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Design, construction, and operation of a novel Open Innovation Test Bed for real-life performance assessment of multilayer building envelope solutions

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ABSTRACT

The building market has recently seen new compelling opportunities in the field of off-site construction and in particular dry-assembly envelope systems, thanks to their advantages. The system, based on the mechanical assembly of materials on a resistant structure, offers high energy performance and superior acoustic and thermal comfort. Nevertheless, the current market highlighted the need for an holistic approach to implement such energy-efficient technologies involving research centers and university with their Living Labs for performance validation. The present work, funded within the MEZeroE Horizon 2020 project, discusses the creation of a unique ecosystem that can accelerate the transition of open innovations, towards the development of Open Innovation Test Beds (OITBs) for testing and upscaling standard and pioneering envelope solutions. The MEZeroE ecosystem brings together different testbeds and in this manuscript, one OITB, the BEE Lab experimental facilities, is presented and validated by first functioning and results analysis. In that context, the paper has a twofold objective. Firstly, it elaborates on the design and development of a novel living Lab (LL) space for the performance assessment in real conditions of full-scale multilayer envelope solutions and secondly, it discusses the results of an applied thermo-hygrometricexperimental analysis to confirm that the test bed works as intended. Aside from the experimental results, what makes the approach innovative is the creation of a network of OITBs across Europe and the definition of a unique online network to accelerate the building decarbonization.

1. Introduction

In comparison to the traditional method of construction the off-site methodologies offer several advantages such as construction speed, cost predictability, quality control, energy efficiency and sustainability, optimization of material production and demolition waste, reduced water consumption, lower disturbance of the construction site, less intensive workforce, high performance and comfort of spaces (Dunton et al., 2024). However, despite these potential benefits, industrialized construction methods remain a marginal segment of the construction industry. Their adoption has struggled to scale up in the European market due to different barriers, and understanding these obstacles is crucial to unlocking their potential and supporting SMEs for boosting the entrance into the market of innovative solutions such as multi-layer dry construction products and systems (Sesana and Dell'Oro, 2024). In parallel the construction industry is facing increasing demands of environmentally friendly practices for the final aim of designing and building spaces with increased energy efficiency, safety and well-being (U.S. EPA & U.S. CPC, 1995). People, in fact, spend approximately 90 % of their lives indoors. Hence, from the early design stages it is fundamental to focus on ensuring safe, comfortable and healthy conditions in buildings, as our working and living environments. Roughly 40 % of the world's energy consumption and more than one-third of global anthropogenic greenhouse gas (GHG) emissions are associated with the building sector (UNEB, 2009), (European Commission, 2007), (European Commission, 2011). The above-mentioned values take into account contributions embodied in the manufacturing processes of the materials (Sesana et al., 2024), in the actual construction of the building, and in its operational phase (Baldassarri et al., 2017), (Conci et al., 2019), (Gustavsson et al., 2010). The operating stage of a building, in particular, is crucial to reach the clean and carbon-neutral economy goals by 2050 (European Commission, 2011). Heating and cooling

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demands for buildings, in fact, account for half of the overall European energy consumption, making them the biggest energy end-use sector ahead of both transport and electricity (European Commission, 2023). The high energy demand for heating, indeed, accounts for a building stock with conventional, poorly insulated envelopes (International Energy Agency (IEA), 2023), which result in substantial system losses estimated to up to 89 % of the total environmental impact (Mirabella et al., 2018). In addition to such widely energy-intensive performance of buildings and building enclosures, which can usually be predicted during the design phase, on-site measurements have shown significant differences in terms of actual operative performance of buildings (Branco et al., 2004). Such deviation is related not only to the technical and technological quality of the construction, but also to the operative conditions (e.g., indoor temperature set-point, ventilation strategy, internal gains) (Teni et al., 2019), (Pihelo and Kalamees, 2025). In the last decades in Europe, there has been a stimulus for building more wood based-buildings compared to the more traditional construction products such (Pajek et al., 2017) as concrete and brick in order to reduce the CO_2 intensity of the sectors (Lopes et al., 2018). However, wood is an organic material, which is moisture sensitive and has a high risk of being attacked by mold growth and the clear identification of the real performance according to specific boundary conditions is needed (Morelli et al., 2021), (Fang et al., 2020), (Arkar et al., 2018). The energy efficiency of an exterior wall depends on how the materials to control moisture and airtightness are designed, selected, combined and assembled. Therefore, it becomes clear how the on-site assessment of the actual performance of the wood-based enclosure can be an extremely powerful tool to potentially prevent this performance gap (Langmans et al., 2012), (Imamura et al., 2024). However, the performance of building envelope components is usually and traditionally assessed through laboratory tests at the product level, rather than on full-scale portions of the solution in realistic spaces and conditions (Pelle et al., 2024), (Evangelisti et al., 2015). Over the last few years, numerous researchers and research centers have indeed focused and endeavored to full-scale test building envelope solutions. Nevertheless, the current regulatory gap associated with testing procedures under real-life conditions has yet to be bridged, and the design principles of such facilities are rarely shared and harmonized. A recent review of the main existing real-scale test chambers, and uses results for design and built and validate new test facility (Luna-Navarro and Overend, 2021). In recent times the European Commission has started fostering through the EU Horizon 2020 research and innovation funding programme the development of another set of entities, namely Living Labs (LLs) and Open Innovation Test Beds (OITBs) (European Commission, 2017), (European Commission, 2018). Their main purpose would be the development and testing of innovative solutions, and technology in general, in either a physical or virtual real-life experimentation environment, involving users as important informants and co-creators (Kusiak, 2007), (Ballon and Schuurman, 2015). European industries face high capital costs and complex regulation and the presence of an unique knowledge sharing hubs can lower these barriers and bring products to market faster. European Commission funds in the past years several projects regarding Open Innovation Test Beds helping to introduce new innovations to the construction industry. Test Beds are, in fact, well-recognized in the development and commercialization of the innovation from labs to the industry (Saad and Agogué, 2024). More in detail, LLs are specifically intended to implement full-scale technologies and solutions in real buildings in order to assess their actual performance and evaluate technology-user interaction under real conditions. For this reason, such new approach was found to be of special interest for the present work, as it would in a sense expand the potential of the previously mentioned labs and test-chambers (Table 1). Living Labs, in fact, would not only enable the medium-long term monitoring and measurement of selected parameters in real conditions, but also the potential live and/or periodical feedback from the users connected to the measurements.

In that context, the present work elaborates on the design and development of a novel real-scale research space for the testing and monitoring of full-scale envelope solutions under real conditions (Levels 2–3 in Table 1). The activity was conducted and funded under the MEZeroE (Measuring Envelope products and systems contributing to next generation of healthy nearly Zero Energy Buildings – G.A. No. 953157) H2020 framework (Saad and Agogué, 2024). The ultimate scope of the above-mentioned project is, in fact, the creation of a vibrant and fertile (Open Innovation Test Beds) in the shape of a multi-sided virtual marketplace (Fig. 1), combining infrastructure facilities and expertise of academic and research centers with pioneering envelope solutions proposed by industry players (Salvalai et al., 2023). This framework is set to encourage the creation of a strong network among players in the construction sector, by providing facilities and services for the modelling, testing, and upscaling of building envelope solutions. In that context, the testbed described in Section3 would serve as a powerful tool to achieve such goal.

Within the MEZeroE (MEZeroE H2020 project) framework, the testbed in question is grafted into a broader network and ecosystem of facilities with similar scopes and activities, similarly devoted to the assessment of full-scale solutions, as summarized in Table 2.

The novelty of this paper lies in the introduction of a pioneering Open Innovation Test Bed (OITB), namely BEE Lab facility, which enables real-life performance assessment of construction technologies specifically, multilayer dry assembly building envelope solutions. This represents a significant advancement, as current state-of-the-art facilities lack a dedicated focus on testing and validating this type of innovative construction technologies. These solutions are becoming increasingly popular, due to their ability to support tailor-made and high energy efficient building envelope technologies.

However, the performance quality of multilayer dry-assembled

Table 1
Definition of three potential levels of building performance assessment and monitoring.

	Level 1	Level 2	Level 3
Environment	Laboratory (standard environment)	Test chamber (demo building)	Living Lab (real and fully operational building)
Object	Small solution or parts of a more complex solution	Full-scale solution	Full-scale solution
Main scope	- Early concept validation - Test of physical properties	- Validation of installation procedures - Monitoring and measurement of selected properties and parameters - Monitoring of user interaction and feedback (periodically through surveys, live through embedded sensors)	- Validation of installation procedures - Monitoring and measurement of selected properties and parameters - Monitoring of user interaction and feedback (periodically through surveys, live through embedded sensors)
Boundary conditions	Controlled environment	Controlled indoor environment Real-life outdoor environment	Real-life environment
User involvement	N/A (generally not habitable)	Temporarily occupied facility (approximation of real-life conditions)	Fully inhabited test building
Expected outcome	Standard validation	Near real-life validation Near-real user validation	Real-life validation Real user validation

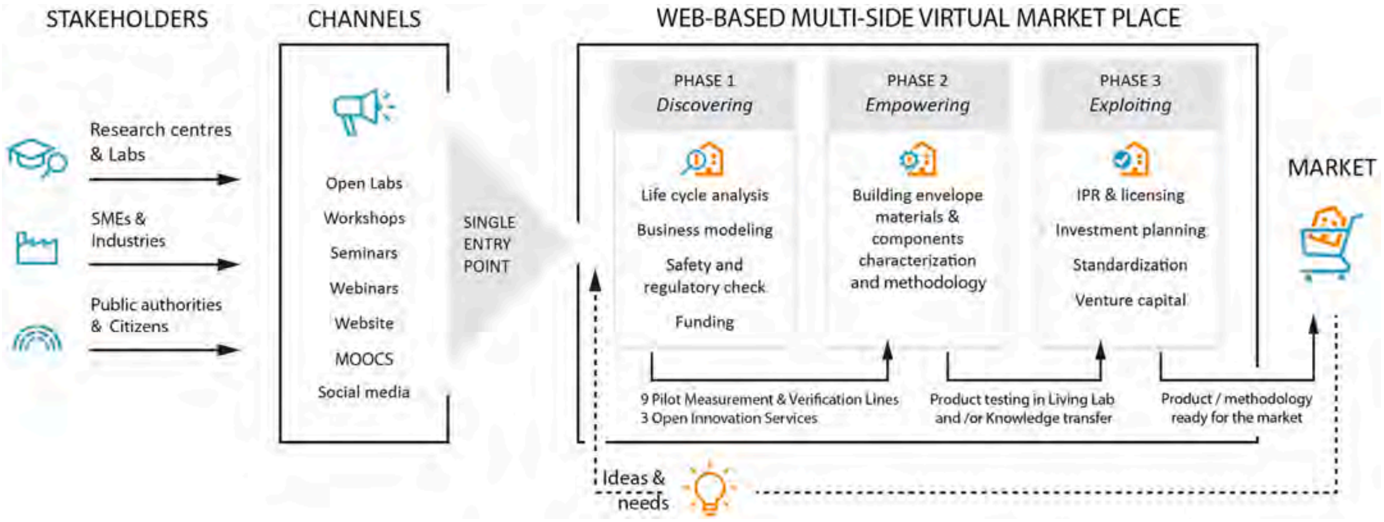


Fig. 1. Overview of the MEZeroE virtual marketplace as a collector of innovation needs, providing services for their satisfaction. Source: MEZeroE.

Table 2
Main full-scale test facilities owned by MEZeroE Consortium partners.

	MEZeroE partner	Location	Performance assessed	Most relevant features
Building façadE performancE Lab (BEE Lab)	Politecnico di Milano – Università degli Studi di Brescia	Lecco, IT	Hygrothermal Acoustic Airtightness Indoor Air Quality	- Focus on multilayer dry envelope components - Rotatable (360°) to comply with test needs - Replaceable wall and roof full-scale components - Two adjacent test rooms and a Living Lab space - Indoor conditions: real-life/controlled - Outdoor conditions: real-life
KUBIK (Tecnalia), (Garay et al., 2015)	(Tecnalia)	Derio, ES	Energy efficiency	- Focus on construction/systems/user interaction - Reconfigurable four-story building - Replaceable wall and roof full-scale components - Renewable energies supplied (geothermal, solar, wind) - Indoor conditions: real-life/controlled - Outdoor conditions: real-life
Façade System Interactions Lab (EURAC)	Eurac Research	Bolzano, IT	Hygrothermal Acoustic Indoor Air Quality Visual Energy efficiency Indoor comfort	- Focus on construction/systems/user interaction - Two test chambers mounted on a rotating platform - Replaceable wall full-scale components - Can accommodate people or thermal dummies - Indoor conditions: real-life/controlled - Outdoor conditions: real-life
Chamber for measuring facade elements in dynamic conditions (ZAG)	Zavod za gradbeništvo Slovenije	Ljubljana, SI	Hygrothermal Visual	- Focus on façade elements - Single chamber - Indoor conditions: controlled - Outdoor conditions: real-life
Test Site UIBK Innsbruck (UIBK)	Universität Innsbruck	Innsbruck, AT	Hygrothermal Acoustic Visual	- Two PAS/PASSYS test cells - "Cold-Box" can create steady state ambient conditions in front of both cells (constant low temperature) - Focus on building components, lighting products, building systems, and control devices - Indoor conditions: controlled - Outdoor conditions: real-life/controlled ("Cold-Box")

systems is highly dependent on the precision and care taken during installation that is fundamental to ensuring the overall performance of the building envelope, particularly in terms of thermal efficiency, moisture control, and long-term durability.

Therefore, the presence of dedicated testing laboratories such as the BEE Lab able to test real scale samples under operation condition, represents not only a novelty within the current landscape but also a growing necessity, given the increasing adoption of these construction solutions. It is thus essential to promote the development and wider diffusion of experimental infrastructures capable of supporting the testing, validation, and optimization of innovative building technologies based on multilayer dry assembly systems.

Besides the novelty of BEE Lab creation and validation, the merit of the work relies on its implementation into a European ecosystem, the so called MEZeroE ecosystem, an European-wide network of OITBs developed in collaboration of other facilities, with the final aim to boost the development of nearly zero-energy buildings (nZEB) enabler envelope technology solutions, transferring know-how, pairing testing needs with existing facilities, providing monitoring in living labs, and standardizing cutting-edge solutions coming from SMEs and larger industries, focused on carbon neutrality and a healthy indoor environment. The proposed holistic approach underscores the Open Innovation relevance, being one of the firsts application of this concept also to the construction sector, after its initial diffusion from manufacturing and automotive.

For supporting the above mentioned concept the paper is structured as follows. Following the introduction, which provides an in-depth review of the relevant literature, Section 2 provides an overview of the overall methodology that was followed for the design of the testbed, addressing topics like standards compliance, design criteria, boundary conditions and performance objectives. The results of such approach are presented in Section 3, which is in fact dedicated to the actual strategies implemented in the design and development phase of the building. Section 4 includes a digression on its initial validation and operation, presenting a hygrothermal performance assessment on a wood-based multilayer wall solution through a long term monitoring. Finally, Section 5 discusses the contents outlined and highlights some possible future developments of the work in the same direction.

2. Objective and vision

The testbed focuses specifically on dry-layered envelope solutions for external walls and roofs. Such technology, sometimes also referred to as "multilayer", consists of the stratification of independent functional technological layers, selected to give specific performances, pre-engineered and installed on-site with mechanical joints and connections, in order to also ease their eventual dismantling. These solutions are becoming more and more popular also in countries with strong masonry traditions, thanks to the possibility to design tailor-made building enclosures to ensure optimal thermal comfort levels, high energy efficiency, and short construction times for both temporary and permanent buildings (Pfluger et al., 2010) (Salvalai et al., 2020) (Fantozzi et al., 2014). Nevertheless, in spite of all these advantages, the moisture intrusion tolerance of dry-layered solutions is generally low, making them vulnerable to moisture-related damages (Piggot-Navarrete et al., 2024) and the presence of multiple layer and high thermal insulation thickness needs specific characterization through experimental measures (Zalewski et al., 2010). This is especially true for wood-based multilayer envelope solutions and components (Hietikko et al., 2024) and mainly in deep cavity wall where the control of water content is relevant (Cho et al., 2019) (Ge et al., 2019). Excess moisture can, for example, result in growth of pathogenic mold and affect the aesthetic appearance of buildings, due for example to wetting during the construction activities, rain leakage, or moisture accumulation from vapor diffusion (Yoo et al., 2019). The thermal resistance of wind barriers as well as proper water vapor barrier have positive effect on the hygrothermal performance of the wood construction. For multilayered prefabricated wood-based wall panels, several studies discussed the need of experimental analysis for model validation (Schroderus et al., 2025), (Ramos et al., 2024a) and that there are considerable mismatch between experimental and numerical results (Ramos et al., 2024b), (Palani and Karatas, 2024).

Looking to the literature there are only few cases of labs and facilities that are designed for real scale building envelope analysis across EU, but no one specifically for multi dry layers, a technological solution which currently is becoming an hot topic being a flagship solution in a new era of the construction which is turning from on site to off-site solutions, boosting industrialization process to reduce construction time, wastes and increasing quality and durability. Moving to the Italian context the BEE Lab represents an unique facility for testing contemporary different tailored made part of a building, such as wall/roof technology, under different orientations.

All those aspects together address a multi-objectives issue, to optimize time and costs, but also to cutting-edge solutions of both universities and research centers and SMEs coming from the close collaboration of SMEs and larger industries with universities and research centers.

The testbed has been designed for monitor and assess different building envelope solutions in real conditions, focusing on the following key aspects: (i) thermal and hygrothermal performance, (ii) impact on indoor well-being (e.g., air quality, thermal comfort), and (iii) impact on energy efficiency. The assessment of full-scale envelope solutions under real conditions (Levels 2–3 in Table 1) has the great advantage of providing real-life validation of such technologies, which cannot be achieved otherwise in a standard and fully controlled environment (i.e., lab). Nevertheless, the exposure to the naturally variable environmental conditions significantly limits the level of control of the researchers over the experimental parameters, generally resulting in benchmarkable results yet obtained through non-standardized procedures. In this regard, a prominent activity that is currently nearing completion and worth mentioning is an extensive and comprehensive analysis of the relevant standards that either specifically address the planned tests performed under real-life conditions, or that could be extended to such activities. The results of this research are believed to be of fundamental interest for other researchers and stakeholders, by informing and potentially impacting the design process of similar facilities, and may thus populate a future follow-up manuscript. As introduced in the previous section, and in line with the testing needs of the different envelope components manufacturers involved, the testbed has been hence designed according to the instructions arising from the above-mentioned standards research as well as to what was identified in literature as key design requirements for real-scale test chambers, that, although, focused almost solely on the building-occupant interaction. Indeed, most of those criteria are also ideal for the above-listed primary purposes of the testbed, which in fact aims at comparing and evaluating the impact of different multilayer envelope solutions not only in objective terms (i.e., thermal and hygrothermal performance, energy efficiency), but also referring to more subjective and user-related aspects (i.e., indoor well-being). To that end, the key design objective that was set for the research space is the accurate performance assessment of different multilayer envelope solutions under real conditions, but with such a set-up as to also include and be suitable to accommodate occupants (e.g., geometrical dimensions, indoor appearance). The results of the application of the proposed approach for the design and development of the testbed in question are further detailed in the following section.

3. BEE lab design and construction features

This section provides an overview of the main outputs of the testbed design process, that led to its actual development, construction, validation and operation. The final result of the research and work is, indeed, a fully functional and operative testbed, named "Building facadE performancE" (abbreviated "BEE Lab", Fig. 2), for the performance assessment of different multilayer envelope solutions in real conditions. What makes it rather innovative for the field, especially in the Italian context, is the possibility to accurately test and monitor such technology in real conditions, under actual operation and in different orientation

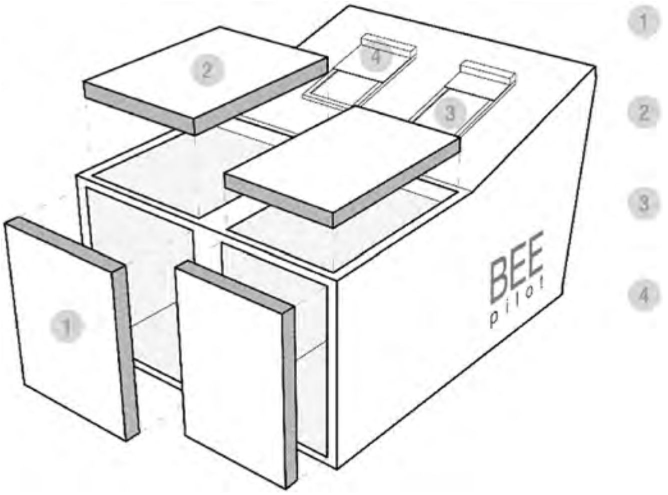


Fig. 2. Schematic representation of the testbed, highlighting some of its key functions.

thanks to the combination between test-chamber (two adjacent rooms) and Living Lab space.

As concerns the project area, the testbed in question is purposely located outdoors, in a dedicated site inside the Lecco Campus of Politecnico di Milano (Fig. 3). Access to the outdoors, in fact, was considered a key design criterion as it offers real environmental conditions for the actual performance assessment of different envelope solutions.

With this respect to the orientation, the south is the most common orientation as refers to the investigation of occupant-façade interaction (Luna-Navarro and Overend, 2021) (Rahim et al., 2023) (Rea, 1984). Nevertheless, different testing needs may arise during the operation of the testbed in question, especially in terms of thermal and hygrothermal performance assessment. Hence, the facility is designed to accommodate different orientations, by full rotation of the testbed on dedicated tracks according to the different test and research needs. The dual nature (Levels 2–3 in Table 1) of the research space in question results in two separate testing areas: the test-chamber portion (level 2) and the Living Lab space (level 3) (Fig. 4). The first one is made of two adjacent and nominally identical test rooms ("Test Room A" and "Test Room B″ in Fig. 5), intended for the simultaneous test of different envelope (wall and roof) solutions. A double chamber set-up can be useful, in fact, for experimental control purposes, as well as to conduct simultaneous measurements that would otherwise be disturbed by the different boundary conditions. The second portion ("Data Room") of the building is dedicated to the assessment of different envelope solutions under actual operation, thanks to the involvement of occupants in a specifically designed and sensorized office environment. This space aims, in fact, to study the effect of different roof windows, shading devices and controls in terms of users' comfort and thermal perception. This is also supported by the control parameters that are made available to the occupants: air temperature, relative humidity, air speed, and natural/-artificial lighting (Mahdavi et al., 2008).

The testbed focuses on full-scale dry-layered envelope solutions, consisting of the stratification of several functional layers that are usually selected according to the boundary conditions and to the target performance. The installation methodology foreseen for such building components involves the use of mechanical joints and connections, easing at the same time also their eventual dismantling and/or replacement for research purposes. Testing alternative envelope solutions is, in fact, one of the essential features of the building in question, and of any occupant-façade research facility in general. Hence, the testbed object of the present work was designed and built so that different envelope technologies can be relatively easily installed and replaced, focusing in particular on external walls and roofs technical solutions. In addition, the multilayered nature of these envelope solutions enables the thorough positioning of sensors at the interface between the different layers, resulting in a more accurate and detailed performance assessment for each solution. In line with the building technology mentioned above, the enclosure of the testbed was designed and built as a continuous sequence of modules made of a wooden structure with insulated cavities (Fig. 6). Besides such core, more layers were selected and added to the building envelope in order to build a completely functional solution and reach the desired performance (e.g., insulation, vapor barrier, airtightness and waterproofing membranes, finishing) (Fig. 7). The party wall is.

The construction of the research facility was conducted at the turn of 2021 and 2022, and involved a series of activities that can be broken down in five major steps (Fig. 8): (i) installation of the construction site, excavation and casting of the foundations, installation of the steel base structure and of the respective rotation system; (ii) assembly of the modular wooden structure; (iii) completion of the building enclosure with the remaining functional layers; (iv) installation of the roof windows and of the entrance glass door; (v) installation of the façade cladding panels (Colombo et al., 2023).

3.1. Monitoring set-up

Besides the actual design and construction of the lab, the research work towards its development has then focused on the design and selection of devices and sensors set-up for the actual measurement of the envelope performance, to enable the final validation of the testbed under real operative conditions.

According to the scope and goals previously defined, the dry-layered envelope performance assessment within the testbed is set to involve the verification of some fundamental requirements that have been identified under the Italian standard UNI 8290 (UNI 8290–1:1981 –, Edilizia residenziale), although they could be fully extended independently of the nation concerned. The standard defines concepts, terminology, and classifications applied to the construction industry. It breaks down the building organism (the whole building) into technological units (e.g., roofs, walls and floors) and technical elements (e.g., windows, beams, cladding) and identifies the required functions that the different building component must fulfill, including: i) structural integrity, ii) fire resistance; iii) acoustic insulation, iv) thermal insulation; v) water tightness, vi) aesthetic and environmental integration. The standard identify also specific performance objectives for building envelope components such as thermal comfort temperature level, moisture and condensation control and energy efficiency throughout the different seasons. Table 3 summarizes the most relevant performances and respective parameters that the testbed aims to assess for each requirement, taking into account its scope, objectives and relevant expertise. To that end, the BEE Lab has been equipped with a wide range of devices,

Fig. 3. View of the BEE Lab testbed after completion, in the context of the Lecco Campus of Politecnico di Milano.

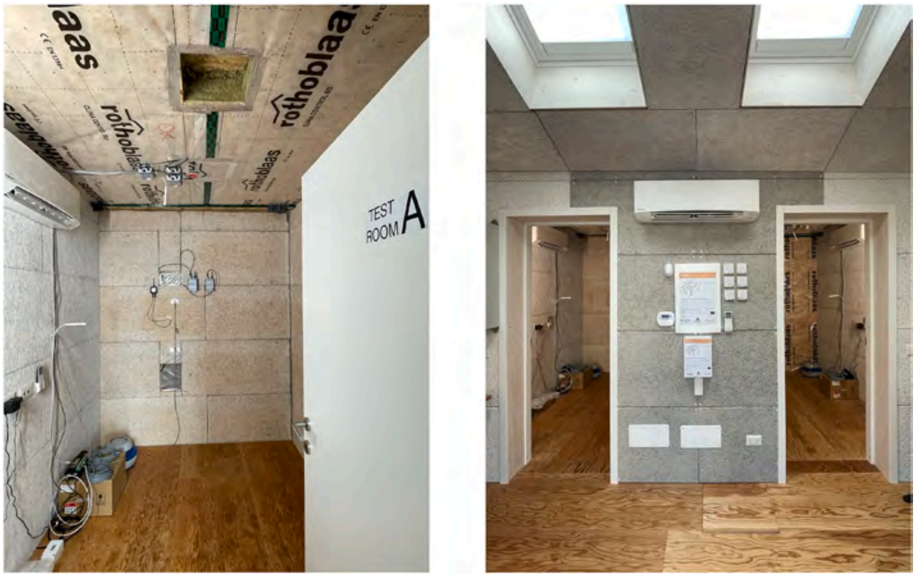


Fig. 4. View of the interior of the BEE Lab testbed after completion.

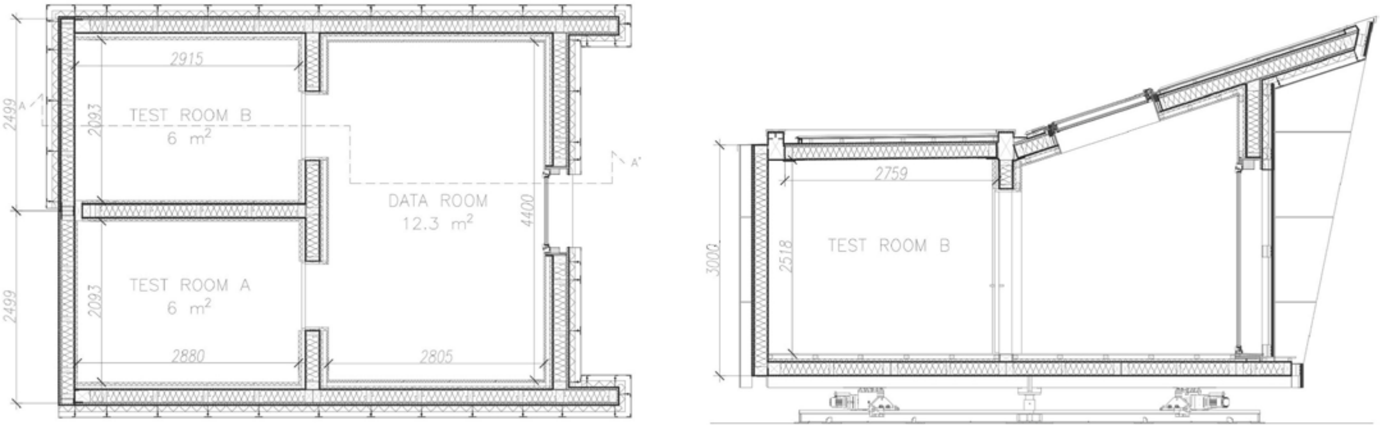


Fig. 5. Building plan and AA' section of the testbed, highlighting its relevant building system as well as its dual nature: test-chamber portion ("Test Room A″ and "Test Room B″) and Living Lab space ("Data Room").

Fig. 6. Installation and assembly of the modular envelope of the BEE Lab testbed.

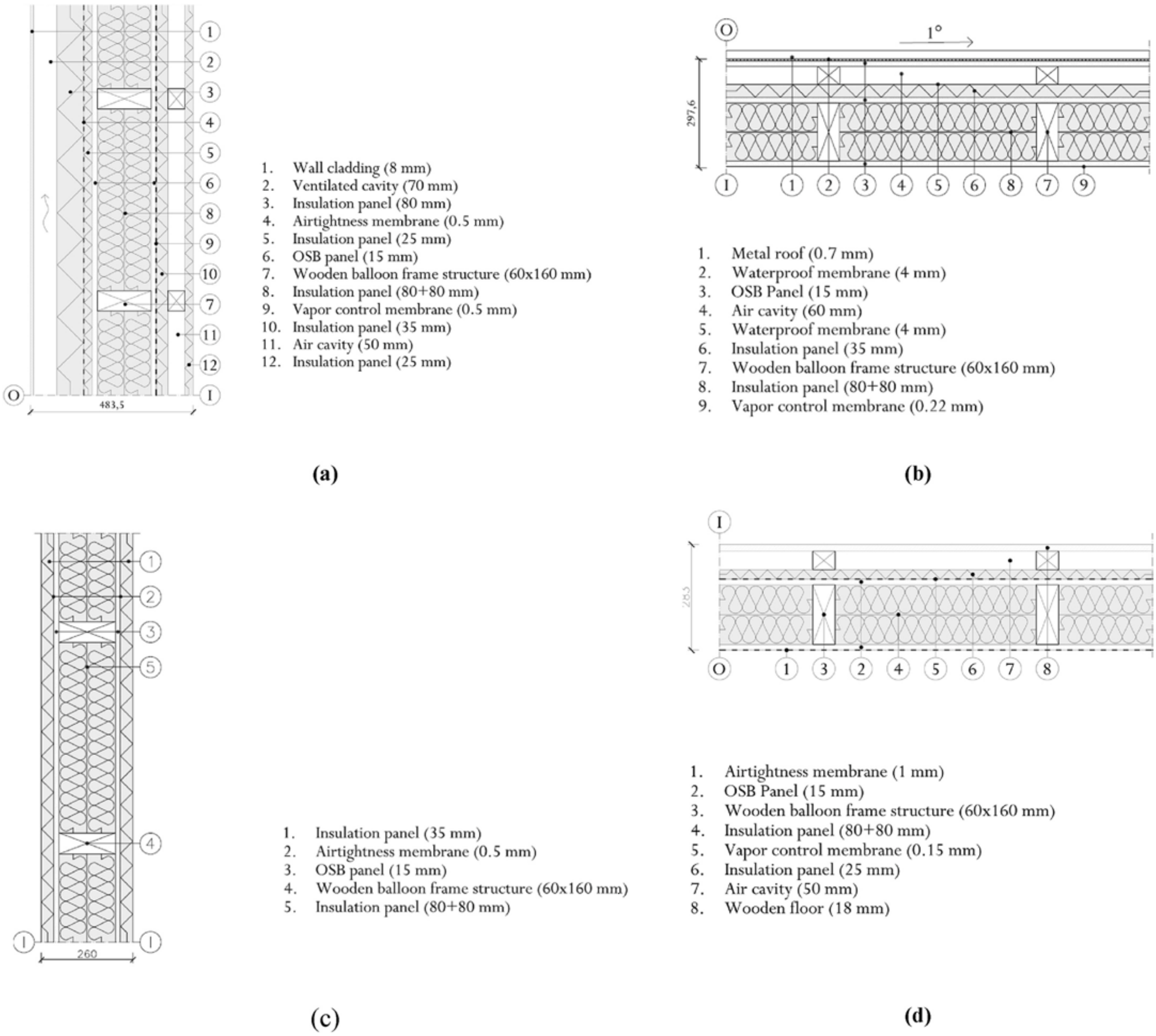


Fig. 7. Example of multilayer dry envelope solutions implemented in the testbed, respectively: wall (a), roof (b) of one of the test room, party wall between the test rooms (c) and the floor (d).

sensors and probes (Fig. 9), that enable the performance assessment of the different multilayer dry solutions object of monitoring.

The selection and placement of the equipment have been conducted in compliance with the instructions from the relevant standards mentioned in the previous section, covering not only the different building components and their respective layers but also the boundary environments. The specific positioning of each sensor within the different envelope components object of monitoring is outlined in greater detail in Fig. 10, which refer, respectively, to Test Room A. Such setups are currently involved in two major activities: (i) a thermal performance assessment, and (ii) a hygrothermal monitoring. The first aims is intended to monitor the hygrothermal performance of four distinct sets and combinations of membranes which provide airtightness, watertightness, and vapor control to the different envelope components in object. The verification of the wall's hygrothermal behavior is fundamental in wood-based building technology mainly in cold humid climate were the condensation effect that makes envelope components predisposed to mold growth and eventually causes fungal decay (Pasztory et al., 2012). Moisture also affects the thermal performance of insulating materials, influencing aging, dimensional stability, and mechanical properties (Eksi Kilicaslan and Kus, 2024) (Zegen Reich et al., 2021).

For the sake of completeness, as well as in view of the validation activity presented in the next sub-section, Tables 4 and 5 list the sensors, probes and devices employed in the BEE Lab, along with their key features and characteristics.

4. Verification of performance and preliminary monitoring results

The current section, in particular, presents the results collected during a hygrothermal long-term performance assessment of a wood-based multilayer wall component, focusing on the vertical closure of Test Room A that is a typical solution currently well-diffuse in the

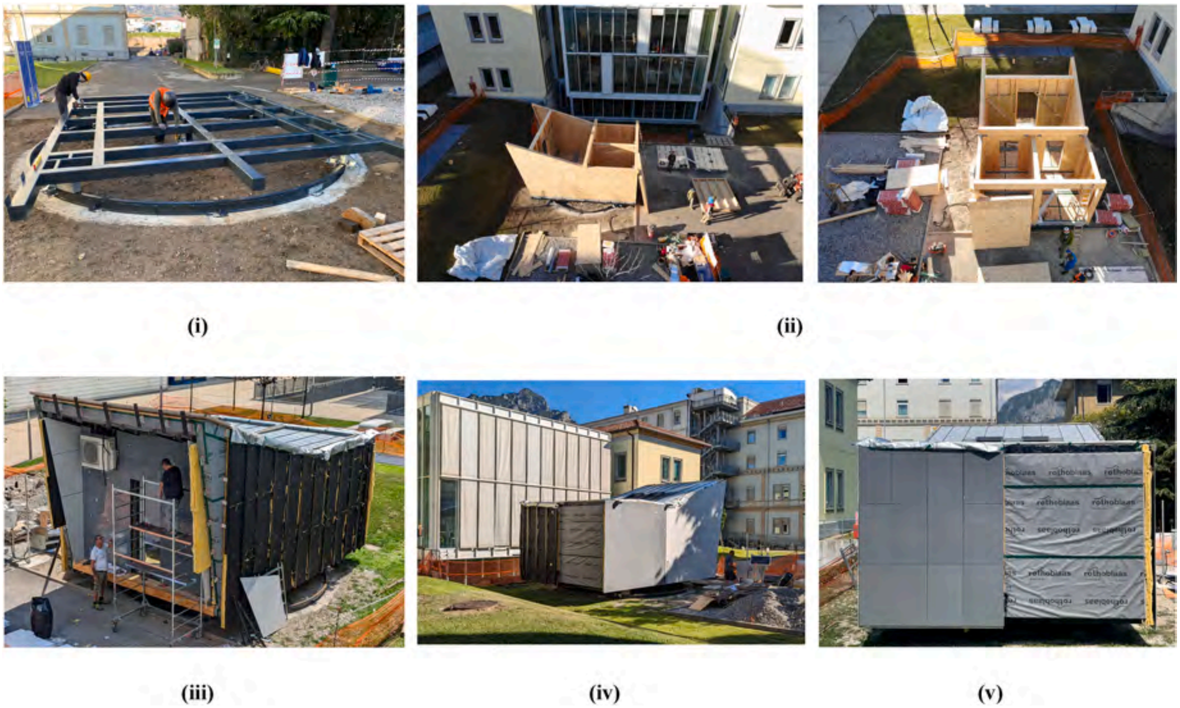


Fig. 8. Breakdown of the construction activities in five major steps.

Table 3
Summary of the most relevant tests offered by the testbed according to the respective standard requirements.

Requirement	Performance assessed	Assessment method	Parameters assessed
Absence of emission of harmful substances	Indoor Air Quality (IAQ)	Sensorization Monitoring Survey	Air temperature, Relative Humidity, Particulate Matter, Carbon Dioxide, Total Volatile Organic Compounds, Formaldehyde, Ozone, Nitrogen Dioxide, Ammonia, Sulfur Dioxide, Methane, Radon
Air tightness	Airtightness	Blower Door Test Infrared (IR) camera	n_{50}
Control of heat dispersion by transmission	Thermal	Sensorization	Temperature, Surface Temperature,
Thermal inertia control		Monitoring	Heat Flow
Thermal insulation		Infrared (IR) cameraSurvey	
Control of interstitial condensation	Hygrothermal	Sensorization	Air temperature, Relative Humidity
Control of surface condensation		Monitoring	
Hygroscopicity		Infrared (IR) cameraSurvey	

market. The experimental analysis consist on temperature and humidity level analysis of different wall layer highlighting the behaviour under different indoor/outdooe conditions. The activity was conducted in collaboration with the MEZeroE Horizon2020 project partner Rothoblaas (ROTHO BLAAS SRL). The company provided, in particular, a set of water-resistance and vapor-control membranes with varying and variable vapor resistance that required real-life performance validation, as summarized in Table 6.

More specifically, the vertical closure of Test Room A, object of the present section, includes two of the above-mentioned membranes (Clima Control 80 and Traspir Evo 160), and it is composed as detailed in Table 7.

The hygrothermal long-term monitoring started in August 2022 and was concluded in August 2024, after 24 months collecting data every 10 min for a total of 105243 records. The activity was carried out with the aid of a continuous monitoring system set to record the local temperature and relative humidity levels within the building envelope component. At the same time, the same parameters were also collected in both the internal and external environments (Fig. 11). The data from the preliminary monitoring campaigns are used to validate the capabilities of BEE Lab and the associated data collection procedure. The aim of the validation was: 1) to verify that the experimental design allows to capture the influence of water proof membrane on dry layer wall construction, 2) to test the typology and position of the sensors and the system for temperature and humidity control; 3) to verify that the experimental campaign collects data with adequate frequency and space resolution.

The sensors and probes were installed at the relevant interfaces between the building envelope layers following the optimal setup agreed with the manufacturer as outlined in Table 8 and presented in Fig. 12.

To better frame the analyses that will be detailed in the following sub-sections, Fig. 13 presents the air temperature and relative humidity trends in both outdoor and indoor environments throughout the whole period of monitoring. It is worth noting that, after a first phase of free-running conditions ("FR"), the indoor boundary conditions were subsequently controlled in term of air temperature and relative humidity ("C") and activated according to the test needs.

Damp and high levels of relative humidity, above 75–80 %, provide mold-favorable conditions. The VTT (Technical Research Centre of Finland) model (Hukka and A Viitanen, 1999) is a mathematical indoor mold growth model based on surface readings of RH and temperature on wood in a controlled environment (Menneer et al., 2022). The RH_limit

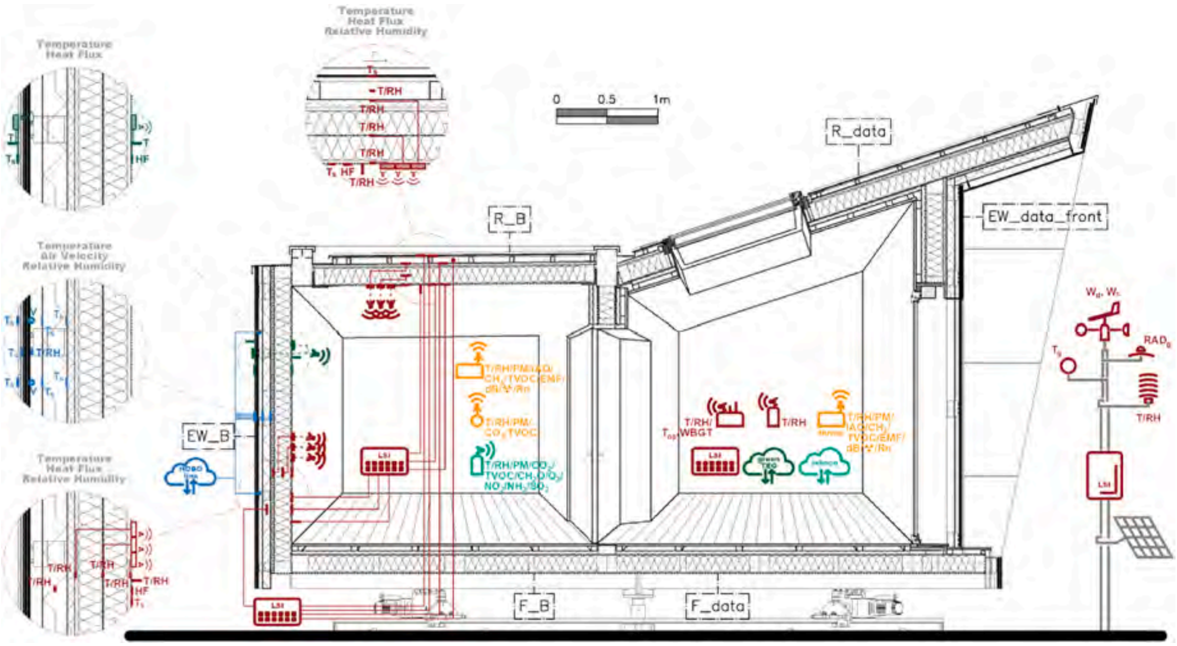
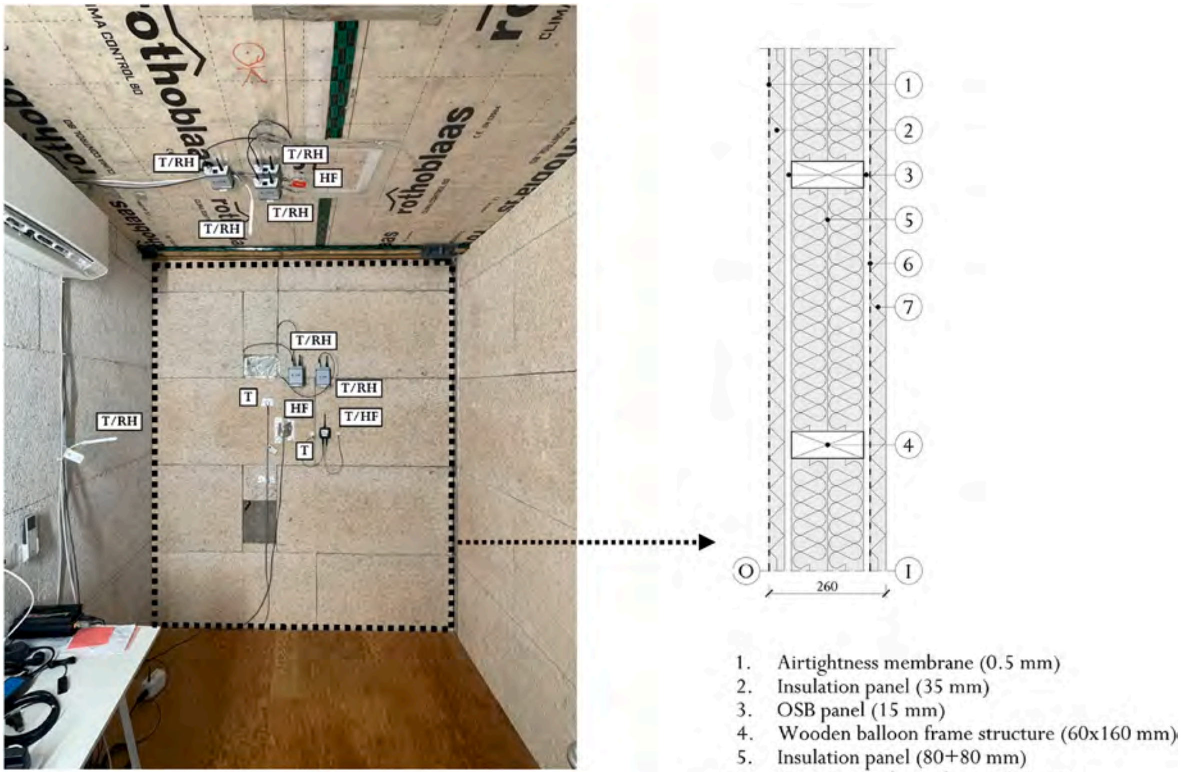


Fig. 9. Schematic representation of the monitoring set-up designed for the BEE Lab testbed.



1. Airtightness membrane (0.5 mm)
2. Insulation panel (35 mm)
3. OSB panel (15 mm)
4. Wooden balloon frame structure (60x160 mm)
5. Insulation panel (80+80 mm)
6. Vapor control membrane (0.5 mm)
7. Insulation panel (35 mm)

Fig. 10. Test Room A: example of identification of the main sensors and probes installed. On the right, vertical section of the wall with layers composition.

that represent the curve for the risk of mold growth in the range of temperature between 5 and 40 °C on a material has been calculated through Eq. (1):

$$RH_{crit} = \begin{cases} -0{,}00267 \times t^3 + 0.16 \times t^2 - 3{,}13 \times t + 100 \quad when\, t \leq 20^\circ C \\ RH_{min} \quad when \quad t > 0^\circ C \end{cases} \tag{Eq. 1}$$

Where “t” is the temperature (°C) on the investigated material surface and RHmin represents the minimum level of relative humidity (%) at which mold growth occur (for the investigated case the RH_{min} is set to 80 %). On these grounds, the vertical closure of Test Room A exhibited notably different behaviors and trends throughout the overall monitoring period, as outlined in Fig. 14. What stands out from this complete

Table 4
List of sensors employed in the BEE Lab testbed and respective characteristics.

Surface temperature sensor		Heat Flux sensor	
Measurement range	−50 ÷ 80 °C	**Measurement range**	−2000 ÷ 2000 W/m^2
Accuracy	±0.15 °C at 0 °C	**Accuracy**	±5 % over 12 h measurement
Resolution	±0.01 °C	**Sensitivity**	60 μV/W/m^2
Air temperature and Relative Humidity sensor			
Measurement range	−50 ÷ 100 °C	**Measurement range**	0 ÷ 100 %
Accuracy	±0.1 °C at 0 °C	**Accuracy**	±1 % at 5 ÷ 95 %
Resolution	±0.01 °C	**Resolution**	±0.1 %
Drift	<0.1 °C/year	**Drift**	<1 %/year
Air temperature and Relative Humidity sensorv			
Measurement range	−40 ÷ 75 °C	**Measurement range**	0 ÷ 100 %
Accuracy	±0.21 °C at 0 ÷ 50 °C	**Accuracy**	±2.5 % at 10 ÷ 90 % ±5 % below 10 % and above 90 %
Resolution	±0.02 °C at 25 °C	**Resolution**	±0.1 %
Drift	<0.1 °C/year	**Drift**	<1 %/year
Air temperature and Relative Humidity sensor (at the interface between envelope layers)			
Measurement range	−20 ÷ 60 °C	**Measurement range**	0 ÷ 100 %
Accuracy	±0.1 °C at 20 ÷ 60 °C ±0.2 °C otherwise	**Accuracy**	±1.8 % at 0 ÷ 80 % ±2 % otherwise
Resolution	±0.01 °C	**Resolution**	±0.1 %
Air temperature sensor		**Air temperature sensor (for U-value calculation)**	
Measurement range	−40 ÷ 100 °C	**Operating range**	−50 ÷ 80 °C
Accuracy	±0.2 °C at 0 ÷ 50 °C	**Accuracy**	±0.1 °C
Resolution	±0.03 °C at 0 ÷ 50 °C	**Resolution**	±0.01 °C
Drift	<0.1 °C/year		
Surface temperature and Heat Flux sensor (for U-value calculation)			
Operating range	−50 ÷ 80 °C	**Measurement range**	−15000 ÷ 15000 W/m^2
Accuracy	±0.1 °C	**Accuracy**	±3 %
Resolution	±0.01 °C	**Resolution**	±0.09 W/m^2
Air velocity sensor		**Air velocity sensor**	
Measurement range	0.01 ÷ 20 m/s	**Measurement range**	0.5 ÷ 10 m/s
Accuracy	±0.05 m/s at 0.05 ÷ 0.2 m/s ±0.052 m/s at 0.2 ÷ 0.5 m/s ±0.087 m/s at 0.5 ÷ 1 m/s ± (0.05 + 0.05va) m/s at 1 m/s	**Accuracy**	±4 % + 0.10 m/s
Resolution	±0.01 m/s		
Wind speed and Wind direction sensor			
Measurement range	0 ÷ 75 m/s	**Measurement range**	0 ÷ 360°
Accuracy	±0.25 m/s or 3 % at 0 ÷ 25 m/s ±2 % otherwise	**Accuracy**	±1 %
Resolution	±0.05 m/s	**Resolution**	±0.3°
Threshold	0.25 m/s	**Threshold**	0.15 m/s
Solar radiation sensor (Global Irradiance)		**Solar radiation sensor (silicon pyranometer)**	
Measurement range	0 ÷ 4000 W/m^2	**Measurement range**	0 ÷ 1280 W/m^2
Sensitivity	10 ÷ 15 μV/W/m^2	**Accuracy**	±10 W/m^2 or ± 5 % Additional induced error ± 0.38 W/m^2 per °C from 25 °C
Drift	<1 %/year	**Resolution**	±1.25 W/m^2
		Drift	<2 %/year

Table 5
List of devices employed in the BEE Lab testbed and respective characteristics.

Radon device		Indoor Air Quality device (TVOC)	
Measurement range	0.1 ÷ 1750 pCi/l	**Measurement range**	0 ÷ 60000 ppb
Accuracy	±6 %		
Resolution	±28 Bq/m^3		
Sensitivity	0.03 cpm/pCi/l or 1.8 cph/pCi/l	**Resolution**	±1 ÷ 32 ppb
Field range	0 ÷ 65000 Bq/m^3		
Repeatability	15 % at 100 pCi/l		
Indoor Air Quality device (CO$_2$)		**Indoor Air Quality device (PM)**	
Measurement range	0 ÷ 5000 ppm	**Measurement range**	0 ÷ 1000 μg/m^3
Resolution	±1 ppm	**Resolution**	±1 μg/m^3
Indoor Air Quality device (Relative Humidity)		**Indoor Air Quality device (Temperature)**	
Measurement range	0 ÷ 100 %	**Measurement range**	−40 ÷ 120 °C
Resolution	±0.01 %	**Resolution**	±0.01 °C
Thermal Imaging camera		**Thermal Imaging drone**	
Resolution	640x480 pixels	**Accuracy**	±2 % or ± 2 °C
Zoom	8x (digital)	**Zoom**	16x
Temperature range	−40 ÷ 2000 °C	**Scene range**	−40 ÷ 150 °C (high gain) −40 ÷ 550 °C (low gain)
Thermal sensitivity	<0.035 °C at 30 °C	**Working range**	−10 ÷ 40 °C
Blower Door Test setup			
Measurement range	19 ÷ 7200 m^3/h −1250 ÷ 1250 Pa (digital pressure gauge)	**Mounting frame size**	0.71 ÷ 1.14 m (width) 1.32 ÷ 2.43 m (length)
Accuracy	±4 % (rings A-C) ±5 % or ± 1.7 m^3/h (rings D-E) ±1 % or ± 0.15 Pa (digital pressure gauge)	**Fan dimension** **Measuring points**	Ø approx. 610 mm Up to 1000 per pressure stage

overview is, in particular, the prominent different behavior presented seasonally by the wall component, due to the real-life outdoor boundary conditions that, in fact, enabled a realistic assessment of the membranes performances inside the wall.

To test the behavior to high relative humidity, the drywall layer was subjected to forced environmental conditions named as WH on Fig. 14. This phase is characterized by a sharp increase in relative humidity, which serves to highlight the wall's hygrothermal response under accelerated and extreme indoor conditions. The following sub-sections will particularly focus on the behavior assessment during three key periods: (i) a typical summer week (marked as “S” on the chart below), (ii) a typical winter week (“W”), and (iii) a range of two weeks under a sharp increase of indoor relative humidity (“WH”).

4.1. *Summer performance assessment (“S”)*

The chart in Fig. 15 aims to introduce the overall behavior of the two vapor-control membranes installed in the vertical closure of Test Room A during a hot and humid summer week (July 29th to August 4th, 2023). During this time frame, the temperature set-point of the test room was set at 20 °C, to maximize the temperature gradient between the interior and exterior and thereby increase thermal stress on the wall.

On such basis, in an attempt to summarize the membranes behavior during a typical summer week, it can be stated what follows. First of all, it is worth remembering that the outer water resistive barrier (Traspir Evo 160) is highly breathable, while the inner water retarder membrane (Clima Control 80) ensures a variable vapor resistance, acting as a vapor control in low humidity conditions, and as a breathable membrane in high humidity conditions. To accurately assess the membranes'

Table 6

Summary of the most relevant characteristics of the different membranes object of monitoring, sourced from the respective technical sheets provided by the manufacturer.

Membrane Property	Clima Control 80	Traspir Evo 160
Brief description	The membrane ensures a variable resistance to water vapor diffusion. It acts as a vapor control in low humidity conditions, and as a breathable membrane in high humidity conditions.	The highly breathable monolithic membrane provides waterproofing and airtightness, as well as excellent fire behavior and high UV stability.
Composition	Top layer: PA functional film Bottom layer: non-woven PP fabric	Top layer: non-woven PP fabric Middle layer: breathable monolithic PE film Bottom layer: non-woven PP fabric
Mass per unit area [g/m^2]	80	160
Thickness [mm]	0.22	0.5
Variable water vapor transmission (Sd) [m]	0.15 ÷ 5	0.1
Watertightness [-]	Compliant in accordance with the EN 1928	Class W1
Temperature range [°C]	−20 ÷ 80	−40 ÷ 100
Thermal conductivity (λ) [W/mK]	0.2	0.4
Specific heat [J/kgK]	1700	1800
Density [kg/m^3]	400	370
Variable water vapor resistance factor (μ) [-]	1000 ÷ 25000	160

performance, it is important to note that indoor relative humidity levels during the analyzed summer period was relative high, ranging from 70 % to 86 %. At the same time, the outdoor relative humidity levels was variable, ranging between 35 % and 99 % depending on the varying outdoor environmental conditions. Throughout the analyzed period, despite elevated indoor humidity levels, the inner vapor barrier allowed controlled water vapor transmission, helping to reduce moisture accumulation within the thermal insulation layer. This layer exhibited, in fact, relative humidity values ranging between 55 % and 73 % which correspond to 20–25 % lower values than those recorded at point A1. During periods of extreme heat, with ambient temperatures above 30 °C and solar radiation on vertical plane above 700 W/m^2, the innermost wall layer experiences short-term peaks in relative humidity reaching 95 %, whereas the thermal insulation layer records values up to 73 %. Considering that the mold growth is affecting by the time length of high and low humidity conditions as well as the humidity and temperature levels the specific analyzed case do not represent a risk condition for a fungal growth.

On typical hot days, the relative humidity in the innermost layer stabilizes at around 80 %, whereas the thermal insulation layer reaches approximately 67.5 %, remaining below the critical humidity threshold (RHcrit). For a clear picture of the results Fig. 16 report the relative humidity versus temperature of the three different measured points of the wall compared with the RHcrit calculated according to the VTT model. The yellow data points, representing the relative humidity in the innermost layer behind the vapor barrier, fall within the range favorable for mold growth if such conditions persist over time. In this specific case considering the short time over the threshold, the high humidity cause no risk for mold growth into the wall layer. The middle and the outer wall layers do not show anyrisk of mold growth, since the measured points are located below the RHCritic curve.

4.2. *Winter performance assessment*

As in the previous section, the chart Fig. 17 illustrates the overall performance of the two vapor-control membranes installed in the vertical enclosure of Test Room A during a representative winter week (January 1st to January 7th, 2024).

. First of all, it is interesting to point out that indoor relative humidity values were relatively low in the winter period, ranging between 25 % and 30 %. At the same time, the outdoor relative humidity levels were variable, ranging between 47 % and 99 % in accordance to the varying environmental conditions. In this context, the inner membrane acts as a vapor control in response to the indoor environmental conditions, successfully maintaining average values that range between 33 % and 39 %. On the outer side of the wall component, instead, the highly breathable nature of the membrane (Traspir Evo 160) allows potentially harmful vapor to escape prior to condensing on the wall surface layers. Finally, the chart in Fig. 18 analyzes the behavior of the two membranes during a period of time under forced indoor relative humidity control (January 9th-23rd, 2024). The two test rooms, in fact, feature an indoor direct air humidifier ("CONDAIR 505″, with power up to 0.50 kg/h), for the control of the internal relative humidity levels. A threshold value was set to 70 % of internal relative humidity.

For an accurate reading of the membranes performances, it is also interesting to point out that indoor relative humidity values can be broken down in three main phases: (i) before the humidity control period (free running), where the indoor environment behaves as described before; (ii) during the relative humidity loading cycles

Table 7

Identification and most relevant characteristics of the different layers constituting the vertical closure of Test Room A.

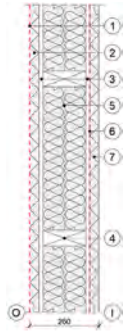
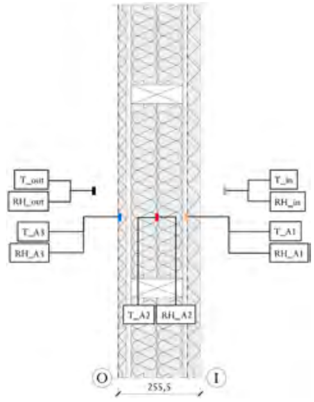
Section	#	Description	Thickness [mm]	Variable water vapor resistance factor [-]	Conductivity [W/mK]	Density [kg/m^3]	Specific heat [J/kgK]
	**1**	Rothoblaas Traspir Evo 160	0.5	160	0.400	370	1800
	2	Insulation panel	35	5	0.065	400	1810
	3	OSB panel	15	30 ÷ 50	0.130	600	1000
	4	Wooden balloon frame structure	160	40	0.150	550	1700
	5	Insulation panel	160	1	0.033	70	1030
	6	Rothoblaas Clima Control 80	0.22	1000 ÷ 25000	0.200	400	1700
	7	Insulation panel	35	5	0.070	430	1810

Fig. 11. Outdoor and indoor views of the wall component object of monitoring and of the respective boundary environments.

Table 8
Setup and positioning of sensors and probes within the building envelope component object of monitoring.

Section		Description	Parameter	Unit
	**T_in**	Indoor environmental air temperature	Temperature	°C
	RH_in	Indoor environmental air relative humidity	Relative Humidity	%
	T_out	Outdoor environmental air temperature	Temperature	°C
	RH_out	Outdoor environmental air relative humidity	Relative Humidity	%
	T_A1	Air temperature behind inner membrane	Temperature	°C
	RH_A1	Air relative humidity behind inner membrane	Relative Humidity	%
	T_A2	Air temperature mid-insulation gap	Temperature	°C
	RH_A2	Air relative humidity mid-insulation gap	Relative Humidity	%
	T_A3	Air temperature behind outer membrane	Temperature	°C
	RH_A3	Air relative humidity behind outer membrane	Relative Humidity	%

(switch-on), with values increasing up to 80 %; and (iii) during the relative humidity unloading cycles (shut-off), with values decreasing all the way to normal conditions. In this context, the results can be analyzed according to the three different phases proposed above. The behaviors of both membranes prove to be substantially affected by the variation of indoor relative humidity caused by the air humidifier. In the initial free running mode (up to January 11th at 12 p.m.), the membranes still behave as described in Fig. 17. In the switch-on phase (between January 12th and 15th), the inner membrane acts as a vapor control layer controlling the amount of water vapor that can pass through it preventing possible condensation within the wall layers. The membrane dynamically regulates its permeability based on indoor temperature and humidity levels, effectively minimizing the potential for condensation. This is also proven by the similar trend recorded right behind the outer highly breathable membrane which, in turn, successfully allows vapor to escape from the building envelope. During the shut-off phase (after January 17th), both membranes are consistent in such behavior, until finally returning to the stable behavior in 6 days (January 22nd). Fig. 19 reports the relative humidity versus temperature for the three different measured points of the wall compared with the critical level of humidity according to the VTT model. The blue markers, which indicate the relative humidity in the outermost layer located behind the waterproof membrane, lie within a range favorable for mold development if sustained. This condition arises from the low surface temperatures of the outermost layer, resulting from its direct exposure to ambient outdoor air.

The analyzed wall is a “forced” technical solution revealing how mold growth depends on the combination of humidity and temperature. The inner layers do not show the risk of mold growth at any time step of the analysis, all the measured points are located under the critical relative humidity curve.

5. Discussion and conclusions

Industrialized and lightweight building technologies have been gaining relevance in the European construction industry. The dry-layer wood based technology is an example of this new and growing trend that has been gathering increased attention due to the comprehensive advantages from the energy performance and the sustainability point of view. The assessment of the actual performance of the building enclosure in real conditions is fundamental for evaluating and potentially preventing performance gaps. Such goal requires, although, the accurate set-up of dedicated facilities, able to provide full-scale tests in realistic spaces and conditions. This requirement automatically excludes the traditional assessment through laboratory tests at product level, as it could only provide a standard validation and measure of the different

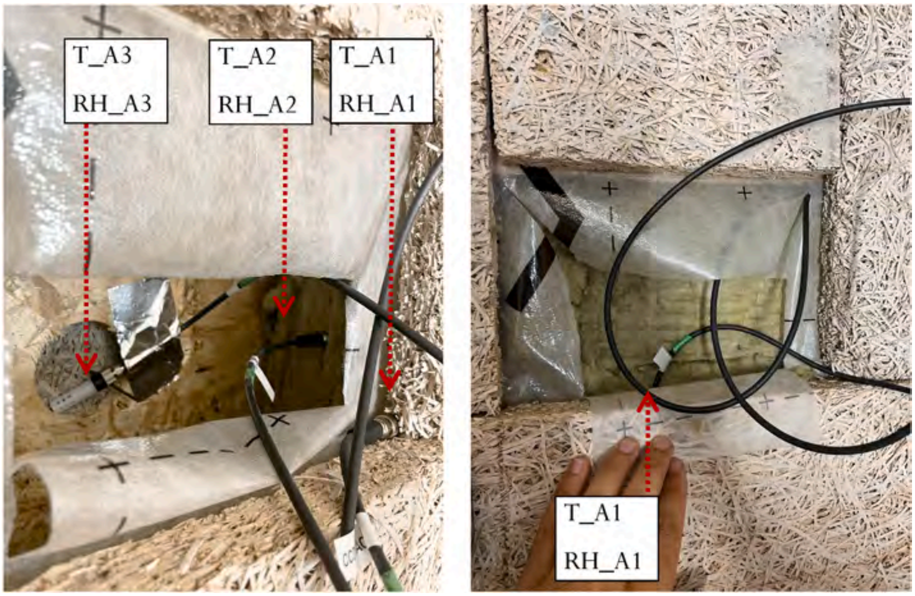


Fig. 12. Key sensors installation steps for the monitoring of the vertical closure of Test Room A.

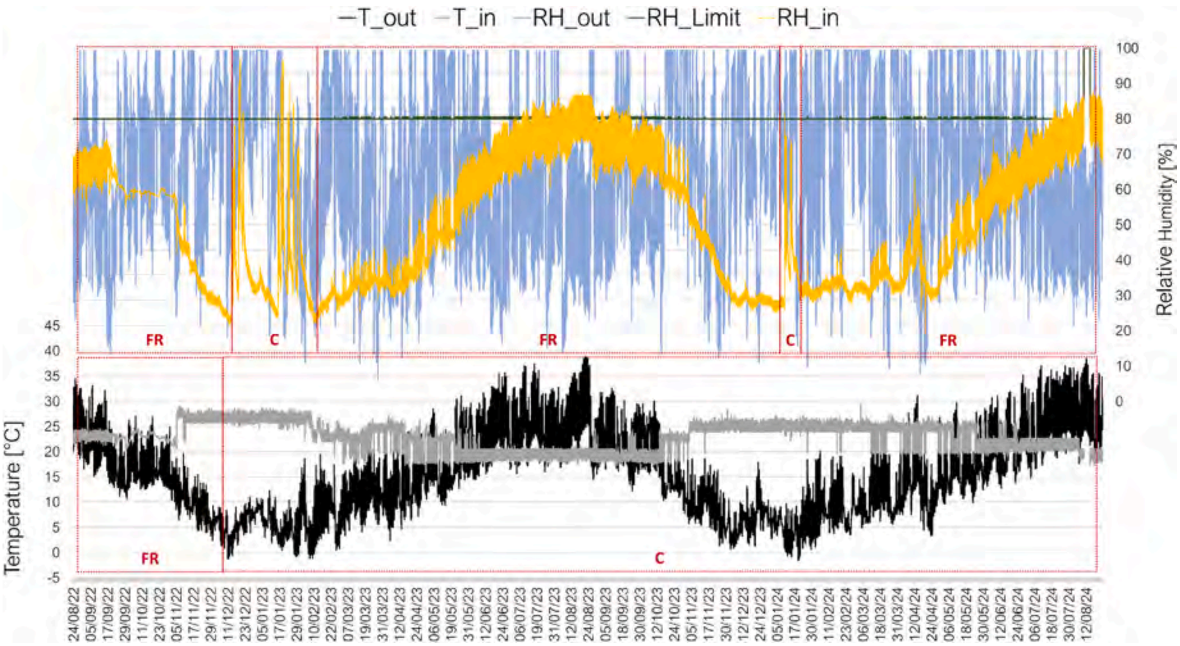


Fig. 13. Indoor and outdoor environments: air temperature and relative humidity trends during the overall monitoring period. The upper part of the graph shows the humidity levels of the different wall layers, while the lower part depict the temperature levels. The red frames highlight, in particular: "FR" when the indoor boundary conditions are "free-running", and "C" when they are "controlled". (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

physical properties in a controlled environment. In that context, the present work elaborates on the design and development of a research space, named "Building facadE performancE Lab", for the real-life performance assessment of the dry-later building enclosure, with a specific focus on multilayer external walls and roofs. Considering the expertise of the associated research team and the specific scope defined by the MEZeroE H2020 project, the building has been specifically designed to focus on the following key aspects: (i) thermal and hygrometric performance, (ii) impact on indoor well-being (e.g., air quality, thermal comfort), and (iii) impact on energy efficiency. To that end, the testbed features a fruitful combination of test-chamber (two adjacent test rooms) and Living Lab (a data room) spaces, as well as dedicated tracks to enable its full rotation according to the different test and research needs. In line with its scope, the building enclosure has been designed and built as a continuous sequence of modules, with a structural wooden frame core and additional functional layers (e.g., insulation, vapor barrier, airtightness and waterproofing membranes, finishing) to reach the desired overall performance. Finally, to enable the accurate assessment of various multilayer dry envelope solutions the testbed has been fully sensorized with a wide range of devices, sensors and probes. The paper in particular, provides a digression on the hygrothermal long-term performance assessment of a wood-base multilayer wall component, towards the characterization of the behavior of different water- and vapor-control membranes with varying and variable vapor resistance.

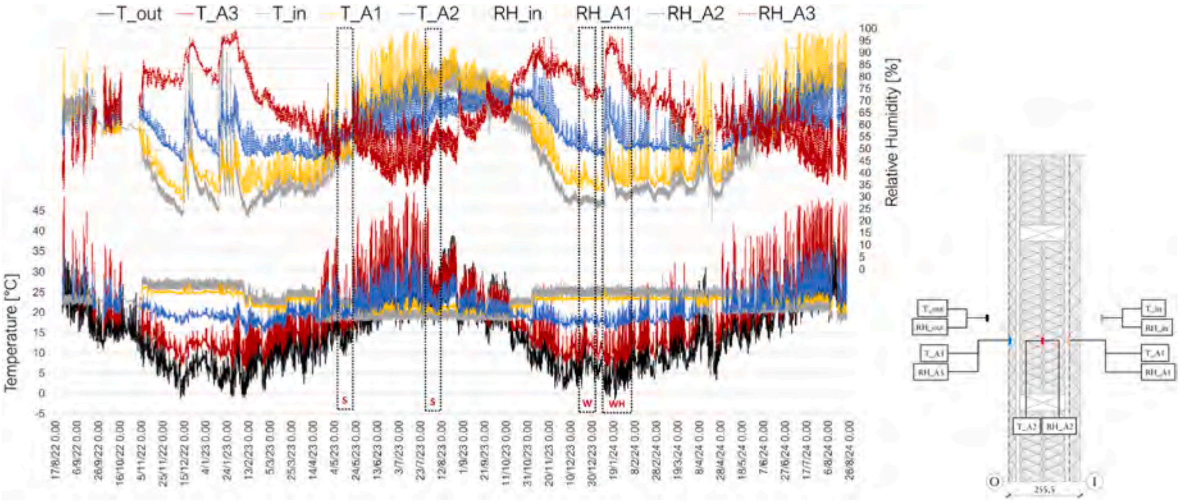


Fig. 14. Temperature and relative humidity values on the overall monitoring period. The upper part of the graph shows the humidity levels of the different wall layers, while the lower part depict the temperature levels. The colors correspond to the monitored points as indicated in the adjacent wall model. The dotted black rectangles highlight the periods of further analysis, respectively: "S" for summer period, "W" for winter period, and "WH" for a period under forced indoor high relative humidity control. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

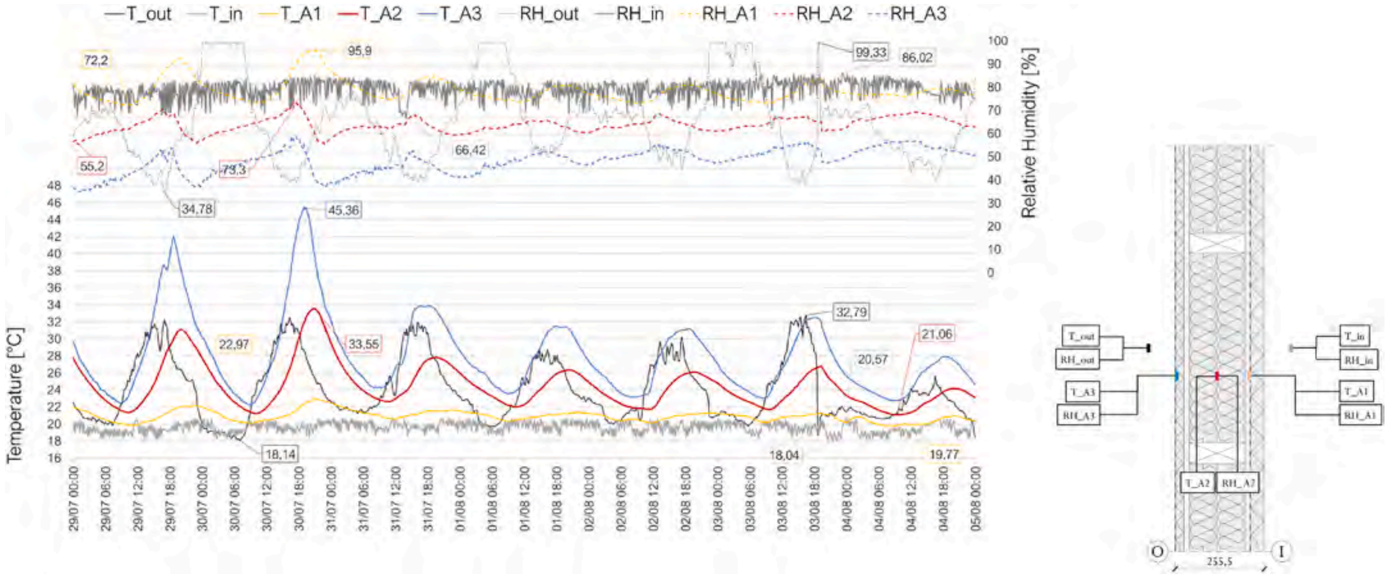


Fig. 15. Vertical closure of Test Room A: temperature and relative humidity values during a summer week. The upper part of the graph shows the humidity levels of the different wall layers, while the lower part depict the temperature levels. The colors correspond to the monitored points as indicated in the adjacent wall model. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The data from the preliminary monitoring campaigns are used to validate the capabilities of BEE Lab and the associated data collection procedure. The aim of the validation was: 1) to verify that the experimental design allows to capture the influence of waterproof membrane on dry layer wall construction, 2) to test the typology and position of the sensors and the system for temperature and humidity control; 3) to verify that the experimental campaign collects data with adequate frequency and space resolution. The experimental activity was set and carried out with a continuous monitoring system over 24 months, able to detect the real performance under real weather conditions. The work allowed not only to compare the winter/summer performances of the dry-layer wall assembly but also to understand the impact of higher indoor relative humidity concentrations. The temperature and relative humidity levels recorded during the monitoring campaign do not show mold formation risk in the thermal insulation layer during both the summer and the winter conditions nor during the forced controlled indoor humidity. The interior smart vapor retarder layer enhances the wall system's ability to dry more quickly and maintain lower insulated cavity RH levels during the warmer months of the year and potentially reduce moisture-related risk. During hot/humid summer days, (with external temperature above 30 °C and room temperature/RH of 20 °C/80 %) the innermost monitored wall layer, shows relative humidity conditions above the RH_{crit} curve for a limited time with minor risk of mold formation. During winter days, the point behind the external water resistive barrier shows potential mold growth due to direct exposure to the external weather conditions highlighting the importance of covering the external membrane with additional layers such as thermal insulation and claddings for increasing the surface temperature level. The results shows that the inner wall layers reaches temperature and humidity levels below the RH_{crit} curve which is the results of an efficient vapor diffusion throughout the wall.

The experimental campaign was designed with three primary

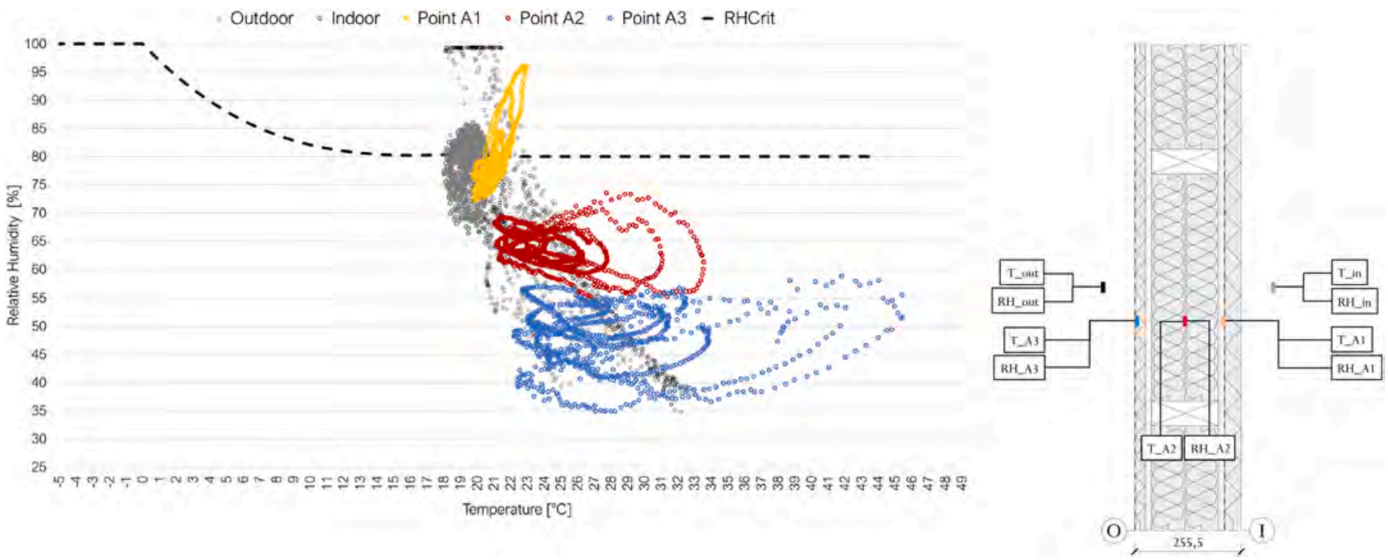


Fig. 16. RHcrit, RH_A1, RH_A2 and RH_A3 in function of temperatures. The colored dots correspond to the monitored points as indicated in the adjacent wall model.

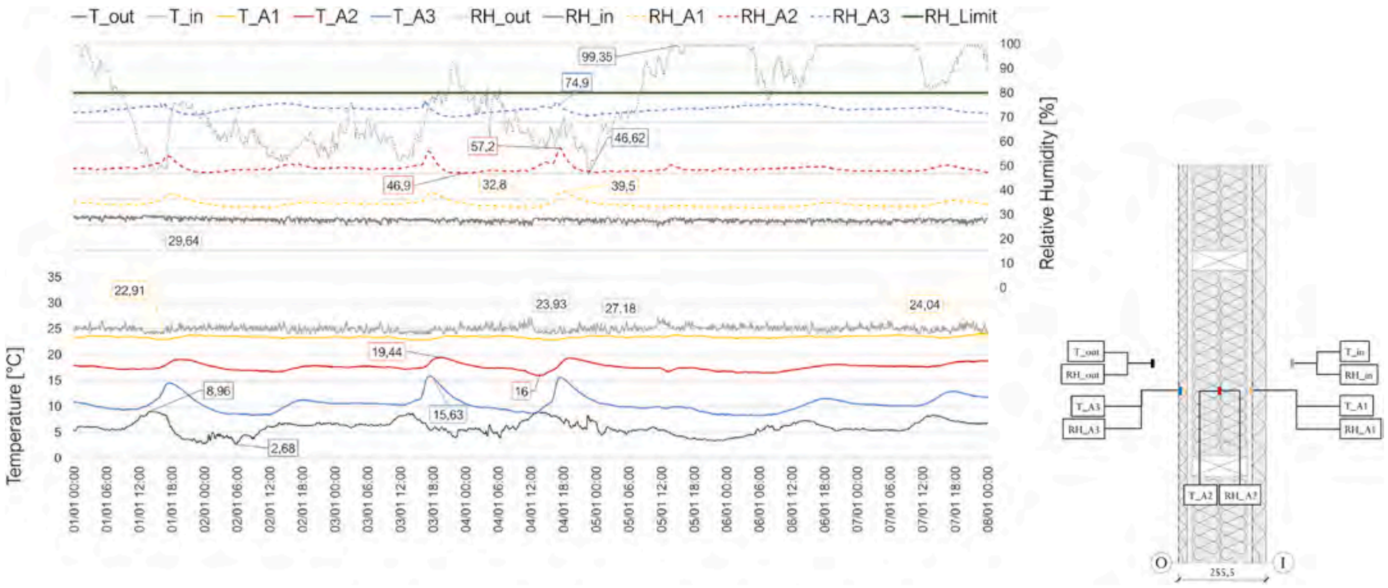


Fig. 17. Vertical closure of Test Room A: temperature and relative humidity values during a winter week. The upper part of the graph shows the humidity levels of the different wall layers, while the lower part depict the temperature levels. The colors correspond to the monitored points as indicated in the adjacent wall model. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

objectives. First, it aimed to verify that the setup effectively captures the influence of the waterproof membrane on the hygrothermal behavior of drywall constructions. The configuration allows for controlled comparison between different seasons, ensuring that differences in moisture accumulation and thermal performance can be clearly identified. Second, the campaign evaluated the typology and placement of sensors, as well as the performance of the temperature and humidity control system. The selected sensors demonstrated high accuracy and responsiveness, and their positioning enabled comprehensive monitoring of temperature surface and humidity within the wall layers. The environmental indoor control system maintain stable setpoints, successfully replicating forced conditions. Lastly, the campaign assessed the adequacy of data collection in terms of frequency and spatial resolution. Measurements were recorded with 10 min intervals, and sensors were distributed across critical layers of the wall, allowing for detailed observation of hygrothermal dynamics over time and across different wall zones. Together, these elements confirm the robustness and reliability of the experimental design.

The work discussed in the present paper is considered not only to be of particular interest to manufacturers, researchers, and designers involved in the field of high-performing envelope solutions but also to pave the way for further research and studies in the same direction. Future work may, for instance, focus on the anticipated critical review of the relevant standards that specifically address the planned tests performed under real-life conditions, as well as on detailed analyses of the performances of different envelope components being monitored within the BEE Lab Living Lab. Future work will need to extend the measurement campaign and increase the number of testing scenarios to evaluate differences in building envelope technologies (for wall and roof) under different indoor/outdoor conditions and at different orientations.

CRediT authorship contribution statement

Graziano Salvalai: Writing – review & editing, Writing – original

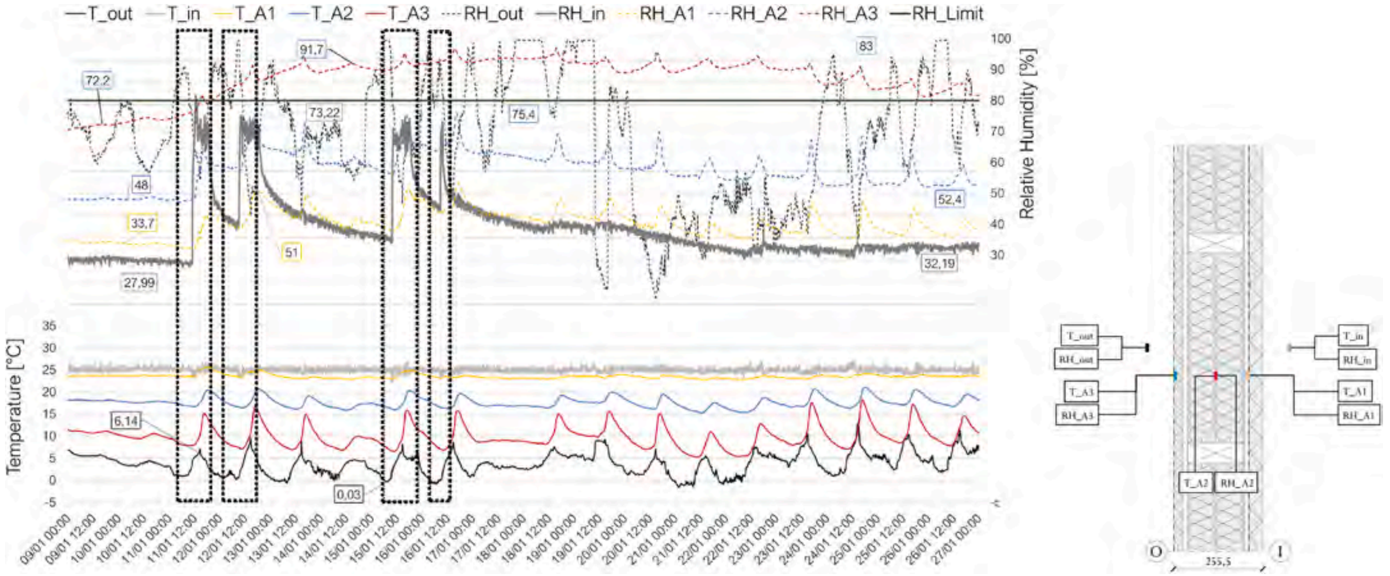


Fig. 18. Vertical closure of Test Room A: temperature and relative humidity values during a period under indoor relative humidity control (humidifier setpoint: 65–70 %). The dashed black rectangles indicate the time with the humidifier in function. The upper part of the graph shows the humidity levels of the different wall layers, while the lower part depict the temperature levels. The colors correspond to the monitored points as indicated in the adjacent wall model. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

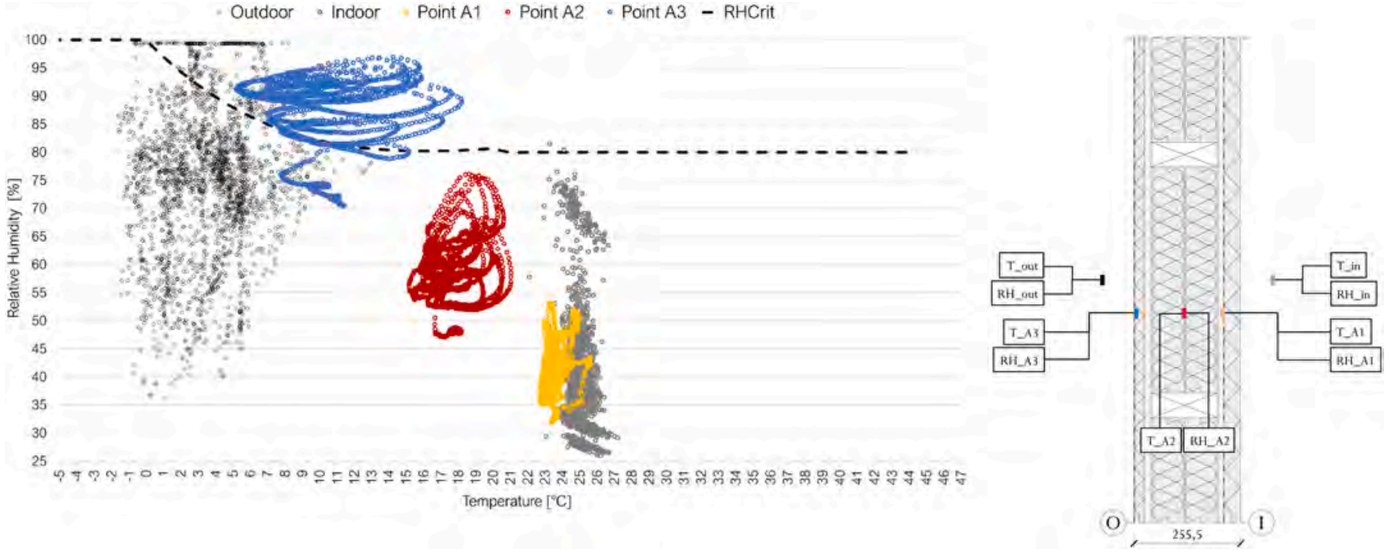


Fig. 19. RHcrit, RH_A1, RH_A2 and RH_A3 in function of temperatures. The colored dots correspond to the monitored points as indicated in the adjacent wall model.

draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Diletta Brutti:** Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Marta Maria Sesana:** Writing – review & editing, Methodology, Investigation, Formal analysis.

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Declaration of competing interest

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Data availability

The data that has been used is confidential.

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