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From single tests to a test-chain: a comprehensive approach for evaluating the interaction between the building envelope and the IEQ

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Abstract. In recent years building envelope systems have become increasingly more com-plex. Especially in high-performance low-carbon buildings, envelopes comprise several passive and active components such as advanced membranes, mechanical ventilation machines and integrated photovoltaics that must be mutually optimized to ensure a global elevated performance. One of the key expectations from these innovative envelopes is better capabilities of providing highly comfortable and healthy indoor environments while using as little energy as possible. However, the complexity of such envelopes poses two major challenges: (i) standard assessment procedures might not be usable to evaluate them either because these do not fully capture their potential or be-cause the complexity of product makes the standard test unfeasible, and (ii) multiple indoor environmental quality (IEQ) domains are simultaneously affected by these envelopes, and thus complementary tests in different domain are needed to ensure that a benefit in one domain does not lead to issues in others. For this reason, a test-chain for a thorough energy demand, indoor occupants' comfort, and behaviour analysis performance has been implemented. It comprises a set of labs and additional simulation capabilities to study the building envelope-IEQ interaction at various technology readiness level. This paper provides an overview of the test-chain and its first application for the evaluation of a multifunctional façade. This façade includes a reversible air-to-air heat pump, a mechanical ventilation system, and openable windows, and aims at easing the achievement of the nZEB target while delivering elevated IEQ.

1 Introduction

In recent years, building envelope systems have become increasingly more com-plex with the development of solutions such as adaptive [1-3] and multifunctional [4, 5] façades which serve more purposes than traditional envelopes and often embed multiple technologies. Especially in high-performance newly built low-carbon buildings but also in the case of deep

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state-of-the-art renovations [6], envelopes comprise several passive and active components such as advanced membranes, mechanical ventilation machines and integrated photovoltaics that must be mutually optimized to ensure a global elevated performance. One of the key expectations from these innovative envelopes is a better capability of providing highly comfortable and healthy indoor environments while using as little energy as possible. However, the complexity of such envelopes poses two major challenges: (i) standard assessment procedures might not be usable to evaluate them either because these do not fully capture their potential or because the complexity of product makes the standard test unfeasible, and (ii) multiple indoor environmental quality (IEQ) domains are simultaneously affected by these envelopes, and thus complementary tests in different domain are need-ed to ensure that a benefit in one domain does not lead to issues in others. Building performance simulation and indoor environmental modelling may also often be used to better design such complex systems [7].

Thus, the aim of this paper is to present how the test-chain for a thorough energy demand, indoor occupants' comfort, and behaviour analysis performance has been implemented, and to provide insights into the first application of the test-chain for the evaluation of a multifunctional façade. This façade includes a reversible heat pump, a mechanical ventilation device with heat recovery, and openable windows, and aims at easing the achievement of the nZEB target while delivering elevated IEQ to the occupants.

2 A test-chain for evaluating the building envelope – IEQ interaction facing health requirements

2.1 The concept of pilot measurement and verification line

A pilot measurement and verification line (PM&VL) is a comprehensive test-chain aimed at supporting small and medium enterprises (SMEs) but also larger companies in the development and testing of building envelope technologies, and it focuses either on one specific type of technology (e.g. transparent components) or performance (e.g. im-pact of the envelope on the indoor environment).

A PM&VL typically comprises a series of laboratories and additional capabilities such as simulation support. The key difference between a simple group of testing facilities and a PM&VL is that the latter has a clear overall strategic purpose described by its vision, mission and fundamentals values, and the fact that its nodes (labs, special equipment, simulation tools, etc.) are logically connected to support the development flow.

A PM&VL can support the development of an innovative technology from the initial concept (technology readiness level 2, TRL2) to demonstration in relevant environments (TRL6), while the final higher TRLs can be achieved by means of the real-building living labs that represent an operational environment. A PM&VL focuses especially on those cases for which there is no standard evaluation procedure.

In H2020 MEZeroE project lifetime, nine PM&VLs were established and validated. Each of them is led by a relevant research partner, and all together they are a fundamental piece of MEZeroE open innovation test bed (OITB) which aims at providing access to the physical facilities and services required for the development, testing and upscaling of nearly Zero Energy Building (nZEB) Enabler Envelope Solutions (nEES).

2.2 The key components of the PM&VL: labs and special equipment

The PM&VL entitled "Building envelope/IEQ interaction facing health requirements" is a test-chain for a thorough energy demand, and indoor occupants' comfort and behaviour analysis and performance characterization. Its vision is to support mate-rials' producers, facades' manufacturers, practitioners, real estate developer, and also end-users that would like to develop and evaluate innovative envelope systems that enable healthy and highly comfortable indoor environments while minimizing the energy consumption.

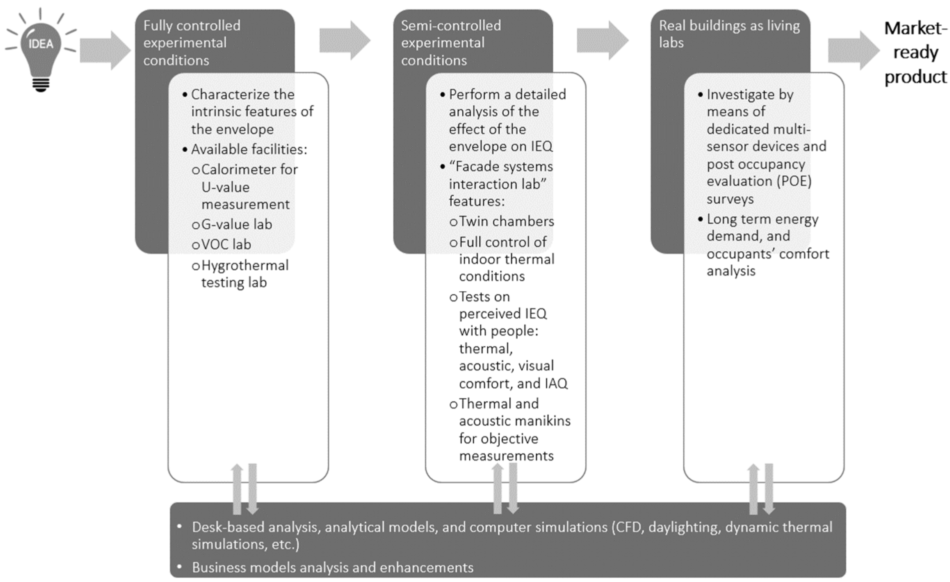

Fig. 1. PM&VL flowchart.

Figure 1 visually describes the complete workflow of the PM&VL. Starting from an idea which can be either a potential new product or a new feature of an existing one, the first testing phase focuses on studying the intrinsic features of the element under evaluation. Depending on the typology of the product, these tests might aim at measuring the U-value, the g-value, the emissions of the volatile organic compounds (VOCs), and the hygrothermal properties of the element. Once the intrinsic features of interest have been evaluated, the experimental work moves forward with the analysis in semi-controlled conditions. In this phase, the aim is to evaluate the performance of a given element under realistic conditions, and to investigate its impact over an indoor environment. Human participants and artificial occupants might be involved at this stage. As opposed to the following step (i.e. the final evaluation in a real building), this phase combines the benefits of being in an experimental environment (higher degree of control over variables and their measurement) with settings that are closer to a real building.

2.2.1 Calorimeter for U-value measurement and additional fully controlled thermal tests

The so-called "Multifunctional façade lab" (Figure 2) consists of a double climatic chamber with a guarded hot box. The sample under evaluation is placed in a frame between the two chambers (internal dimensions: height 3.20 m, width 3.10 m, and thickness 0.50 m). Air temperature and relative humidity can be controlled in both chambers, and the sun irradiation can be simulated by using specific lamps on the "cold" chamber side which represent the outdoor exposure. Temperature ranges are 18°C to 40°C and -20°C to 40° in the hot and cold chambers, respectively. Solar radiation values up to 1000 W/m^2 can be achieved.

Primarily conceived for U-value measurements, this lab enables to test the thermal and energy performances of non-homogeneous envelope systems such as doors and windows, opaque walls, and façade modules under both stationary and dynamic conditions. The facility may reproduce the testing conditions required by EN ISO 12567 [8] and EN ISO 8990 [9] standards.

Fig. 2. "Multifunctional façade lab". From the left: hot chamber with inside the metering box, frame to hold the sample with a sample installed, and cold chamber with openable back side (white doors) to add the sun simulator (© Eurac Research - Annelie Bortolotti).

2.2.2 G-value laboratory

The g-value measurement system is based on the "cooled plate method" [10]. It comprises a lamp to simulate the solar radiation (compliant with ISO 19467 [11]), a climatic chamber with one transparent side made by high-transmittance glass which does not affect the solar spectrum of the incoming irradiance, and, inside this chamber, a specimen holder and a fan. The fan is used to control the convective heat transfer co-efficient of the lamp-facing side of the specimen, while on the other side of the holder there is a water-based absorber which is connected to a hydraulic circuit. By measuring the incident radiation, the water flow rate in the absorber, and the water temperatures before and after the absorber it is possible to calculate the g-value.

2.2.3 VOC lab

The core of this lab includes two emission test chambers of 1 m^3 and 6 m^3 (Figure 3) both fully in compliance with the main standard methods for VOC and formaldehyde emission tests (EN 717-1 [12], ISO16000-9 [13], EN 16516 [14], ASTM D5116 [15], etc.). The chambers can be used to test a broad spectrum of building materials and components. The inner walls of the chambers are made of stainless steel to prevent the adsorption of VOC generated from the specimen ensuring accurate testing. A clean air producing unit constantly provides clean air to the chambers and maintains a total VOC (TVOC) back-ground concentration of less than 20 $\mu g/m^3$ required for the emission test. The test chambers are airtight to avoid uncontrolled air exchange with ambient air. They are thermally isolated and equipped with heating elements allowing the control of the temperature inside the chamber. The temperature can be regulated from 23°C to 65°C in the case of 1 m^3 test chamber and between 23°C and 50°C in the 6 m^3 chamber. Relative humidity can be controlled to any value between the value of the inlet air and 80% at 23°C. Air velocity inside the chambers can be also modified according to the experimental requirements.

Fig. 3. Volatile Organic Compounds Lab (© Eurac Research - Annelie Bortolotti).

This facility can perform emission tests, decay tests, and sensors' testing and calibration. In emission tests, gaseous chemicals emitted by the tests specimen are monitored over an interval of time (days/weeks). In decay tests, the ability of the test specimen to remove airborne chemicals is evaluated over an interval of time (days/weeks). Lastly, external sensors can be tested in a range of concentrations and under different conditions of temperature and relative humidity. Sensor readings are compared to reference instruments for validation.

During the tests, two types of measurements can be taken, namely real-time formaldehyde measurements by using a fluorimeter that is connected to the chamber, and off-line VOC measurements. In this case, air samples are collected from the chamber at specific time intervals using sampling cartridges. These cartridges are later analysed in the lab using standard analysis methods (GC-MS or HPLC-UV).

Related standards to the tests developed in this node are EN717-1 [12], ISO-16000-3 [16], ISO-16000-9 [13] and EN 16516 [14].

2.2.4 Hygrothermal testing lab for material properties measurements

The Hygrothermal Testing Lab performs measurements of the thermal and hygrometric properties of building materials. The following properties can be measured: basic properties (apparent density), thermal properties (thermal conductivity, and specific heat capacity), hygrometric properties (vapor permeability, water uptake curve and water absorption coefficient, drying curve, liquid -capillary- conductivity, moisture storage function in hygroscopic regime - sorption/desorption curve -, and moisture storage function in over-hygroscopic regime - moisture retention curve).

The material properties can be measured individually or, alternatively, a complete hygrothermal characterization of the material can be carried out. In the latter case, all properties of the material are measured, the laboratory raw data are post processed and converted into numerical functions that can be used to model the material in hygro-thermal simulation software in dynamical regime (such as WUFI, DELPHIN, Pro-CasaClima Hygrothermal, software following the requirements of the standard EN 15026 [17] or any other software that simulates the combined transport of moisture and heat in building materials). The use of these type of software enables the simulation of the behaviour of the material in real design conditions and gives the possibility to investigate design solutions and practical applications.

This lab can perform tests related to ISO EN 12571 [18], ISO EN 12572 [19], ISO EN 15148 [20], EN 16322 [21], and EN 15026 [17].

2.2.5 Façade system interactions lab

The "façade system interactions lab" was conceived to perform experiments in semi-controlled conditions. The lab (Figure 4) comprises two environmental chambers (internal dimensions width 4 m, depth 8 m, height 3 m each) each with a side that can be closed with a given façade sample. This means that one side of the sample is ex-posed to the outdoor conditions, while the other faces fully controlled conditions. In-side each chamber it is possible to control independently air temperature, relative humidity, each surface temperature (floor, ceiling, inner long wall, outer long wall, and short wall opposite to the façade sample), and the way in which air is supplied to and extracted from the room (both from the ceiling, one from the ceiling and the other from the floor, or the opposite). Air temperature can go from 15 °C to 35 °C and relative humidity from 20% to 90%. The maximum façade sample size is width 3.7 m, height 2.8 m, thickness 0.5m. The entire lab is mounted on a rail that enable a ±180° degree rotation to achieve the desired orientation for the façade sample.

Fig. 4. Façade system interactions lab.

Hence, the lab can be used for two complementary purposes, namely (i) to evaluate the performance of a certain façade element in realistic conditions while being able to have full control over the indoor conditions, and (ii) to evaluate the effect of the façade over the indoor environmental conditions. When the focus is on the indoor conditions, inside the lab it is also possible to install additional IEQ-related technologies to be tested such as ceiling fans or radiant systems for heating or cooling. For this type of experiments, a suitable generic façade may be used if the focus is on technologies different that the façade itself.

Human participants may be involved for studying their comfort perception. In this type of experiments, the chambers are usually configured to look a relevant typical building room such as a living room, an office, or a small school classroom. Artificial occupants might be used, too. An in-house developed monitoring system enables to accurately measure the parameters that are relevant for a given tests. Due to its nature, this lab is not focused on standard testing, but mainly on realistic conditions.

2.2.6 Elio: a breathing thermal manikin

Artificial occupants cannot completely replace humans in assessing indoor perception. However, their use enables to perform perfectly comparable and repeatable experiments, and to optimize the experimental set-up before involving human participants or to take measurements that cannot be easily taken with human participants.

Elio (Figure 5) is a thermal manikin system used for accurate and repeatable assessment of the thermal comfort with breathing capability. It has a natural body shape (175 cm tall male) with a dense 2.2 mm wiring optimized to create a uniform heat loss across the body, and 27 body zones with independent measurement of skin temperature and heat flux. It usually reaches the set-point conditions within 10 minutes, and it can be placed standing, seated, or reclined depending on the application. It can be dresses as required and it complies with ISO 15831 standard [22] for testing of clothing. It can be operated in ambient temperatures from -20°C to 50°C, the skin temperature can be set from 15°C to 45°C, and the heat loss range goes from 0 to 300 W/m^2. It also includes a respiration module for inhale and exhale air control including a special valve for adding tracer gas, natural fingers on both hands, and its digital model for the inclusion in computational fluid dynamics (CFD) simulation software.

Fig. 5. Thermal manikin. Preliminary tests in the "Façade system interaction lab" to enhance the set-up for human participants within H2020 MEZeroE experimental studies.

2.2.7 SoundLab: acoustic equipment and soundscape

Within the PM&VL, two sets of instruments are available, namely one covering standard building and room acoustics measurements and another for enabling sound-scape analysis.

The former concerns monaural sound level recording and analysis, reverberation time measurements, impulse response acquisition, evaluation of room acoustics parameters (e.g. clarity, early decay time), airborne sound insulation between two rooms and of façade elements through field measurements in real buildings. It comprises a Class 1 sound level meter and analyser (Figure 6), a 1/2" pre-polarized free-field microphone, a precision sound level calibrator for 1/2" microphones, a digital amplifier, and directional source for façade measurements.

The latter set includes a "head and torso" simulator equipped with ear and mouth simulators, mobile headset for aurally accurate binaural sound recordings, and an acquisition and playback system for both instruments. The head and torso simulator al-lows for binaural measurements even in low noise environments (inherent noise:16 dB SPL(A)) up to 148 dB SPL. The simulator complies with recommendation ITU-T P.57. The “head and torso” simulator provides geometric and acoustic characteristics according to recommendation ITU-T P.58 and thus replicates all acoustically relevant structures of the human anatomy. The simulator enables measurements in sending and receiving directions. While the ear simulators of the artificial head simulate the receiving direction, a two-way mouth loudspeaker reproduces the complete spectrum of the hu-man voice (ITU-T P.58).


a)

b)

Fig. 6. “Head and torso” simulator with artificial ears and mouth (a) and sound level meter and analyser (b).

2.3 The complementary role of computer simulations

In the PM&VL, three types of computer simulations are used to support and enlarge the applicability of the experimental findings, namely building performance simulation, component-level simulations, and indoor environmental modelling. The first type is typically used to evaluate the performance (energy, thermal comfort, indoor air quality, etc.) of a building of its relevant portion over a certain period of time such as one year or a season of particular interest. Software such as Trnsys and EnergyPlus are used for this purpose. These simulations usually require a limited computational power to simulate long periods and complex buildings, but do not enable to capture details that require a finer spatial resolution either within a component or a room. Thus, the other techniques are used to overcome this limitation.

Tools such as Mold Simulator and Delphin are used for heat, moisture, and matter transport in porous building modelling. They enable to study the hygrothermal conditions of façade components in detail to evaluate condensation risks and humidity levels within layers. They allow for 3D models and for choosing a suitable time frame. Radiance is used to perform analyses of daylight availability and glare, annual and point-in-time. Different simulation approaches can be used according to the type of façade technology considered and the indicators to be analysed. Specific bidirectional scattering distribution function (BSDF) based models can be developed for complex shading systems. The distribution of the air within the façade (e.g. for double skin facades) or in-side a building can be simulated by using CFD with tools such as Ansys and Comsol. The latter is a finite element method (FEM) software which enables to model also complex multi-physics problems that often occur in advanced envelope systems. Lastly, Contam is also used for airflow, contaminant concentrations, and personal exposure studies.

3 A case-study application

This section provides an overview of one of the very initial applications of the PM&VL to support the development of an envelope system. In this paper, the focus is on the process followed within the PM&VL, while the detailed performance analysis will be presented at later stages.

The element under evaluation is a prefabricated multifunctional façade system from a major façade manufacturer. It was conceived for integrating different functions and related technological elements (such as building services' components) for easing the achievement of the nZEB target while delivering elevated IEQ to the occupants. This envelope system includes a reversible heat pump, a mechanical ventilation device with heat recovery, and openable windows for natural ventilation which are equipped with actuators for automatic opening and closing and with shading blinds integrated in the glazing unit. The full envelope system is automatically operated according to an algorithm (developed by the façade manufacturer) whose aim is to constantly adapt the façade operation to ensure occupants' thermal, visual, acoustic comfort, and good IAQ.

The path within the PM&VL enabled to evaluate both the intrinsic features (i.e. properties of the element itself) of such a complex system and the performance in terms of comfort level generated by the façade to the occupants.

For this initial case-study application, the "Multifunctional façade lab", the "Façade system interaction lab", human participants, and the thermal manikin were used as described in the following sections.

3.1 Analysis of the intrinsic features of the case-study envelope system

This part of the analysis was performed in the "Multifunctional façade lab" with the aim of studying the performance in terms of operation of the heating/cooling heat pump, the ventilation machine, and the shading system (Figure 7). Surface temperature of potentially critical nodes in which condensation might occur were evaluated. Moreover, the test enabled to compare the values recorded by the façade sensors (i.e. those included by the manufacturer to operate the façade) with those measured by the lab sensors.

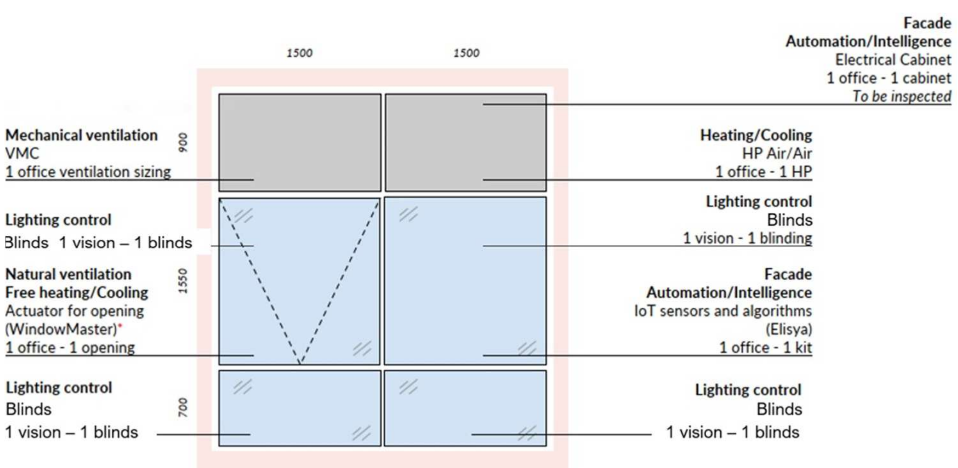

Fig. 7. Scheme of the envelope system tested in the "Multifunctional façade lab".

The façade was tested both in winter and summer conditions. During summer conditions' tests, the solar simulator was oriented towards the opaque components of the façade in which the heat pump and the ventilation machine are located to stress the cooling system in conditions of high external temperature and elevated solar radiation. The sun simulator was never used for winter tests. During all tests, the openable windows were kept close. During summer tests, the temperature in chamber that simulates the outdoor environment was set to 38°C, while in the indoor side either a lower set-point or free-floating conditions were applied depending on the phase of the experimental work. During the winter tests, outdoor temperature down to -12°C were considered to evaluate the condensation risks and the heat pump operation. In general, out-door conditions were defined by using the Meteonorm "10-year extreme" values for Rimini (Italy) where an installation of this façade system is planned at the end of this lab study.

Overall, the test results were positive. Tests under winter conditions highlighted the system's ability to avoid condensation risks although challenges were noted in maintaining setpoint temperatures. In addition, the exhaustive set of thermocouples in-stalled on the façade components did not detect particularly critical temperatures in both winter and summer regimes.

3.2 Performance evaluation with human participants in semi-controlled conditions

The tests in the "Façade system interaction lab" were designed to investigate the effect of the façade to the indoor environmental quality which has been objectively (by performing measurements) and subjectivity (through questionnaires) evaluated.

39 participants were recruited aiming to ensure a reasonable gender balance and age distribution. Only adults (18+) in good self-reported health conditions were in-volved as participants. Before starting the experiment, the experimental protocol went through the relevant ethical approval procedures. Participants received a small compensation for their participation. The tests took place in summer 2023.

Participants filled two complementary questionnaires. The former was designed to assess participant's satisfaction with the IEQ conditions generated by the façade. It was completed two times during an experimental 1-hour session, namely at the beginning and at the end of the session, and it included questions on their IEQ perception (thermal, air quality, ventilation, lighting, acoustic, and global perception). For each environmental domain, perception (e.g. for thermal: hot, warm, etc.), preference (e.g. warmer, cooler, no change, etc.) and acceptability (acceptable, slightly acceptable, etc.) were rated using Likert-type scales. With reference to the overall IEQ, an open question was also included asking the participants what changes they would have done to im-prove the indoor environment. The latter questionnaire was instead designed to acquire demographic information about the participant, and information of their self-reported sensitivity to noise and environmental conditions in general. Questionnaires were made available to participants in English.

Statistical analyses were run in R. Frequency distributions were first calculated to explore the responses (Figure 8 and Figure 9). The presence of differences between the ratings at the beginning and the end of the experimental session were assessed by using non-parametric tests, due to the non-normal distribution of the results. Wilcoxon signed-rank test was used to assess the presence of a median difference between paired observations. Comparing the answers given at the very beginning and at the end of the session, the percentage of participants who reported a neutral thermal sensation in-crease by 18 percentage points, indicating a significant change from a "slightly warm" to a "neutral" perception ($p < 0.001$). Likewise, the percentage of participants wanting to change the thermal environment decreased by the same amount (from 51% to 33%).

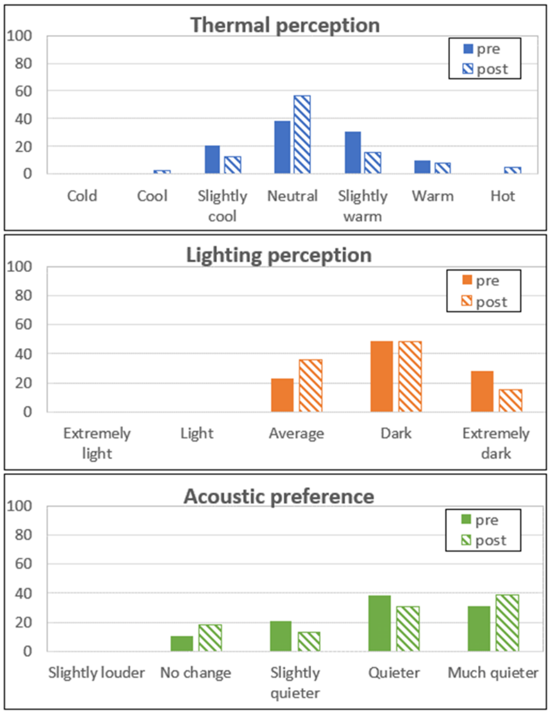

Fig. 8. Results of the questionnaire on the IEQ conditions: thermal, lighting and acoustic aspects.

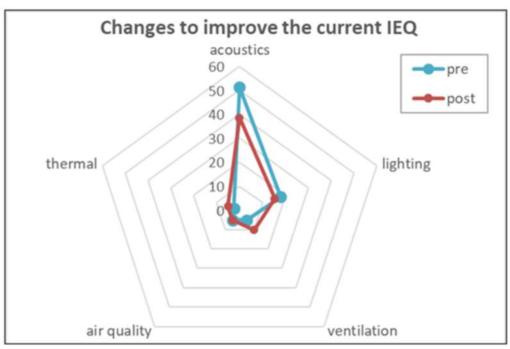

Fig. 9. Results of the questionnaire on the IEQ conditions: percentage of participants who expressed a desire for change.

About IAQ, the participants described the air as "fresh, odourless and humid", with most of them (79.5%) judging it as "slightly polluted", and only 5% of the participants judged the air quality as being "unacceptable on a personal level". At the end of the testing session, the description of the participants considerably changed, the air being described as more "dry" (44%) and "smelly" (31%). The acceptability rating worsened, with the percentage of participants finding the air quality unacceptable increasing to 15%.

Concerning ventilation, no significant changes were found in the ratings of the participants during the experimental session (all ps > 0.05). The ventilation was judged as acceptable by most of the participants, with the unacceptability index changing from 15 to 19%. However, participants clearly expressed a preference for having "more natural ventilation" in the room both at the beginning (60% of the respondents) and at the end (54%)

of the testing session (windows were opened and closed automatically ac-cording to algorithm developed by the façade manufacturer).

Focusing on visual comfort (lighting), participants judged the lighting in the room as "dark" (median value = 1.1; $p < 0.05$), both at the beginning and at the end of the session. No significant difference was found between the two assessments ($p > 0.05$). The frequency of judgments preferring "More natural lighting" was significantly higher than the other categories (beginning: 59% "more natural lightning", 33% "no changes"; end: 49% "more natural lightning", 41% "no changes"). The slight increase in the percentage of participants feeling close to an optimal lighting environment sug-gest a positive impact on the participants perception of the algorithms developed by the manufacturer to control the shading system of the façade.

Concerning the acoustic environment during testing, participants judged it as completely dominated by the sound of ventilation, with a significant increase of more than 10 percentage points in the last part of the session (from 39% to 54%). On aver-age, the participants indicated their preference for a "quieter" or even "much quieter" acoustic environment, with more than 80% of the respondents expressing a preference for change. The percentage of participants judging the acoustic conditions as "unacceptable on a personal level" was over 50% and did not change during the session.

When asked about the acceptability of the overall IEQ (thermal, visual, acoustic and air quality), this was reported as "unacceptable" by 30.8% and 35.8 % of participants at the very beginning and at the end of the session, respectively. Participants clearly highlighted the need for improving the acoustic environment (i.e., reduce the noise emitted by the ventilation system) and the lighting (i.e., increase the amount of natural lighting from the windows).

4 Conclusions

This paper aimed at presenting how a test-chain for a thorough energy demand, in-door occupants' comfort, and behaviour analysis performance has been implement-ed, and providing evidence of the advantages of such a comprehensive test-chain over a single-test approach by using one of its first applications.

After the PM&VL implementation and initial application, the results showed that having a unique and well-connected flow in the development and testing enabled to smoothly feed the output of a certain test (e.g. on intrinsic thermal features) to another one (e.g. tests in semi-controlled but more realistic conditions) ensuring the overall robustness of the output of the entire study and minimizing the uncertainties and unknow aspects. This eases the process of bringing an innovative and potentially high-impact idea to the market as a well-studied (especially when no standard assessment methods for that time of solution were available before) and fully exploited product, and of opening new directions for further development (both technological and in terms of economic exploitation).

Future publications will provide additional details about the evaluation of this envelope system. This includes the use of the thermal manikin to perform a preliminary analysis of the thermal environment and heat exchange processes in the "Façade system interaction lab", CFD simulations to compare multiple indoor configurations starting from a model validated with experimental data, and building energy simulations to evaluate long-term (e.g. annual) energy and average comfort conditions.

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