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Wood fiber vs synthetic thermal insulation for roofs energy retrofit: a case study in Turin, Italy

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Abstract

In this paper the thermal performance of synthetic and natural insulation materials under real applications are investigated through an experimental activity as well as numerical simulations. During the refurbishment of two houses in Turin (north – west Italy) one roof was insulated with a natural material (wood fiber panels) and the other one with a business as usual synthetic material (XPS and polyurethane). An experimental activity was carried out, both during summer and winter seasons, and the results were used to validate a simplified model. During winter, as expected, the strongest influence on the global performance is related to the insulation thickness. As far as the summer season performance is regarded, for smaller roof surfaces, as for the analysed case study, no particular difference was noticed between the two solutions. A better control of the indoor air temperature was evaluated for the wood fiber insulation when applied on a large surface of the roof. In order to define the best cost-benefit retrofit solutions, ad-hoc evaluations need to be performed.

Keywords: refurbishment, roof insulation; natural vs synthethic; embodied energy; wood fiber

1. Introduction

As it is shown in the state of the art, around the 11% of the building heat transmission occurs through roof top. This building envelope element, in refurbished building, where the attics are converted in residential houses, constitutes the largest dispersing surface. Because its slope, roofs are also responsible of heat gain, assessed around 70%, and associated discomfort problem [1]. Therefore the importance to identify an appropriate materials for the

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retrofit of existing buildings [2,3]. Since design stage the choice of the material for roof insulation, requires specific evaluations, considering the energy performances, as well as technological and economic issues. The performance level required by the standards, as well as the higher commercial value of buildings with low energy consumption, is moving the construction sector to the adoption of new solutions and materials. A high performance level of building envelope and a low energy consumption is a key factor in real estate and a “A Class" energy label is, nowadays, fairly common for the brand new buildings. Moreover, the use of natural material as well as the recycled one represents another highlighted issue and innovation factor driving the real estate market in Italy. This option can be a competitive advantage for designers and construction firms. In this framework, the designers, the construction firms and materials producers are looking for performing and economically sustainable technical solutions. Furthermore, in some cases the peculiarity of the local weather data, makes necessary to evaluate and to design the building envelope both for the winter and the summer season. It is clearly a technological dilemma and a compromise needs to be reached between the passive insulation and the thermal mass. This topic was investigated by means of an experimental activity together with some simulations on two different case studies.

The energy performance of two roofs located in Turin, north western Italy, both with residential use and positioned in a similar environment, was examined. For one case study, it was adopted a natural insulation material: wood fiber and timber fiberboard, with a relatively high specific heat, whilst in the second case study, the roof was insulated with more common materials, i.e. polystyrene and polyurethane panels. In both solutions, the regional standards regarding minimum thermal resistances are fulfilled. The projects are located in Turin (Italy) with hot summer season, from June to the beginning of September, as well as a pretty long and cold winter. A fairly good insulation is required but this environmental profile doesn’t allow a passive strategy following the northern and central European schemes. In other words, the cold climate design issues must be associated with the hot climate design features. Nevertheless, the synthetic based insulation that we can consider as a «business as usual» solution do not presented a satisfactory behavior in summer due to the low thermal capacity of the insulation material. On the contrary high performance standards as required by local regulations can be achieved through the use of the wood fiber for its higher thermal capacity which confer the roof a better thermal performance along the whole year. Moreover, the wood fiber insulation was adopted by the designer to comply with an energy incentive protocol, provided by the local authorities of the City of Turin. The goal is to promote the achievement of thermal comfort during the summer season through the adoption of building envelope solution able to noticeably reduce the use of air conditioning. In this framework the adoption of a high thermal mass material, such as the wood fiber, can theoretically allow a better performance. To give evidence of the better summer behavior of such an option compared to the synthetic insulation, the shift in indoor air temperature was calculated, showing a considerable delay of the indoor temperature peak in regard of the exterior air temperature variations.

This paper discusses the results of an in-field measurement campaign and of related simulations of two real case studies aimed at assessing the actual thermal performances of a synthetic based insulation vs a wood fiber insulation, both adopted as roof-top refurbishment solutions. After the state of the art on the investigated materials, the methodology of the analysis is presented both for the in-field experimental and the simulation activity.

Nomenclature

C*	thermal equivalent conductance [W/m^2K]
EPD	Environmental Product Declaration
E_{24}	daily energy [Wh/m^2]
E_n	normalized daily energy [Wh/m^2]
$E_{n,tot}$	normalized total daily energy [Wh/m^2]
GWP	Global Warming Potential
HDD	Heating Degree Days [°C]
HF	Heat Flux [W/m^2]
I	solar irradiance [W/m^2]
mon	referred to a monitored data
sim	referred to a simulated data
t	temperature [°C]

2. State of the art

Among natural materials, wood fibre panels, or fibreboard panels, are not acknowledged as an innovative insulation material because they have been widely employed in North America since the XXth century. In these countries the wood was commonly used as a building material and indeed the manufacture of fibreboard was fairly inexpensive. Fibreboard can be used in many ways for industrial as well as building purposes. One of the most popular fibreboard material is the MDF, or medium density fibreboard. His density is about 600 kg/m^3 and it can be used for furniture or other industrial use. For insulation purposes, fibreboard panels also called wood fibre, have a lower density, ranging between 50 up to 250 kg/m^3. The thermal conductivity value of this kind of fibreboard, varies between 0.038 W/mK up to 0.042 W/mK. The wood fibre panels characterised by lower thermal conductivity, present almost the same conductivity as synthetic insulation material (i.e. the polystyrene considered in this study), and they have also acoustic insulation property. Furthermore, they show a good vapour permeability and a comparable cost with a good quality synthetic insulation material. But the most interesting advantage in the use of wood fibre is its relatively high thermal capacity.

The main drawback in the application of fibreboard as insulation materials is the vulnerability to the biological attack and the flammability.

It is possible to state that from the literature review the wood fibre is characterised by an interesting behaviour as thermal insulation during cold season, as well as by a good control of the overheating phenomena, in hot seasons. Moreover, from the environmental point of view, the wood fibre is recyclable and made mostly by waste material from the wood products industry. This property makes preferable this type of material instead of the synthetic solution from a sustainable point view. As far as the environmental impacts is concerned, the embodied energy of wood fibre vs synthetic material can be considered quite similar. In order to carry on a correct comparison it was taken into account the different density of materials analysed, i.e. wood fibre, polystyrene and polyurethane, for the functional unit of the environmental assessment, the volume of the materials instead of the density are used. The embodied energy of wood fibres can be estimated [4], and the Environmental Product Declaration (EPD) of similar products made by the same materials, as about 4942 MJ/m^3 [5] whilst the embodied energy of the Extruded polystyrene foam (XPS) panels as about 3236 MJ/m^3 [6] and for the polyurethane panels around 3045 MJ/m^3 [7].

Although the embodied energy of the production process of wood fibre is quite high, in order to evaluate the environmental performances of this material, another issue needs to be consider, as the capability of wood to capture and storage CO_2 over its lifetime. Furthermore, at the end of their lives, wood products can be recycled to produce energy as biomass replacing fossil-fuel energy sources.

Considering thus the use at the end of life of the wood fibre as fuel for energy production the CO_2 balance becomes in favour of the wood fibre panels against the synthetic insulation panels. The mean values of Global Warming Potential (GWP) 100 of the wood fibre panels lifecycle, except of the use phase, is about 110 kgCO_2/m^3, [5] against about 172 kgCO_2/m^3 of the polystyrene.[6] This balance the CO_2 emissions during the production, considering the reuse of waste for power generation and the substitution of fossil fuel.

3. Case studies

Two different residential case studies located in Turin, Italy (45°04’N; 07°42’E) have been experimentally analysed. The weather of the north west of Italy is characterized by a fairly wide range of outside air temperatures through the different seasons and following the Köppen classification Turin climate is in the Humid sub-tropical category.

Both case studies are residential flats in a condominium building, recently refurbished. The two case studies have some common properties, they are both positioned in the attic floor, with a sloping tile roof and with insulation below and both roof gross structure is made of wood beams. The orientation of the roofs is quite the same (south-south west) and the surrounding urban environment is similar, dense urban area. The coordinates for the location of the first roof (case study A) are 45° 04’42.70” N and 7°38’59.80” E, elevation 256 m.a.s.l., the coordinates of the location of the second (case study B) are 45° 03’54.70 N and 7°42’32.03” E, elevation 222 m.a.s.l.. The distance between the two locations is 4.8 km.

Case study A is an historic building recently refurbished in Turin, in order to make the attic of the building liveable. The rooftop of the building was insulated with two different layers of wood fibre for a total thickness of 20 cm as showed in Fig. 1 (left). Case study B, used as the reference building, presented an insulated roof with XPS and polyurethane panels, as represented in Fig. 1 (right). The measurements were carried out with no occupants and the heat emitter was the same, a hot water radiator system, while during summer no plant system was used.

3.1. The rooftop technologies

Technical data sheet of the wood fibre panel declared a thermal conductivity value of 0.038 W/mK for 170 kg/m^3 density and 0.050 W/mK for 250 kg/m^3. Firstly, thermal transmittance and summer dynamic parameters were calculated for the two assemblies following the standards [8,9]. Results of the calculation are shown in Table 1. The calculated thermal transmittance (U-value) for case study A was 0.18 W/m^{2}K and for case study B 0.37 W/m^{2}K. As far as the periodic thermal transmittance (Yie) is concerned a value of 0.04 W/m^{2}K for case study A and 0.40 W/m^{2}K for case B was calculated.

Table 1. Calculated thermal properties of roofs for case study A and B.

	Thickness	U-value	Yie	Φ	F
	[m]	[W/m^{2}K]	[W/m^{2}K]	[h]	[-]
Case study A	0.262	0.18	0.04	14.0	0.20
Case study B	0.112	0.37	0.40	1.5	0.98

For the case study B, as showed by the values of thermal transmittance and periodic thermal transmittance, it is clear that no attenuation of heat fluxes crossing the rooftop is provided. As far as it regards the summer behaviour it is possible to assess that the case study A solution complies with the regulation in force for Region Piedmont being the Y_{ie} lower than 0.12 W/m^{2}K and the time shift greater than 11 hours (reference value in “Allegato Energetico per la Città di Torino”[10]). The same consideration is valid for winter, in case of refurbishment the thermal transmittance limit is lower than the limit value (0.30 W/m^{2}K + 30%) in force during the refurbishment (D.G.R. n. 46-11968, 04/08/2009). It is important to point out that the two roof assemblies presented different thickness. For this reason the experimental results collected in the real application were used to simulate a comparable configuration of rooftop and to evaluate if the difference calculated in Table 1 were measured in the real case studies.

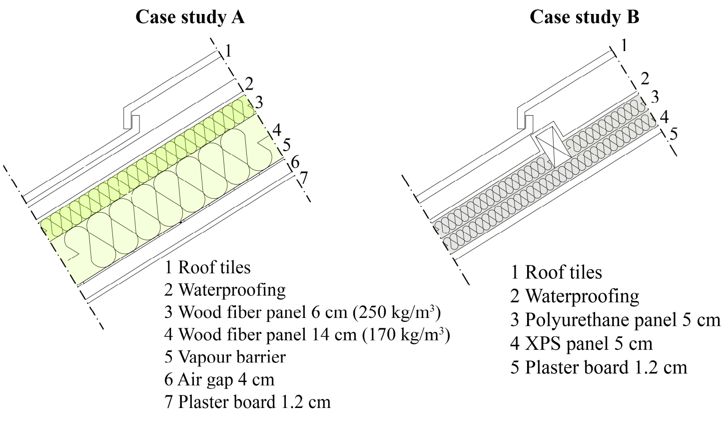

Fig. 1 Schematic section of the two roofs. Case study A (left); Case study B (right).

4. In-field measurement and modelling activity

The research activity was built in two main phases: the in-field measurement activity and the modelling one. The two case studies presented some differences: the type of insulation, natural and synthetic material, the insulation material thickness and the room geometry. For this last reason a direct comparison between the measured data was not possible. The following procedure was thus used: firstly winter results of the monitored activity were analysed in order to characterise experimentally the two technologies, secondly the summer monitored data were used to validate and calibrate a simplified model in order to directly compare the two different insulation materials.

4.1. Experimental set up

A monitoring activity was carried out during summer and winter 2013 to characterise the thermal performance of two real cases studies. The measurement apparatus consisted of temperature sensors and heat flux meters connected to a data-logger that recorded data every 15 minutes. The thermocouples were preliminary calibrated in the laboratory and all the other instruments were previously tested. The measurement accuracy of each thermocouple was assessed according the SIT standards, considering the uncertainties of the reference thermoresistance and of the thermostatic bath used during the calibration. As result of this procedure, the highest likely uncertainty, using the 95% confidence limit, was ±0.3 °C. This value was conservatively adopted for all the thermocouples. Hukseflux HFP01 sensors characterised by thermal resistance lower than 6.25 10-3 m^2K/W were used to measure the heat flux. As declared by the manufactures, their measurement accuracy was ±5 % with a confidence interval of 95 %, while the nominal sensitivity was of about 50 $\mu V/W/m^2$. Before positioning the sensors, an infrared thermal campaign on the investigated roof was conducted. This analysis allowed defining a significant position for the sensors, avoiding thermal bridges and discontinuity of material. Heat flux meters were fastened to the internal side of the two roofs and the thermocouples were placed on the internal surface of the roof, close to the heat flux meter, and on the external side. The external temperature sensor was shaded to direct solar radiation. Indoor and outdoor air temperature were even monitored through thermocouples.

4.2. The methodology of analysis

Data collected during winter season (surface roof temperatures and surface heat fluxes) were elaborated to calculate the equivalent conductance (C* in W/m^2K). The C*-values were calculated applying the progressive average method, to specific heat flux and surface temperature differences, according to equation (1a) [11]. Once the C* values are calculated, both for case study A and B, the internal and external surface resistance (R_{si} and R_{se} in m^2K/W) reported in national standard [12] are added to calculate the equivalent thermal transmittance (U*-value) as shown in equation 1b. Furthermore, the thermal performance characterization of the tested envelope was assessed through the evaluation of daily energy crossing the roof of case study A and B (E_{24} in Wh/m^2). It was calculated as the integral (over the 24 h) of the surface heat flux ($\dot{q}$) in W/m^2 monitored through the heat flux meter (equation 2a). Conventionally a negative heat flux value corresponds to heat loss. Daily normalized energies (E_n in Wh/m^2) were calculated as the integral of the heat fluxes (measured along the day divided the Heating Degree Days (HDD) (Equation 2b). Heating Degree Day were calculated as the difference between indoor and outdoor air temperature following the methodology proposed in [13]. Normalizing the energy makes possible to stem the difference of indoor air temperature registered in the two case studies and it is indeed possible to directly compare the two case studies. With E_n it is indicated the global value of normalized energy over the analysed period.

$$C^* = \frac{\bar{\dot{q}}}{\Delta \bar{t}_s} \quad (1a) \qquad U^* = \frac{1}{R_{si} + 1/C^* + R_{se}} \quad (1b)$$

$$E_{24} = \int_{24}^{00} \dot{q}(\tau)\ d\tau \quad (2a) \qquad E_n = \frac{\int_{24}^{00} \dot{q}(\tau)\ d\tau}{HDD} \quad (2b)$$

4.3. Modelling activity

Starting from the measured data a simplified numerical model applying the UNI 10375:2011 [14] was run. The reason to use a numerical model is to generalize the results collected during the specific experimental activity and to perform a direct comparison between the two case studies (A and B), modelling synthetic and natural solutions with the same thermal transmittance (respectively: B2_sim and A_sim).

The geometry of the case study A with a roof surface of 12 m^2 was implemented in the simplified model. Firstly a validation and a calibration procedure was applied to the simplified model of the case study A. As input, it was used the monitored weather data while the natural ventilation rate and the environmental parameters were varied in order to obtain a good reliability between the indoor air monitored values and the simulated ones.

A fictitious rooftop assembly, named B2, with the same thermal transmittance of the case study A was modelled in order to do a direct comparison between natural and synthetic insulation material. In detail three roofs were modelled:

- A_sim, an assembly with the same properties of the case study A roof (view data in Table 1),
- B_sim, an assembly with the same properties of the case study B roof (view data in Table 1),
- B2_sim, as the previous assembly but with a thermal transmittance equal to the one of the case study A. Both the thickness of the polyurethane and XPS panels were increased up to 10 cm each.

After comparing the wood fibre vs synthetic insulation material another variable was investigated: the influence of the roof surface on the global performance, considering the ratio between surface occupied by the roof top and the other surfaces contributing to the energy balance of the environment (in this case quite massive). The dimensions of the roof were thus increased of 10 time (from 12 m^2 to 120 m^2) in order to evaluate the influence of the roof insulation material when predominant with respect to the other surfaces.

Table 2. Modelling activity.

	Thickness [m]	U-value [W/m^2K]	Yie [W/m^2K]	ϕ [h]
A_sim assembly	0.262	0.18	0.04	14
B_sim assembly	0.112	0.37	0.40	1.5
B2_sim assembly	0.222	0.18	0.16	3.8

5. Results and discussion

5.1. Winter results

During winter, both the case study A and B, were contemporary monitored for one week. The selected days presented typical winter season boundary condition; minimum outdoor air temperature registered was 0 °C while the maximum was 11.6 °C, with an average daily external air temperature varying between 2.4 °C and 6.1°C. The indoor air temperature for case study A was maintained by the plant system around an average daily value of 22°C and small fluctuations of temperature were monitored during the day. Case study B did not present a well-controlled indoor air temperature and during the analysed days, since the temperature fluctuated greater than the case study A. In any case, the average daily temperature value calculated for the two case studies were around 20.4 and 22.6 °C. Generally, the temperatures registered in case study A were slightly higher than the ones of case study B as shown in Table 3.

In order to characterize the two roofs structure the equivalent thermal conductance values are calculated through average method shown in equation 1. In Fig. 2 the trend of the equivalent C* values is shown. The values of the parameters tend to stabilize after the first days. Final values of C* calculated for case study A was 0.16 W/m^2K with a standard deviation of 0.02 W/m^2K while for case study B was 0.39 W/m^2K with a standard deviation of 0.03 W/m^2K. As predictable, the value calculated for the case study A is lower than the conductance value (C*) of the case study B, hence roof B presents a higher propensity to heat transmission (Fig. 2). Adding the standard internal and external surface resistance [3] to the calculated equivalent thermal conductance it was possible to evaluate the thermal transmittances of 0.17 W/m^2K and 0.37 W/m^2K respectively for case study A and B. The calculated results are in line with the calculated values, presented in Table 1.

Daily energy values crossing the two roofs were reported in Table 3. Negative energy values were calculated for the two case studies and during the whole period of analysis, meaning that heat losses occurred through both roofs. As expected, the energy crossing the roof of the case study B was always higher than the values calculated for case study A, being the thermal transmittance value of the case study A lower. A reduction in terms of energy crossing (E_{24}) was evaluated around 41% and 54% for the roof A when compared to roof B. Daily energy values were around -80 Wh/m^2 for case study A and between -130 and -140 Wh/m^2 for case study B. The daily energy performance registered during the monitoring period, presented a repeated behaviour for both case studies, confirming the validity and repeatability of the measurement. In order to deepen the analysis, normalized energy (E_n) were calculated following equation 3. Heating degree day (HDD) calculated for case study B were lower than the value of case study A, due to the lower indoor air temperature in case study B. Globally the normalized energy value $E_{n,tot}$ calculated for case study A was -0.98 Wh/m^2 against -1.76 Wh/m^2 of the case study B, confirming the behaviour evaluated for daily energy.

Table 3. Winter boundary condition, daily energy for case study A and B (E_{24}).

	Daily average temperature				
	t out [°C]	t int A [°C]	t int B [°C]	E_{24} A [Wh/m^2]	E_{24}B [Wh/m^2]
20/02/2013	6.2	22.5	21.8	-57.4	-123.9
21/02/2013	4.5	22.6	21.7	-58.2	-115.2
22/02/2013	2.5	22.4	20.5	-77.6	-131.4
23/02/2013	2.5	22.2	22.1	-77.6	-139.7
24/02/2013	2.4	22.0	21.3	-80.5	-137.3

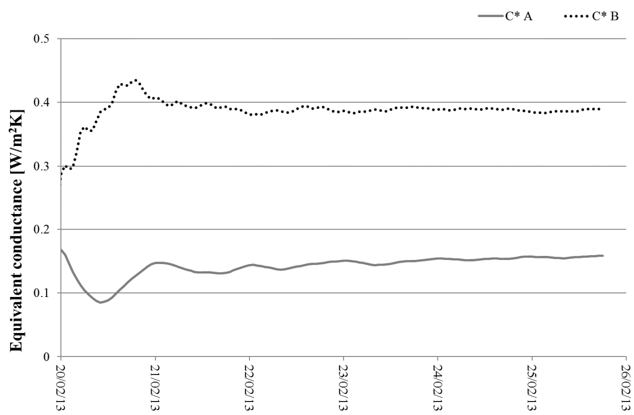

Fig. 2 Equivalent thermal conductance for case study A and B.

5.2. Summer results

The monitored data of the case study A, rooftop refurbished with wood fibre insulation (roof U-value=0.18 W/m^{2}K), were used to validate and calibrate a simplified model. The calibration was carried out for one representative summer day (6th of July). During this day the boundary conditions showed an average outdoor temperature of 29.2°C, a minimum of 23.4°C and a maximum of 36 °C (Fig. 3 left). The indoor air temperature was not controlled by a plant system and the average indoor air temperature registered for case study A was 29.4 °C.

In Fig. 3 right, the comparison between the monitored indoor air temperature and the simulated one are plotted. It is possible to notice a good reliability between the simulation results and the measured data with a maximum difference of 0.2°C.

Once the model was validated, the simulation tool was run with the three different assemblies (represented in Table 2). As shown in Fig. 4, the application of the wood fibre insulation material presented a slightly better performance than the synthetic solution but no relevant differences between the natural insulation material (A - wood fibre) and the synthetic solution (B2) with the same thermal transmittance (U-value=0.18W/m^{2}K), were observed. The same consideration can be outlined also comparing different thermal transmittance values i.e. in the comparison between the natural insulation material (A) and the rooftop with the assembly B. Moreover no differences concerning the time shift resulted for the natural solution when compared to the synthetic one. The main reason is due to the fact that the rooftop surface covers only the 18% of the building envelope and that the rest of the building envelope presents a high level of thermal mass.

For these reasons the surface of the roof was increased of ten times in order to become the driving force in the energy balance of the modelled room. Results are reported in Fig. 4 (right graph). Increasing the exposed surface, the influence of the massive insulation (wood fibre panels) on the indoor air temperature profile can be noticed. In this case it is evident that the largest difference is revealed between synthetic insulation material (B) and natural material (A) with different thermal transmittance. The solution B presents the peak of the indoor temperature around 16:00 when the outdoor boundary condition do not permit free cooling through natural ventilation. As expected results show a drastic improvement of performance at the increasing of insulation thickness (B vs B2).

Comparing the two assemblies with the same thermal transmittance (Fig. 4, right), A and B2, smaller fluctuations of the indoor air temperature are calculated for the natural solution (A) compared to the synthetic one (B2). The peak indoor air temperature reached with the synthetic insulation material (B2) is higher of 0.8°C than the wood based solution (A) and it is reached around 18:00 while for case study A two hours later (around 20:00).

To wrap up, for the geometry of the case study A, the refurbishment with a natural insulation material for the rooftop would not be the turning point for the indoor air temperature control in a free floating condition but for larger roof surface the results are significantly different and the application of a wood based material could significantly improve the indoor thermal comfort.

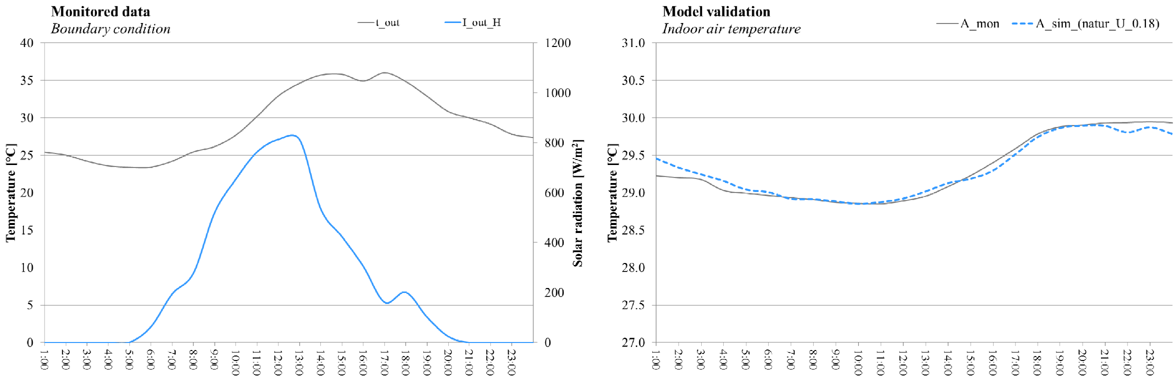

Fig. 3 Boundary condition (left) and model validation, case study A, comparison between modelled and measured indoor air temperature (right).

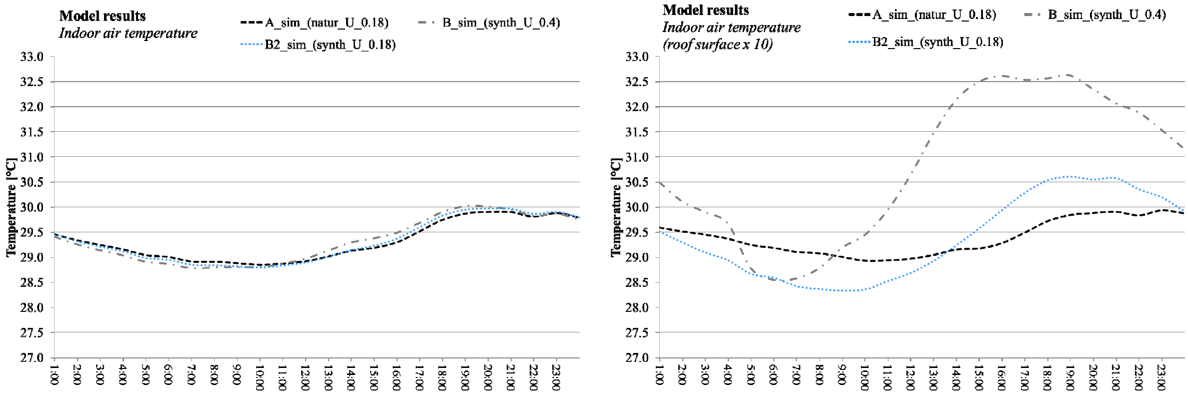

Fig. 4 Model results comparison between natural and synthetic insulation material for rooftop (left) and for a roof surface 10 time greater (right).

6. Conclusion

In this work the thermal behaviour of two solutions adopted for the energy refurbishment of a roof-top, one adopting a massive natural material and the other a lightweight synthetic insulation material, is investigated.

In order to choice the most cost effective insulation material, different aspects need to be investigated, according to the case study location: the thermal performances both for heating and cooling seasons, the construction costs, the operating costs, as well as the environmental compatibility issues.

This topic was faced from a technological and building physics point of view. Two case studies were analysed through an experimental activity in order to evaluate the thermal performances of two different solutions: one a business as usual and the other one a wood fibre based thermal insulation solution. The two tested technologies were characterized by means of experimental data and a good agreement was found between measured and calculated values. The winter experimental campaign results are used to verify the thermal properties of the two roofs. An equivalent thermal transmittance of 0.17 W/m^{2}K and 0.37 W/m^{2}K, are respectively calculated, for case study A and B. The daily energy performance registered during the monitoring period, presented a repeated behaviour for both case studies, confirming the validity and repeatability of the measurement.

For summer condition the simulation results revealed no particular difference between the two solutions when the intervention concerns small surfaces in relation to the other surfaces.

On the contrary for larger surfaces refurbished, a more constant indoor air temperature, with a reduction of the maximum temperature up to 0.8°C and a time shift of two hours, was calculated for the wood fiber based insulation. To explain the relatively tiny difference in the two solutions we can point out that the indoor air temperature curve is influenced by the whole thermal mass of the building. In the case of building with the synthetic insulation we have to take into account the relatively bigger thermal mass per floor surface unit if compared with the wood fiber roof. Such an observation can explain the slight difference in summer performances between the two cases when a much larger difference was expected.

In addition when comparing the two solutions we have to consider not only the thermal resistance and the operational energy but also the environmental impact of the materials and the related embodied energy. Indeed, although the two insulations show a quite similar thermal behavior in the winter season as well as in the summertime, it has to be considered the smaller carbon footprint of the wood fiber. As a general conclusion it is thus important to stress that no recipes can be used when facing an energy retrofit but ad-hoc multi-disciplinary considerations need to be done in order to choose the most cost effective solution, in financial terms as well as environmental.

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