures (11°C, 15°C, 17°C). Temperature and relative humidity around the unit, particularly near the supply air zone, were continuously monitored, with daily trends recorded for specific days. The tests showed that supply air temperature significantly influenced surface temperature and relative humidity on the ventilation unit case. When supply air reached its lowest temperature (approximately 15°C during cooling mode), relative humidity peaked at 80% on the lateral side of the venilation unit case, without additional aerogel insulation, while in the remaining area covered by 10 mm of aerogel relative humidity reached 54% to 56%. Indeed, the surfaces with aerogel insulation consistently maintained temperatures 3-4°C higher than the uninsulated lateral sides, resulting in 10-20% lower relative humidity levels, depending on operating conditions. Despite the lack of aerogel insulation on the lateral face, relative humidity never exceeded 90% during the entire testing duration, and no condensation occurred. The study concluded that supply air temperature plays a crucial role in determining both the external surface temperature of the ventilation unit and its corresponding relative humidity levels.

6 – CONCLUSION

An all-in-one industrialized envelope kit for building renovation was developed, integrating an innovative HVAC system and distribution to speed up renovation and minimize disturbance. The system provides insulation, fresh air supply, and air-based heating or cooling, making it a viable solution for deep building renovation. Two viable configurations were developed, tested and validated: a façade-integrated system and a parapet-mounted solution. Both configurations demonstrated satisfactory performance in terms of thermal efficiency and moisture management, with different insulation requirements (100 mm for façade integration and 30 mm for parapet mounting) successfully maintaining overall façade performance. The system integrator established a new manufacturing procedure, assessing time, costs, and organizational impacts compared to traditional methods. The successful integration of HVAC systems into prefabricated timber façades has been demonstrated through comprehensive engineering, testing, and prototyping. The development process addressed several critical challenges and yielded significant insights for future implementations. The structural adaptations required for HVAC integration were successfully resolved through innovative engineering solutions, including asymmetric drilling for duct passage, reinforced support systems, and the development of accessible maintenance compartments.

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While the integration of HVAC components significantly increased manufacturing time compared to the passive elements, the implementation of plug-in connectors and standardized assembly processes shows promise for future improvements. The use of alternative insulation materials, such as granular or blown-in options, could potentially optimize the manufacturing process by better accommodating complex duct geometries.

Specifically, the performance of this integrated façade was assessed through numerical simulations and validated with laboratory tests on a full-scale prototype. Tests mainly focused on airtightness, thermal performance and condensation risk assessment. The integration of the energy and fresh air distribution kit inside the façade resulted in a slight reduction in airtightness, but it remains within acceptable levels. However, precise installation and effective sealing are crucial. Thermal performance was assessed using a calibrated numerical model to quantify the equivalent thermal transmittance of the façade with the integrated ventilation unit. The presence of ducts and a ventilation unit does not alter the thermal transmittance, which remains at 0.22 W/(m²K), the same as the reference façade without any integration. However, when the ventilation system is activated, the thermal transmittance indicator decreases to 0.11 W/(m²K) at a supply air temperature of 30°C, and further reduces to 0.07 W/(m²K) at 40°C. Regarding condensation risk, preliminary simulations indicated a slight risk under specific critical boundary conditions. However, laboratory tests confirmed that no condensation formed, and minimum surface temperatures remained within acceptable limits. During testing at a minimum supply air temperature of 15°C, the relative humidity on the surface of the ventilation casing and the supply air duct remained below 90%, thus effectively preventing condensation. The addition of a 10 mm aerogel insulation layer further improved hygrothermal performance by maintaining slightly higher surface temperatures and reducing humidity levels. The supply air temperature significantly affects the minimum surface temperature, highlighting the need to avoid excessively low temperatures to prevent condensation and ensure optimal performance.

These developments provide a foundation for the broader implementation of integrated HVAC systems in prefabricated timber façades, demonstrating that technical challenges can be overcome while maintaining structural integrity, thermal performance, and system functionality. Future work should focus on optimizing manufacturing processes, real case implementation and exploring alternative materials to reduce assembly times while maintaining performance standards.

7 – REFERENCES

[1] European Commission, web article, In focus: Energy Efficiency in Buildings, link, 2020 https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en#:~:text=Collectively, buildings in t

[2]M.Hummel, R. Büchele, A. Müller, E. Aichinger, J. Steinbach, L. Kranzl, A. Toleikyte, S. Forthuber. "The costs and potentials for heat savings in buildings: Refurbishment costs and heat saving cost curves for 6 countries in Europe", Energy and Buildings, 2021

[3] M Gubert, S Avesani, JA Ngoyaro, M. Juaristi Gutierrez, R Pinotti, D Brandolini - "Comparative cost analysis of traditional and industrialised deep retrofit scenarios for a residential building" - Journal of Facade Design and Engineering, 2023

[4] Maartje van Roosmalen, Anna Herrmann, Akash Kumar, "A review of prefabricated self-sufficient facades with integrated decentralised HVAC and renewable energy generation and storage", Energy and Buildings, Vol.248, 2021

[5]Fabian Ochs, Dietmar Siegele, Georgios Dermentzis, Wolfgang Feist, "Prefabricated Timber Frame Façade with Integrated Active Components for Minimal Invasive Renovations", Energy Procedia, Vol.78, 2015

[6] European Commission, Build up portal, publication: "Boosting the Renovation Wave with Modular Industrialized Renovation Kits: mapping challenges, barriers and solution strategies", link, 2022

[7] Smith, J., Miller, A., & Garcia, R. (2020). Multifunctional façade systems for energy-efficient buildings. Journal of Building Engineering, 30, 101-234.

[8] Müller, L., Schneider, K., & Bauer, T. (2022). Integrated façade solutions: Advances in design and performance. Building and Environment, 209, 108-612.

[9] Holz, M., Bergmann, S., & Kaufmann, H. (2021). Prefabricated timber façade systems: Opportunities and challenges. Renewable and Sustainable Energy Reviews, 135, 110-456

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