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HYGROSCOPIC COFFER: Digital parametrization and realization of timber bilayer composites for passive dehumidification in built environments

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ABSTRACT

The integration between renewable materials and passive design strategies for the improvement of the built environment comfort leads to a reduction in energy consumptions and in the use of active HVAC systems. Sustainability concerns the materials employed as well as their performance. Natural materials with embedded responsive properties, for example, respond to specific external stimuli, changing some of their physical or chemical properties. This kind of behaviour can be considered as an additional and innovative advantage in built environments. As biomimicry suggests, it is possible to take advantage of the embedded hygroscopic behaviour of wood to create a hygromorphic composite material that passively reacts to relative humidity variations of the indoor air. These composites are realized with a cross-grained double-layered structure, joining a thicker veneer (active layer) and a thinner one (passive layer), to reproduce the principles that cause pinecone scales to bend after exposure to humidity variations.

The double-layered panels, called “unplywood”, can be digitally parametrized and used as a false ceiling for the passive dehumidification of an indoor environment, using only the convective motion of the humid air and the stack effect. This is particularly useful when the relative humidity increases excessively, exceeding comfort levels.

The result is a passive dehumidification system where the timber panels act as sensors and as decorative architectural elements at the same time and contribute to improving the indoor environment from a hygrometric point of view as well as from a perceptive one.

Keywords: passive hygrometric control, timber composite, natural ventilation, digital parametrization, hygromorphic bilayers

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1. Introduction

Specific energy-saving guidelines have been issued at the European level to pursue energy sustainability, with short, medium, and long-term objectives that have been set with the EU Directive 2018/844. Focusing on Italy, this trend is followed by the ever-increasing diffusion of wooden constructions, characterized by a low environmental impact, which is linked on the one hand to the sustainable management of the Italian forest heritage, and on the other to the awareness of designers and companies deeply linked to reinforced concrete constructions (Buchanan and Levine, 1999; Cabeza et al., 2013). In recent years, Italian research has achieved important results in this sector, which is currently very active internationally (Espinoza et al., 2016); looking for gradual European decarbonization, further research efforts should target the development of the Italian wood chain. These production chains manufacture environmentally sustainable materials that are controlled from production to disposal, obtained through energy-efficient production processes with reduced polluting emissions and characterized by long life and high recyclability (Corona et al., 2017).

Thanks to the prefabrication of the structural elements (such as cross-laminated timber, “XLam”) and the optimization of the construction phases on-site, these wooden structures are characterized by their high speed of construction, compared to traditional ones. The structural elements are factory-made with numerically controlled machines that guarantee extreme precision and compliance with the overall project, thus eliminating the risk of error and avoiding material waste. The subsequent assembly is carried out quickly, thanks to ptimization of the timing and on-site coordination. Platform-frame and XLam structures are also adaptable to various architectural needs and therefore leave the designer full freedom of composition.

The importance of timber structures can be further extended considering the role of wood as a natural smart material (Ugolev, 2014): its hygroscopic behaviour makes it responsive to relative humidity variations. It is known that wood constantly tries to reach hygroscopic equilibrium with the surrounding environment, which results in swelling and shrinking (Giordano, 1981). Despite being one of the oldest materials used by man, this responsive behaviour makes it comparable to the most modern and sophisticated intelligent materials, with the advantage that wood has a reduced cost and low environmental impact. Renewable materials and passive design strategies can be used together for the improvement comfort in the built environment (Omrany and Marsono, 2016), reducing the necessity to use active HVAC systems (Rodriguez-Ubinas et al., 2014).

Biomimicry can suggest strategies and be a source of inspiration for solving many problems (Benyus, 1997; Pawlyn, 2011). An interesting example is presented by pinecones. When they are subjected to relative humidity variations, their scales react like sensors, closing if the level of humidity increases and opening if it decreases, to avoid a short distance dispersion of the seeds caused by rain. The bilayer structure of the scales makes them bend: the scales are composed of two different tissues, which absorb/expel water when relative humidity increases/decreases, respectively. While the active layer, which has a higher coefficient of hygroscopic expansion, reacts very strongly to the moisture gradient, the passive layer, with a lower coefficient, is less responsive, so the scale bends instead of expanding linearly (Dawson et al., 1997). Based on the example of the structure of pinecones, a bilayer composite can be realized using a hygroscopic material as active layer and a non-hygroscopic material as passive layer (Reyssat and Mahadevan, 2009). An entirely wood-made hygromorphic panel (Holstov et al., 2015a) (Fig. 1), can exhibit the same behaviour, bending when subjected to humidity variations if the layers are cross-grained (the tangential direction of the active layer corresponds to the longitudinal one of the passive layer, which is almost non-reactive to humidity) (Menges and Reichert, 2012; Wood et al., 2018). The exploitation of the intrinsic properties of materials can lead to a re-evaluation of what is commonly considered a defect to be corrected before subjecting the material to any processing aimed at the construction sector (as in the case of the hygroscopic behaviour of wood). This strategy has a double advantage: on the one hand, there is are considerable economic and time savings by eliminating the need to correct these behaviours; on the other hand, these can be positively used, for example, to create complex geometries that would otherwise require long and expensive processing, simply by supporting the material in the environmental conditions in which it manifests these properties (Grönquist et al., 2019).

This paper presents a case study of a timber test room made with wall stratigraphies that are optimized from the energy performance point of view thanks to digital parameterization; "unplywood" panels (Bianconi and Filippucci, 2019) are installed as false ceiling, which acts as sensors in the event of changes in relative humidity and as actuators of natural ventilation to dehumidify the environment.

2. Materials and method

A temporary test room has been built at the Department of Civil and Environmental Engineering of the University of Perugia through the POR FESR 2014-2020 funding of the Regione Umbria (Fig. 1). The test room develops on a single level with a platform-frame structure of about 20 m2 and an average height of 2.4 m, which rests on a concrete slab, characterized by three completely opaque walls and a single glazed opening in the south direction. On the roof, approximately 25 m2 of thin-film photovoltaic panels with storage batteries power the heat pump, necessary for cooling and heating, for the simulation of the internal typical winter and summer thermo-hygrometric conditions of a residential environment.

Fig. 1: Pictures of the test room at the Department of Civil and Environmental Engineering of the University of Perugia

2.1 Monitoring the test room

The north-facing wall has been optimized through an algorithm created with Grasshopper for Rhinoceros. The wall is removable, so it can be replaced with other walls characterized by different stratigraphies for testing the energy performance of timber walls, optimized through an algorithm. The aim of this part of the study is the search for the outputs that define the summer and winter behaviour of the wall. The algorithm needs the thermal properties of the materials, the thickness of each layer and the total cost of materials and installation as inputs and returns as outputs the thermal transmittance U, the periodic thermal transmittance Yie, the decrement factor f and the time shift φ, also verifying the absence of interstitial condensation through the Glaser diagram. The optimization process of the stratigraphy was carried out through the Octopus plugin for Grasshopper, which allows the application of evolutionary principles to parametric modelling to optimize specific parameters.

The software, after several iterations, gives as output the walls that simultaneously minimize cost, transmittance and decrement factor, while maximizing time shift and verifying the absence of interstitial condensation. Among about 5000 possible solutions, only those belonging to the Pareto Front have been selected. Through this tool, based on the digital parameterization of the solutions and multi-objective optimization, the designer can analyse and combine large amounts of data obtaining solutions that simultaneously present the best values of the parameters chosen as inputs and return the required outputs.

To monitor the parameters necessary to characterize the performance of the wall, the test room has been equipped with several sensors and instruments.

2.1.1 S.A.L.E. monitoring system

The S (Sistema, System) A (Affidabilità, Reliability) L (Legno, Wood) E (Edilizia, Building) (SALE) monitoring system allows on-site moisture content monitoring, and anomaly detection (i.e., detection of conditions that may accelerate biodegradation). The monitoring is carried out through wireless sensors and software for the collection, storage and management of alarm messages. The sensors are removable and visible (Figs. 2-3).

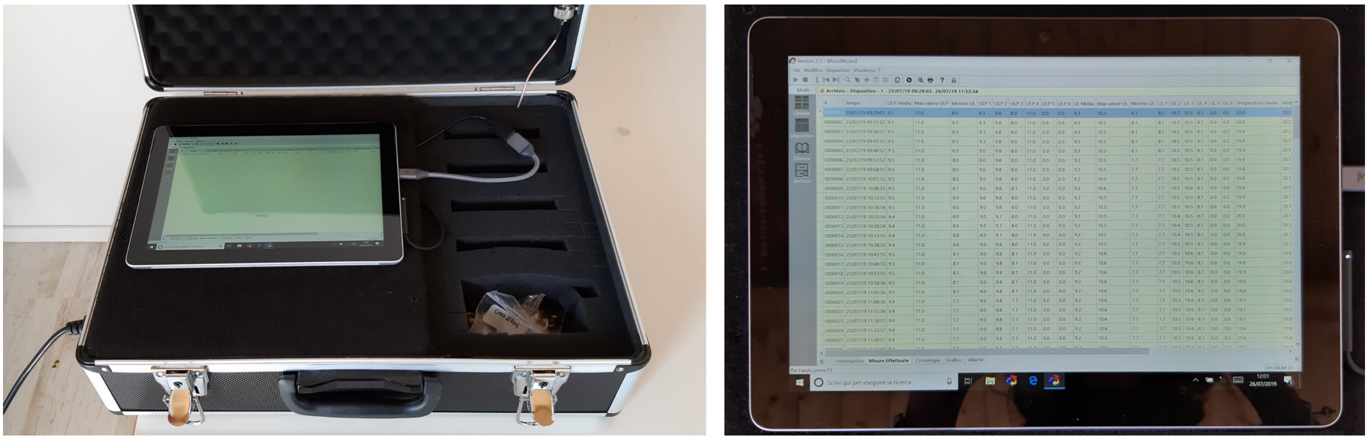

Figure 2: Case with S.A.L.E. monitoring system.

Figure 3: Installation of the wood contact electrodes (left); installation of the wireless sensor on the electrodes (right).

- Thermocouples
  Used for air and wall temperature monitoring, both internally (Fig. 4 left) and externally (Fig. 4 middle).
- Fluxmeters
  Used for measuring the thermal transmittance U of walls (Fig. 4 left).
- Temperature and humidity probes
  Used for measuring temperature and relative humidity of the indoor and outdoor air (Fig. 4 right).

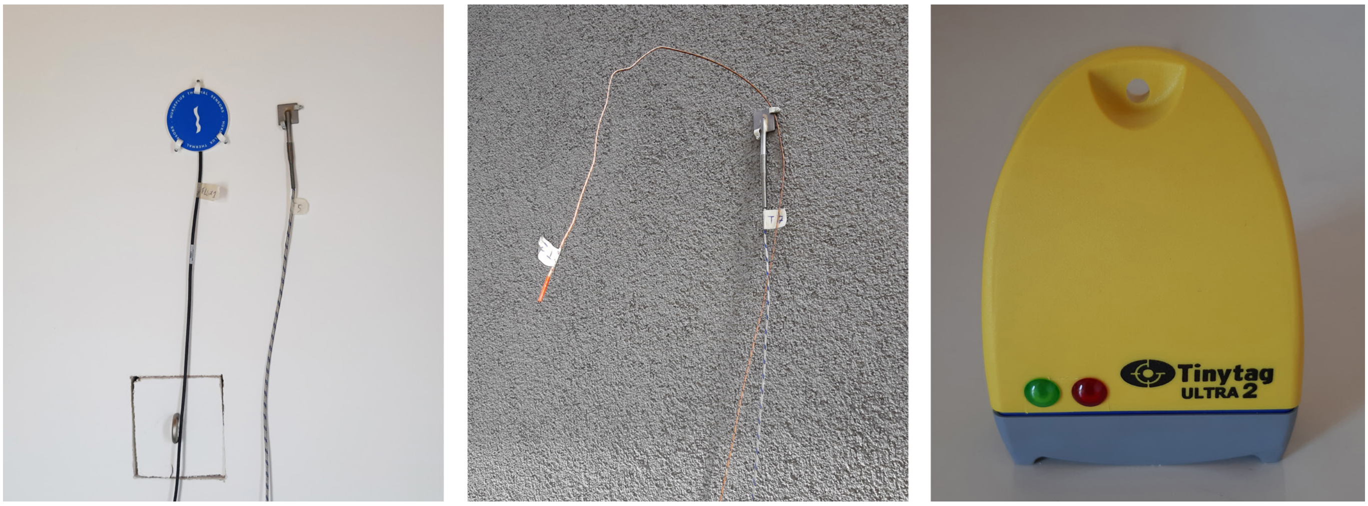

Figure 4: Internal (left) and external (middle) thermocouples and fluxmeter on the north wall; temperature and humidity probe (right).

2.2 "Unplywood" panels

The false ceiling is composed of "unplywood" panels that guarantee a natural ventilation system exploiting the stack effect (Wong and Heryanto, 2004). If the humidity level in the room is such as to cause discomfort to the occupants (Wolkoff and Kjærgaard, 2007), the ceiling panels will open (Fig. 5). Humid air is lighter than dry air and therefore moves towards the false ceiling which, opens up due to the effect of humidity, allows it to pass through an 8 cm gap directly connected to the outside of the building. By exploiting the convective movements of the warm, humid air and the stack effect, there is passive dehumidification of the internal environment without any external energy contribution. Each panel has been fixed to the false ceiling using two aluminium latches, to make it easy to remove for maintenance or to carry out tests on different types of panels (Fig. 6). Anemometers have been inserted in the ventilation cavity to measure the air speed, to characterize the trend of the airflow triggered by the stack effect.

Figure 5: "Unplywood" panel opening during humidity exposure.

Fig. 6: The "unplywood" panels fixed to the false ceiling.

The "unplywood" panels were studied through the curvature change coefficient $f(m,n)$ (1), that depends on the thickness ratio (m) and the stiffness ratio (n) between passive and active layer concerning the responsivity of the composite (Bridgens and Holstov, 2015; Reichert et al., 2015):

$$f(m,n) = \frac{6(1+m)^2}{3(1+m)^2+(1+mn)\left(m^2+\frac{1}{m}\right)} \qquad (1)$$

where,

$$m = \frac{t_p}{t_a}\,,\; n = \frac{E_p}{E_a}$$

where t_p and t_a are the thicknesses and E_p and E_a are the Young's moduli of the passive and active layer, respectively.

2.2.1 Active layer

For the active layer, beech (*Fagus sylvatica* L.) wood was used. Beech has an average density of about 750 kg m-3 (Giordano, 1981) and it shows a microscopic structure characterized by a diffuse porosity and good permeability both in sapwood and heartwood.

All these properties allow the adsorption/desorption of a significant amount of saturation water and a rapid responsiveness time, considering the hygroscopic shrinking coefficients (α) of beech in the radial, longitudinal and tangential directions (Giordano, 1981) are:

$$\alpha_{rad} = 2 \div 9\%$$

$$\alpha_{long} = 0{,}3\%$$

$$\alpha_{tang} = 9 \div 20\%$$

2.2.2 Passive layer

The passive layer must prevent active layer deformations, forcing it to bend. The species is not so important, because the different orientation of the grain in the active and passive layers is primarily responsible for the composite deformation. However, as softwoods usually present higher dimensional stability, spruce (*Picea abies* Karst.) (which also is characterized by low density) was used in some specimens and European larch (*Larix decidua* Mill.) heartwood in others.

2.2.3 Adhesive

As suggested by Rüggeberg & Burgert (Rüggeberg and Burgert, 2015), a monocomponent polyurethane adhesive was used to glue the layers, as it is non-toxic, water-resistant and elastic. The two layers have been conditioned at 40% RH before gluing, to start bending for humidity higher or lower than this value.

2.2.4 Fibre direction

Both active and passive layers are quarter cut veneers oriented according to the wood anatomical directions, as shown in Fig. 7. The dimensions are 10x10 cm and different thicknesses of the active layer were tested (5 mm, 4 mm, 3 mm, and 2.5 mm), while the passive layer is always 0.7 mm thick.

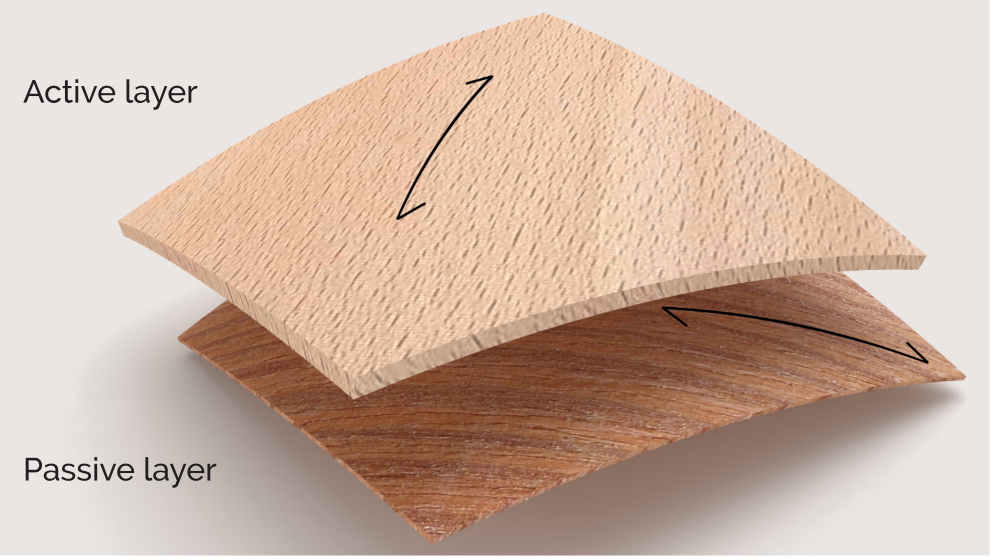

Fig. 7: the cross-grained configuration of the two coupled layers.

We reported a graph that compares the reactions over time of panels with different thicknesses: the experimental data, i.e., the maximum deflections f measured minute by minute, provide the radius of curvature *r* (equation 2.2), the curvature *k* (equation 2.3), and the velocity of curvature *v* (equation 2.4):

$$r = \frac{f}{2} + \frac{l^2}{8f} \tag{2}$$

$$k = \frac{1}{r} \tag{3}$$

$$v = \frac{k}{t} \tag{4}$$

(*l* is the length of the chord between the two contact points of the specimen with the support base, *t* is the time).

Many factors influence the reaction of the panel to humidity variations; the acquired data allowed to find out the following functions (equation 2.5, 2.6) that best approximates the experimental curves, to have the ideal trends:

$$y = a(1 - e^{-bx}) \tag{5}$$

However, the curve fitting has graphically shown a better approximation of the experimental curves if a third parameter, *c*, is added:

$$y = a(1 - e^{-bx^c}) \tag{6}$$

The parameters *a*, *b*, and *c* are specific for each measured specimen. Fig. 8 shows the curve fitting of different specimens in 5 hours exposure to 80% relative humidity. The thinner one (F2L4540) has the best responsiveness. The tested specimens have been named following Table 1: the first letter represents the species used for the active layer, followed by its thickness and the second letter represents the passive layer species. The specimen configuration refers to the orientation of the fibres: 45° means that the fibres are parallel to the diagonal of the square 10x10 cm panel. The last number represents the initial relative humidity corresponding to the flat condition of the panels.

Table 1: The names of the specimens.

F	5	LL	45	40
Active layer species	Active layer thickness	Passive layer species	Specimen configuration	Flat condition RH
F = beech (Fagus sylvatica L.)	5 mm 4 mm 3 mm 2.5 mm	L = larch (*Larix decidua* Mill.) LL = double larch layer A = spruce (*Picea abies* Karst.)	45°	40%

3 Results and discussion

3.1 Thermo-hygrometric indoor comfort

The UNI EN ISO 7730 standard sets the ranges of temperature and relative humidity that must be respected in indoor environments: between 20 and 24 °C in winter and between 23 and 26 °C in summer, while the relative humidity must always range between 30% and 70%.

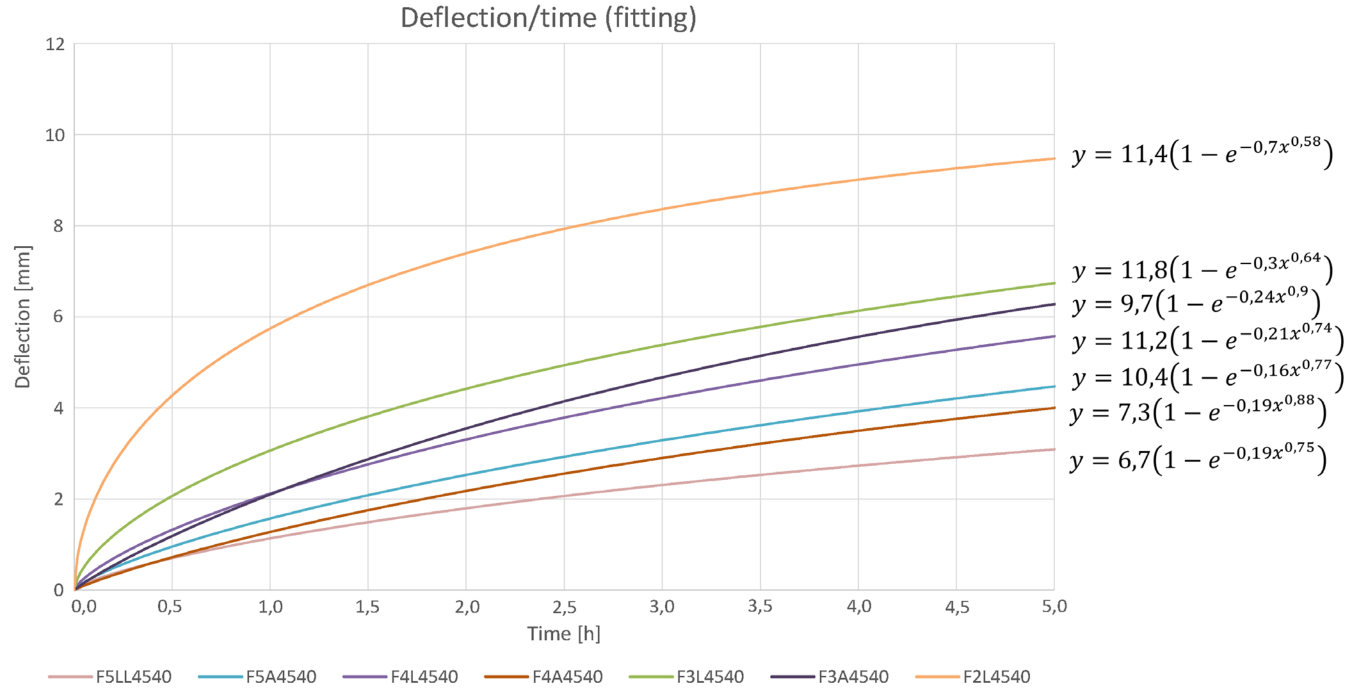

Figure 8: The curve fitting deflection over time of some specimens.

In indoor environments, relative humidity variations are mainly caused by the occupants and by the air change through windows and doors. In a space like the test room, about 50 m3, which can represent any room in a house, it is easy to reach high relative humidity values. In a generic indoor environment, we can consider an air change of 0.5 vol/h: after 1 hour, half the volume of the indoor air will be at initial conditions of temperature and relative humidity, while the other half will be at outdoor air conditions, which infiltrates through the room openings. It is also known that an adult at rest produces 0.05 kg of vapor in 1 hour (Minárová, 2014). Table 2 shows the values related to the vapor produced according to the different activities.

Table 2 indicates that every human activity in a room produces vapor under certain conditions. The test room can be used to simulate those conditions, when the "unplywood" panels installed in the false ceiling would react to the increased humidity and open, allowing the passive dehumidification of the room thanks to the stack effect. Figure 9 shows the range of humidity within which the panels bend, between 40% (flat condition) and 80%, which is a high, but possible, humidity value in a house. Anemometers have been inserted in the ventilation cavity to measure the air speed, to characterize the trend of the airflow triggered by the stack effect

3.2 Transmittance calculation

Through thermocouples and fluxmeters, it was possible to calculate thermal transmittance. Taking into consideration only the north wall and concerning the measurement period 21st- 24th of July, when the temperature gradient remained rather high, wall sensors were considered for the calculation of the in situ transmittance rather than air sensors to obtain the transmittance value with standard convective coefficients. Then the conductivity and the wall transmittance were calculated, considering the standard convection (internal surface resistance = 0.13 m2K/W and external = 0.04 m2K/W). The conductive part is predominant over the convective part since the wall is made up of a large insulating layer (8 cm insulation, 12 cm interposed insulation and 5 cm internal insulation).

Table 2: The vapor production depending on the activity in the room (Minárová, 2014)

Activity of	Vapor production G in kg/h
Adult person – at rest	0.05
brainwork	0.07
light manual work	0.1
hard manual work	0.2
Child under 12 years	0.023
Flaming candle	0.011
Flow heater	6
Boiling water (3L pot)	0.175
Animal (horse or cow)	0.3

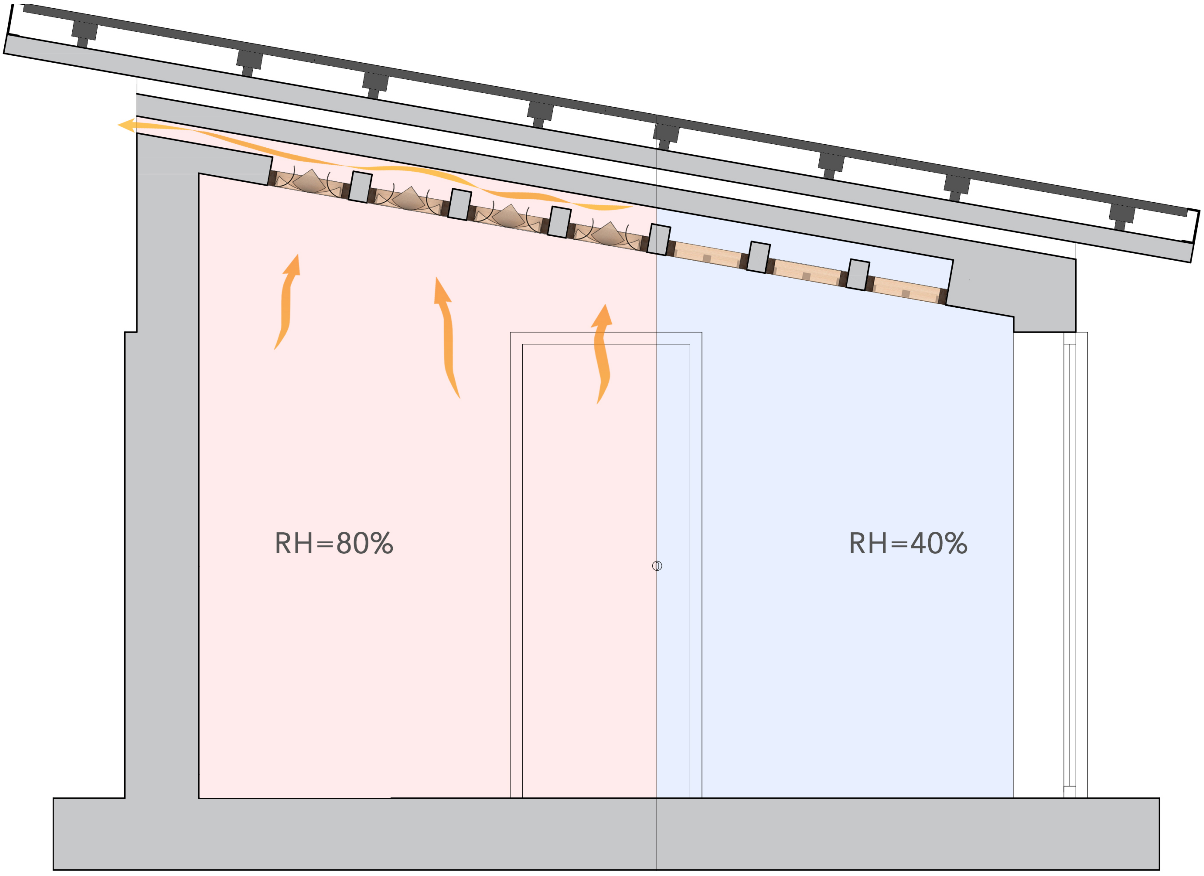

Figure 9: The behaviour of the "unplywood" false ceiling with different relative humidities.

The following parameters have been evaluated for the north wall:

- Thermal resistance: R= 5.233 m2K/W
- Thermal conductance: L= 0.191 W/m2K
- Thermal transmittance: U= 0.185 W/m2K

An error rate of ± 10% shall be added to the transmittance measurement so that it is 0.185± 0.02 W/m2K.

The in situ measured transmittance is, therefore, greater than that calculated by the algorithm, equal to 0.131 W/m2K. Considering the 10% uncertainty percentage of the direct measurement, due to multiple factors, as well as the fact that the declared values of the thermal conductivities of the insulating materials also present percentages of variability, one can conclude that the real behaviour reflects quite exactly that obtained from the simulations.

4 Conclusions

This paper presented an example of sustainable timber architecture, in which the walls have been optimized through a special algorithm, maximizing energy efficiency and minimizing costs. In the initial part of the research the algorithm has calculated the winter and summer energy parameters of various optimized walls. The selected wall has been then built in the test room and its theoretical transmittance, in particular, has been compared to the measured one of the real walls. Comparing the in situ measurements carried out during the summer period with the expected values obtained from the simulation and applying the necessary corrections, considering also the summer season and the difference between the conductivities of the declared materials and the actual ones, one can say that the simulation is quite reliable.

At the same time, previously defined panels are inserted in the test room, which, thanks to their embedded responsiveness, constitute a passive hygrometric control system that varies its configuration to respond to changes in relative humidity of the surrounding environment, allowing dehumidification through the stack effect. The long-term behaviour of the panels should be studied in future developments; in the short term their responsive behaviour is completely reversible during humidification/dehumidification cycles. No cracks or detachments between the layers occur if the gluing has been correctly done. This represents a further advantage, since the maintenance of the system should be easy and inexpensive. These low-cost and low-tech panels are, therefore, at the level of the most technologically advanced smart materials since they act independently and can be programmed to react differently according to needs.

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