Monitoring and thermal performance evaluation of two building envelope solutions in an apartment building

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Abstract. A bio-based multi-layer building envelope assembly has been developed for its integration in newly built and retrofitted buildings. Forest-based materials and biocomposite profiles are used as an alternative to fossil-based insulants and metallic framing, providing a well-insulated and low-thermal-bridge technical solution. The wall assembly has been installed as the external envelope of one apartment of a housing block in Donostia-San Sebastián (Basque Country, Spain). A comparative study has been performed for the bio-based wall and the reference wall of the building. Their in-situ thermal resistance has been obtained by means of three different methods: (1) the steady-state average method, (2) a semi-dynamic method from heat balance at the internal surface, and (3) a dynamic multiple regression method. Reasonably consistent results have been obtained with the three methods: a discussion is provided on the influence of measuring periods and boundary conditions. Outputs from this experimental campaign are valuable as a counterpoint to desktop studies and tests under controlled laboratory conditions. Learnings and outputs from the present study should contribute to a better understanding of the in-situ performance of building envelope assemblies and their assessment methods.

1 Introduction

The global awareness of a climate emergency has highlighted the pressing need for reducing greenhouse gas emissions. It is widely recognised that a clean energy transition is needed and that buildings have a key role to play. Buildings are currently responsible of 36% of global energy use and 40% of associated greenhouse gas emissions [1]. Most of the building-related energy is consumed during operation phase for heating, cooling, ventilation, lighting, appliances, etc. The remainder (ranging from 10 to 30% according to different sources [1, 2]) relates to material manufacturing, construction and demolition.

The Intergovernmental Panel on Climate Change (IPCC) recognises that the building industry is the sector with the greatest potential for reducing greenhouse gas emissions, with the added advantage that related costs are offset through reduced fuel expenses. The energy intensity of buildings can be reduced by adopting sustainable material choices and achieving better insulation levels, among other interventions.

European building regulations are adopting more stringent requirements for insulation, airtightness and ventilation, targeted at better heat retention. Regulatory values have tightened over recent years and it is expected that they will continue doing so. Regarding embodied carbon of construction materials, little regulation exists and efforts for improvement remain mostly voluntary. However, in recent years, a slow but growing shift can be observed from concrete and steel construction towards bio-based approaches featuring timber structures and natural insulation materials.

In this spirit, a novel multi-layer wall assembly has been developed within the framework of the OSIRYS project [3]. This solution is conceived as an alternative to infill façade assemblies that are common in steel-frame construction, and features innovative biocomposite materials as an alternative to synthetic construction materials and metallic framing systems. The natural origin of such materials also results in increased hygroscopic properties and moisture buffering capacity, which provides advantages in certain applications [4]. The main goal of the bio-based wall assembly is the contribution to reduced greenhouse gas emissions, which is pursued through the sustainable use of natural resources with low environmental impact [5] and the reduction of energy consumption through thermal insulation properties. The latter is the main subject of the present study.

Following an initial full-scale test of a prototype [6], a new residential building has been selected as a pilot case for the installation of the product. In a part of its thermal envelope, the reference wall of the building has been substituted by the bio-based wall. The thermal performance of both the reference and the bio-based wall has been monitored and compared. For this purpose, an experimental campaign has been performed, and data has been recorded and analysed using different methods. The outcomes from this work are presented in this paper.

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2 Case study

A newly built seven-storey social housing apartment block (developed by Visesa, Basque Government) in Donostia-San Sebastián (43.31°N, 1.98°W) has been selected as a case study for demonstrating the application of the bio-based wall in a real environment. The building has a reinforced concrete structure and an external wall featuring both external and internal insulation over a brickwork substrate. A bright-coloured aluminium corrugated sheet is installed as a rear-ventilated cladding, providing the external image of the building (Fig. 1).

The demonstration unit is a two-bedroom apartment located at the south-east corner of the second floor. This apartment has its portion of façade built with the bio-based wall system assessed in this study, and it is externally expressed through a 3D-curved cladding designed by UNStudio and manufactured by Acciona.

Fig. 1. Demonstration building, with the bio-based external envelope enclosing a corner apartment on the second floor.

A monitoring campaign was performed over the demonstration apartment, and a reference apartment was also monitored for comparison purposes. An equivalent flat located directly above the demonstration unit (on the third floor) was selected for reference.

The layering of the reference and bio-based wall assemblies is detailed in Table 1. Both walls feature a cladding finish with a ventilated cavity to the rear. In the reference wall, a rendered and plastered brickwork leaf makes up the wall core, with mineral wool insulation added both externally and internally. An aluminium sheet faces the ventilated cavity, while composite boards with a plasterboard finish and a vapour control layer are installed to the room side. In the bio-based wall, the core element is a prefabricated assembly comprising a biocomposite substructure and pre-cut cork insulation boards sandwiched between a fire-resistant board (directly facing the cavity) and a biopolymer board. Internally, additional cork insulation was installed behind a wall board finish. Considering both external and internal climates, no membranes were deemed necessary for moisture or vapour control in this particular building.

Table 1. Layering of external wall assemblies.

Reference wall (from ext. to int.)	**Bio-based wall** (from ext. to int.)
• Aluminium cladding • Ventilated air cavity • Aluminium sheet • Mineral wool insulation (between metal profiles) • Cement waterproofing • Single wythe brickwork • Gypsum plaster • Mineral wool insulation (between metal profiles) • Vapour control layer • Plasterboard	• Thermoset panel cladding • Ventilated air cavity • Fire-resistant wood-plastic composite panel • Cork insulation (between thermoset biocomposite profiles) • Biopolymer wall board • Cork insulation (between thermoset biocomposite profiles) • Wall board

3 Experimental campaign

The thermal performance of both bio-based and reference wall was monitored in a campaign extending from 25th July to 27th August 2018.

The thermal performance of the walls was monitored in a non-destructive manner using portable equipment. Heat flux readings were taken using Phymeas Type 7 sensors, and Pt100 RTDs were used to measure temperatures. Readings were processed using ALMEMO 2590A data loggers and recorded on SD cards at one-minute intervals.

Heat flux was monitored at room-facing surfaces, and surface temperatures were measured over both wall surfaces facing the room and the ventilated cavity. While the calibration accuracy of heat flux and temperature sensors is estimated at ±5% [7], the total uncertainty of measurements might increase due imperfect thermal contact between surface and sensors, convective perturbations and multidimensional heat flows. To avoid distortion from thermal bridge effects, measurements were taken midway through the projection of the substructure profiles, and a sensible distance was kept from all junctions with windows and intermediate floors. All sensors were placed away from heating sources such as radiators or electronic equipment. A thermographic camera was used to confirm that sensor locations were unaffected by thermal bridges and heating sources, which could be identified through differences in surface temperature. Care was taken to protect all sensors from direct solar radiation through the shading provided by external cladding and window blinds.

In-situ measurements of thermal performance are usually performed in winter, when internal to external temperature differences are highest. In this case, calendar constraints imposed by the project timeline forced a summer measurement campaign. A temperature difference was artificially generated by switching on the heating system of the building and raising the indoor temperature set point up to 35 °C.

Outdoor and indoor ambient conditions were measured with intervals of 5 minutes, using commercial Netatmo weather stations connected to a wi-fi router.

Sensors were hung by strings and located at mid-height of balconies (outdoor) and living rooms (indoor), at positions shaded from direct solar radiation.

Recorded ambient temperature and relative humidity are shown in the time-series plots of Fig. 2. Initially, the apartments took a period of several days to reach the set point temperature. This temperature was maintained for a couple of weeks, except for a short fault in the reference apartment. The heating system was then switched off and the temperature of both apartments decreased gradually. The effect of thermal inertia is evident from the shape of the temperature curve, which resembles an exponential decay. Finally, the heating system was switched on again, raising back indoor temperatures up to the set point. The period of no heating is indicated using vertical dotted lines in Fig. 2 and subsequent figures.

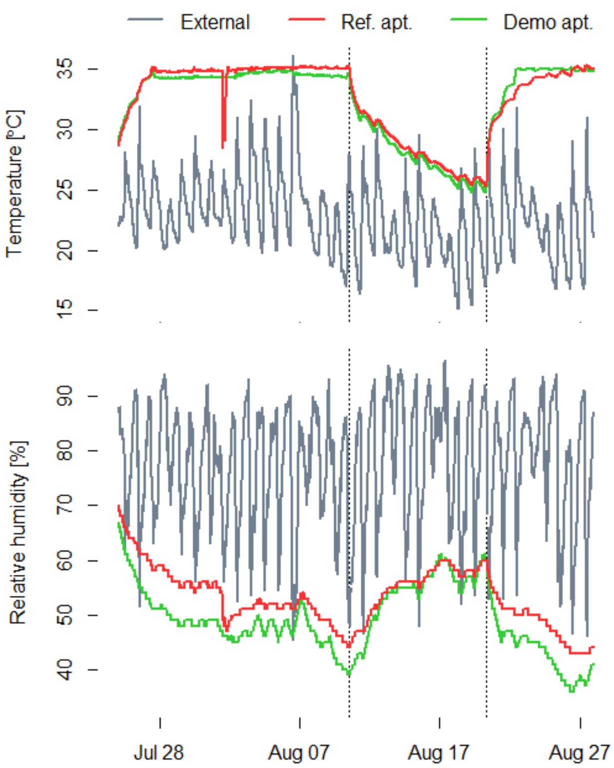

Fig. 2. Ambient indoor and outdoor conditions over the experimental period.

Relative humidity (Fig. 2 bottom) is closely related to temperature (Fig. 2 top). However, while heating is on, relative humidity in the demonstration apartment with the bio-based wall remains consistently below the reference apartment, despite being slightly colder. During the experiment both apartments were unoccupied and facing similar conditions. However, in regular use, indoor ambient conditions are more dependent on occupancy, heating regime and ventilation than they are on the moisture interaction with walls (vapour transmission, moisture absorption and desorption).

The ambient conditions in Fig. 2 are relevant insofar as they provide the context for the thermal performance experiment. However, such measurements have not been used for the data analysis, which has been performed from heat flux and surface temperature measurements.

4 Analysis of thermal performance

The thermal performance of the bio-based and the reference wall has been analysed by means of three different analysis methods, as described below.

4.1. Steady-state method

Firstly, the thermal resistance of the walls has been assessed through the commonly used average method described in ISO 9869-1 [7]. An estimate of thermal resistance R is obtained by dividing the time-aggregated difference in temperature among the internal surface (T_{si}) and the external surface (T_{se}) by the aggregated heat flux through the internal surface (q_{si}).

$$R = \sum (T_{si,t} - T_{se,t}) \,/\, \sum q_{si,t} \qquad (1)$$

This is a steady-state method as it does not consider the thermal inertia of the wall. The principle is that, if temperature differences and heat fluxes at every timestep t are averaged (or simply aggregated as shown in Equation 1) and a sufficiently long time span is considered, the estimate of thermal resistance R tends to converge towards the true thermal resistance. Such an estimation can be considered acceptable if the variation in stored heat (transient part) is sufficiently low compared to the heat passing through the assembly (stationary part). Thus, the required time span for the experiment depends on the indoor-outdoor temperature difference (a stable, elevated temperature difference tends to faster convergence), as well as on the thermal properties of the wall (resistance and storage capacity) which are unknown in principle. The standard [7] lists a set of convergence criteria, based on achieving a certain stability of the estimation of R over time.

The lines in Fig. 3 show the evolution of the estimation of thermal resistance R over time for the two walls assessed. It can be observed that the variation tends to reduce as time goes on, since the total heat passing through the component grows higher and thus the relative influence of stored heat is reduced.

The points in Fig. 3 indicate daily estimates of thermal resistance, corresponding in each case to data measured during the previous 24 h. When indoor conditions are stable and a temperature difference is maintained, the daily value is reasonably close to the final estimate. However, given that heat flux is measured at the internal surface, the thermal resistance R is underestimated while the wall is absorbing heat (corresponding to transient periods at the beginning of heating cycles, see Fig. 2 top). Conversely, R is greatly overestimated when the wall releases heat after heating is switched off (period between dotted lines, see Fig. 2 top). Such values distort the results unless their effect is evened out over time. This highlights the key role of stable boundary conditions in getting a reliable estimate of R with the average method.

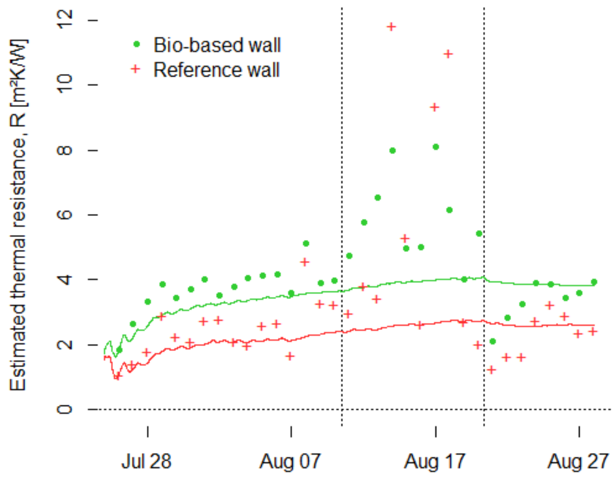

Fig. 3. Thermal resistance estimated using the average method for bio-based and reference wall assemblies: daily averages from 24 h of data (points) vs estimations for whole measuring period from beginning of experiment (lines).

4.2. Semi-dynamic method

A pseudo-transient model is proposed, which assumes that the heat capacity of the wall is concentrated at the internal surface (point of heat flux measurement). Equation 2 expresses an energy balance on the internal surface, where the heat input from the room q_{si} equals the heat flowing through the component (stationary part) plus the heat stored in the heat capacity of the internal surface (transient part).

$$q_{si,t} = R^{-1}\,(T_{si,t} - T_{se,t}) + C_{si}\, dT_{si,t}/dt \qquad (2)$$

R^{-1} (in units of W/m²K) is the thermal conductance, reciprocal of the thermal resistance. Note that C_{si} (despite having units of J/m²K) is not a true estimate of overall heat capacity, as it is only related to internal thermal admittance – external temperature fluctuations do not have any influence over it. It considers the temperature variation at the measurement instant but is not affected by previous temperature history. However, the model can partly explain the influence of internal temperature changes and therefore should converge faster than the simpler steady-state method described before.

The derivative of internal surface temperature over time can be approximated from the difference between the previous and subsequent readings divided by the time interval between these measurements. Equation 2 can then be reformulated as follows:

$$q_{si,t} = R^{-1}\,(T_{si,t} - T_{se,t}) + C_{si}\,(T_{si,t+\Delta t} - T_{si,t-\Delta t})/(2\,\Delta t) \quad (3)$$

Monitored values at each timestep t are available for heat flux q_{si} and surface temperatures T_{si} and T_{se}. Following Equation 3, a linear regression model can be fitted over the measured data, allowing the direct estimation of the parameters R^{-1} and C_{si} and their confidence intervals.

In order to filter out the day-night periodic variation in external temperature (which this semi-dynamic model cannot describe), a time step of Δt = 24 h has been adopted. The model remains sensitive to changes in internal temperature, which in this experiment are much slower than for external temperature (Fig. 2).

The outputs of the proposed semi-dynamic model applied to the experimental data are graphically shown in Fig. 4. Dotted lines indicate the position of the estimated values, while contour lines show the growth of the error (difference between prediction and measurement in q_{si}) as we move away from such estimates. For each of the two walls assessed, the uncertainty is much higher for C_{si} than it is for the thermal resistance R. Comparatively, the reference wall results in greater uncertainty than the bio-based wall. This semi-dynamic method is expected to work better for lightweight assemblies (where the most relevant heat capacity is close to the internal surface) than for internally insulated walls (where most of the heat capacity sits far from the internal surface).

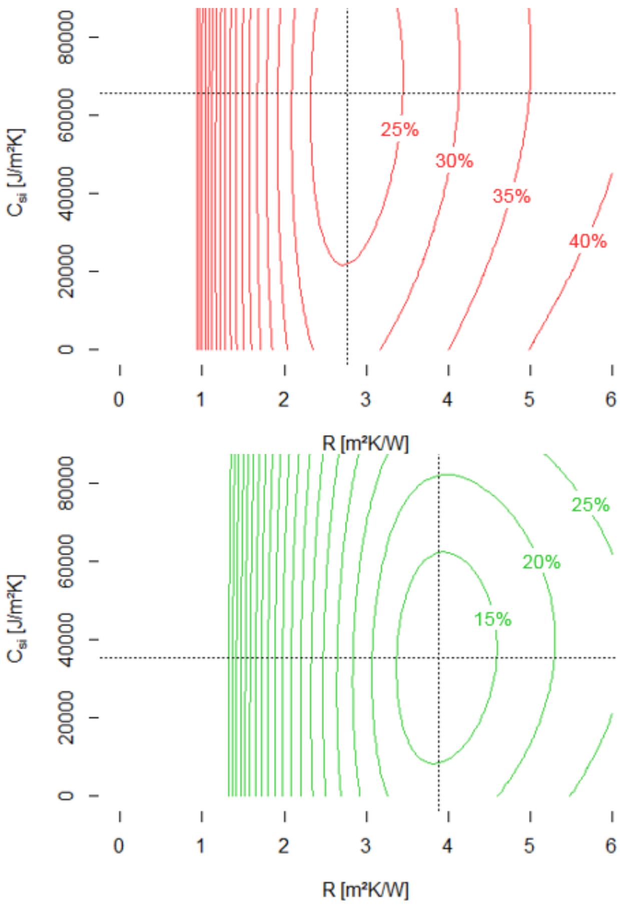

Fig. 4. Estimation of parameters R and C_{si} through semi-dynamic method, for reference wall (top) and bio-based wall (bottom). Dotted lines indicate values with lowest divergence between measurement and prediction. Contour lines plot the root mean square error of the prediction normalised by measured heat flow, CV(RMSE).

4.3. Dynamic method

Finally, a dynamic multiple regression model developed by Anderlind [8] has been applied. In this method, the heat flowing through the wall is split in a stationary part (analogous to the formulation of the semi-dynamic method above) and two transient parts (relative to the history of temperature change over indoor and outdoor surfaces, respectively).

$$q_{si,t} = R^{-1} (T_{si,t} - T_{se,t}) + \sum A_n \Delta T_{si,n} + \sum B_n \Delta T_{se,n} \quad (4)$$

The method can be formulated as shown in Equation 4, where n is a finite number of time intervals. This number is determined by the *influence time* (how far back in time goes the temperature history considered by the model) and the time step chosen. In this case, given the difference in thermal inertia and response time for the two walls, we adopted a time step of 2 h for the bio-based wall and 5 h for the reference wall. In both cases, the influence time has been limited to $n = 5$ time steps.

Coefficients R^{-1}, A_n and B_n can be obtained by multiple linear regression. As noted in [9], this method can be regarded as a more direct alternative to the dynamic method in Annex B of ISO 9869-1 [7]. However, unlike the method in the standard, the parameters in Equation 4 have a direct physical interpretation. The parameter R^{-1} is the thermal conductance (reciprocal of the thermal resistance R), while parameters A_n and B_n contain information on the heat capacity of the wall, describing its transient response to internal and external temperature changes.

5 Results and analysis

5.1. Thermal performance over whole campaign

Table 2 shows estimates of thermal conductance (R^{-1}) through the three different methods applied in this study. Unlike the average (steady-state) method described in ISO 9869-1, the semi-dynamic and dynamic methods in this study can provide an indication of uncertainty. However, given that residuals of time series regressions tend to be serially correlated, standard deviations (shown in brackets within Table 2) should not be understood as the true uncertainty associated with each analysis method.

Table 2. Estimates of thermal conductance and standard errors obtained with the different methods

Method	**Bio-based wall**	**Reference wall**
Steady-state	0.2616 W/m²K	0.3865 W/m²K
Semi-dynamic	0.2574 W/m²K (± 0.0005 W/m²K)	0.3607 W/m²K (± 0.0015 W/m²K)
Dynamic	0.2586 W/m²K (± 0.0017 W/m²K)	0.3637 W/m²K (± 0.0060 W/m²K)

Thermal resistances can be obtained as the reciprocals of thermal conductance values listed in Table 2. These values (in units of m²K/W) are plotted in the chart of Fig. 5. Regardless of the method chosen, the bio-based wall has a higher thermal resistance than the reference wall. The increase in thermal resistance for the bio-based wall compared to the reference wall is estimated at between 40 and 48%, depending on the method chosen.

The steady-state method appears to underestimate thermal resistance, presumably because of the influence of the first days of the experimental campaign when the wall is absorbing heat (Fig. 3). The underestimation is higher for the reference wall, which is the one with the greatest thermal inertia. On the other hand, the semi-dynamic method and the dynamic method give very similar estimates, diverging less than 1% among them.

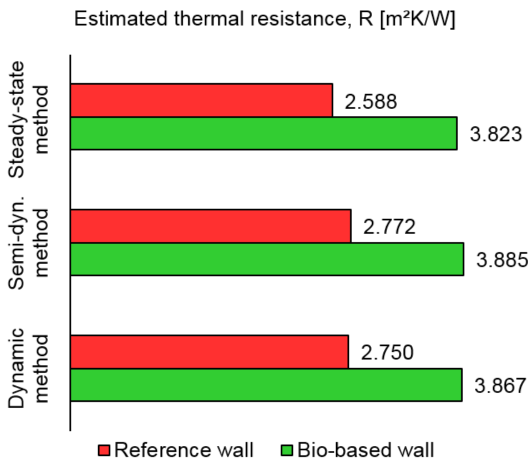

Fig. 5. Estimation of thermal resistance R for reference wall and bio-based wall obtained with the three different methods.

5.2. Comparison of methods for fast campaigns

In-situ thermal resistance measurements for walls often require long measurement campaigns, especially if they are well insulated and/or have high thermal inertia. Faster campaigns are desirable, as they reduce the hassle to potential occupants and allow a more efficient use of equipment. We have compared the performance of the 3 methods described in this paper (steady-state, semi-dynamic and dynamic) over 5-day measuring periods contained within the experimental campaign. For this purpose, 29 overlapping periods have been considered, each taking five full days (from midnight to midnight). This allows tracking the variation in results for each method and the influence of the boundary conditions (Fig. 2 top) in the estimations.

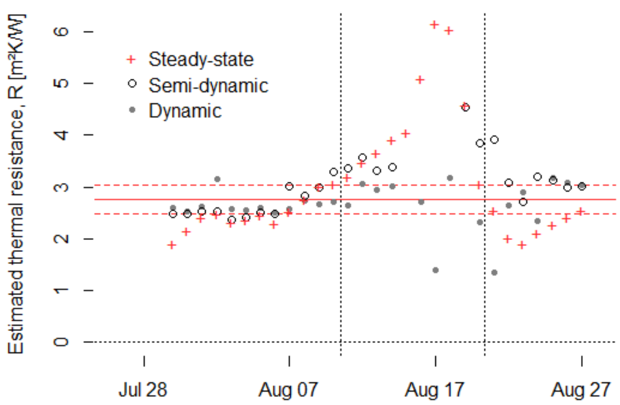

Fig. 6. Estimations of thermal resistance R for reference wall, obtained with the three different methods from 5-day long data.

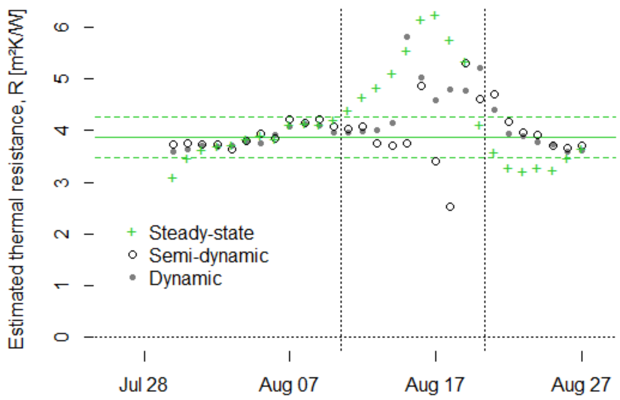

Fig. 7. Estimations of thermal resistance R for bio-based wall, obtained with the three different methods from 5-day long data.

Results are plotted in Figs. 6 and 7. Each point represents the estimation at the end of a 5-day period. Horizontal lines indicate the estimated thermal resistance for the whole campaign from the dynamic method (solid line) and a 10% uncertainty band around this value (dashed lines).

Both the deviation and the bias for each method are quite similar among the two different walls, and thus seem to be more influenced by the boundary conditions than by the specific layering of the wall. For all methods, the most accurate results are achieved after series of stable days with quasi-stationary characteristics (approximating a constant internal temperature and a sinusoidal external temperature with a 24 h period). The steady-state method underestimates thermal resistance while the wall is absorbing heat (initial and final periods in Figs. 6 and 7), and it leads to an overestimation while it is releasing heat (period between vertical dotted lines). The direction of the bias is not so straightforward for the dynamic and the semi-dynamic methods. Generally, estimates from these methods tend to be more accurate than those from the steady-state method. However, reliable estimates could not be obtained in some periods with no indoor heating, particularly for the wall with the highest thermal inertia (Fig. 6).

6 Conclusions

A bio-based lightweight wall assembly has been developed, aimed at promoting the use of natural resources and providing improved insulation properties. This wall assembly was installed as the external envelope of one of the apartments in a newly built housing block. The rest of the external walls of the building were built as per the architects' design (termed *reference wall*), featuring a brickwork core with both external and internal insulation. This paper presents the in-situ monitoring campaign and subsequent data analysis for the comparative thermal performance of both the bio-based wall and the reference wall.

The experimental campaign was performed in summer and lasted approximately one month. Given that thermal properties are better identified if an indoor-outdoor temperature difference exists, the heating system of the building was switched on for two sub-periods within the experiment. Three different methods were used to identify the thermal resistance of the walls: (1) the steady-state method standardised in ISO 9869-1, (2) a newly proposed semi-dynamic method concentrating heat capacity over the internal surface, and (3) a dynamic multiple regression method as described in [8].

Results are reasonably consistent among the three methods. The highest differences are found in the steady-state method, but such deviations can be well explained by heat capacity effects not being considered by the method. Thermal resistance is underestimated if the wall has absorbed heat during the considered period (as is the case for the overall experimental campaign), and it is overestimated while the wall has released heat. The error is somewhat reduced for longer campaigns and for walls of lower heat capacity. In periods of consistently stable conditions (fixed indoor set point temperature and little variation in stored heat), all three methods give reasonably close estimates.

For the two walls assessed (which are quite well insulated), long campaigns are needed to obtain reliable thermal resistance estimates from in-situ monitoring. Shorter campaigns (e.g. 5 days) performed over well-controlled experimental conditions can yield acceptable estimates (uncertainty < 10%) but longer experimental periods are required for better precision. Considering the whole experimental campaign, thermal resistance estimates obtained using the semi-dynamic method and the dynamic method diverge less than 1% among them.

Results from in-situ monitoring indicate that the bio-based wall has a 40% higher thermal resistance than the reference wall. Outputs from this research provide a valuable counterpoint to desktop studies and sample measurements in climatic chambers. While the latter allow for an accurate identification of steady-state thermal performance under controlled conditions, in-situ observation can provide valuable information on dynamic thermal performance under service conditions, as well as the impact of workmanship issues and thermal bridges at junctions [6].

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