Innovative Systems for Energy Efficient Building Envelopes
Applications at middle latitudes (temperate/mesothermal climates)

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ABSTRACT: This research intends to verify the thermal performance of innovative lightweight building envelope systems using dry construction techniques that were originally developed in continental climates (e.g. Central Europe), and to test their potential application in office buildings at middle latitudes (e.g. Southern Europe), using thermodynamic simulations. Their energy performance in use (annual, winter and summer) was evaluated in three Italian climate zones and possible problems were identified. As a result a proposal for improving the analyzed building envelope was developed, energy performance in use of the optimized building envelope was verified and design criteria for the applications in building at middle latitude were derived.
Keywords: building envelope, thermal comfort, thermal inertia, dry construction, mesothermal climates.

INTRODUCTION
Considering the building envelope as a dynamic interface between the surrounding and the internal environment, , its primary role is to contribute to guarantee internal comfort, whilst limiting the use of non renewable energy sources. As a result, this research has identified a number of building envelope systems that can be assembled off-site and combine their lightweight structure with a high energy performance [1], particularly with respect to reduced thermal transmittance and increased thermal inertia. Following a detailed analysis of the products that have been developed in Central Europe in recent years, three groups of innovative products - not yet available or applied in Southern Europe (middle latitudes) - have been identified with respect to satisfying those needs / requirements: VIP (Vacuum Insulation Panels), TIM (Transparent Insulation Materials) and PCM (Phase Changing Materials). These products in fact show interesting energetic characteristics, which are difficult to be found in other materials used in the construction of building envelopes across Southern Europe:
- VIP can combine a high thermal resistance with an extremely reduced weight and thickness, due to their evacuated condition [2];
- TIM also feature a high thermal resistance combined with reduced weight and thickness. If attached to an opaque wall, they can greatly increase its thermal storage capacity [3];
- PCM can greatly increase the thermal inertia of a non-massive structure due to their capacity of changing phase.

CASE STUDIES AND BUILDING ENVELOPES
With the intention to evaluate the applicability of those products in Southern Europe, a number of existing central European buildings, characterised by the use of VIP, TIM or PCM, were selected. As a result of the analysis of their performance (monitored for at least one year), the buildings identified to be particularly innovative and energy efficient are:
- a single family house (Fig. 1-2) in Neumarkt (Germany) using VIP. The house with its longitudinal axis in east-west orientation is characterized by a highly insulated northern facade and metal balconies at its southern side. The balconies provide sun protection during summer and are not attached to the structure of the house in order to prevent thermal bridges;
- an office building (Fig. 3-4) in Erfurt (Germany) using cellulose honeycomb TIM. This project is an energetic retrofit of an already existing 6 floor building. The load-bearing structure of beams and columns in reinforced concrete was kept, whereas the building envelope was completely substituted within only three months;
- the “Haus der Gegenwart” (Fig. 5-6) in Munich (Germany), using gypsum panel with PCM . The house is a prototype for “current” collective housing, developed during a competition. The private rooms are located at the ground floor with independent access ways. The common rooms are located on the first floor, where the building envelope was analyzed.

Figure 1: Case study 1 - single family house in Neumarkt (Germany), using VIP. Image by:Variotec.

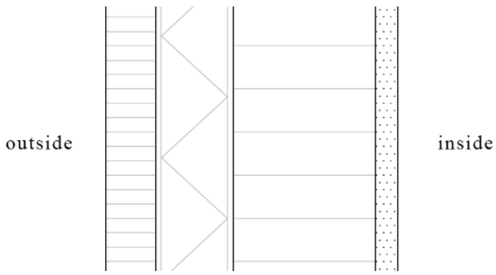

Figure 2: Case study 1 - section of envelope type 1, scale 1:5.

Table 1: Case study 1 - technical data of envelope type 1 (VIP).

	s [m]	λ [W/mK]	ρ [kg/m^3]	R [m^{2}k/W]	C J/k gK
h_e				0,043	
plywood panel	0,033	0,130	450	0,254	1610
sandwich panel QASA with VIP- (manufacturer: Variotec)	0,051	0,010	200	5,100	1050
gluelam	0,094	0,130	500	0,723	1610
gypsum panel	0,015	0,350	1200	0,043	1010
h_i				0,123	

Figure 3: Case study 2 - office building in Erfurt (Germany). using TIM made of cellulose. Image by: Nicole Winter.

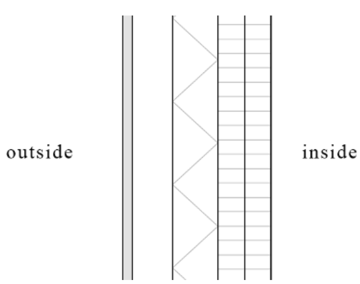

Figure 4: Case study 2 - section of envelope type 2, scale 1:5.

Table 2: Case study 2 – technical data of envelope type 2 (TIM).

	s [m]	λ [W/mK]	ρ [kg/m^3]	R [m^{2}k/ W]	c J/k gK
h_e				0,043	
low-energy glass	0,006	1,000	250	0,006	2500
air space	0,027	1,730	0	0,156	
TIM in cellulose honeycomb (manufacturer: Gap-solution)	0,030	0,080	96	0,375	2340
2 wood panels “Pavatex”	0,036	0,016	240	2,250	2100
h_i				0,123	

Figure 5: Case study 3 - “Haus der Gegenwart” (Fig. 3) in Munich (Germany), using PCM. Image by:Florian Holzherr.

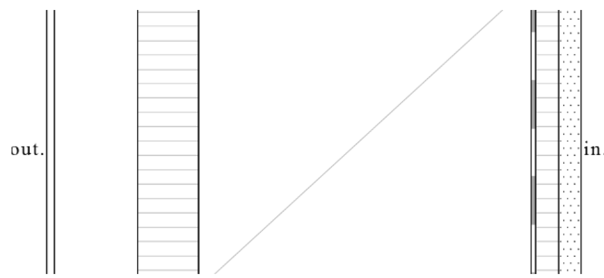

Figure 6: Case study 3 - section of envelope type 3, scale 1:5.

Table 3: Case study 3 – technical data of envelope type 3 (PCM).

	s [m]	λ [W/mK]	ρ [kg/m^3]	R [m^{2}k/W]	C J/k gK
h_e				0,043	
galvanized steel sheet	0,005	50	7800	0,0001	450
air space	0,055	1,730	0	0,156	
multilayer wood panel	0,85	0,150	550	0,566	1660
insulation panel	0,040	0,130	650	3,076	650
moisture barrier	0,005	0,500	980	0,001	980
oriented strand board	0,015	0,130	450	0,1154	770
2 PCM heat storage gypsum panels (manufacturer:BASF)	0,030	0,196	770	0,1531	dependent on temperature
h_i				0,123	

Other than their innovative energy efficient light dry construction envelope (Tables 1, 2 and 3), the three selected buildings share an energy concept that considers the building as a unitary thermodynamic system [4]. The energy performance of each building depends not only on the envelope but also on all aspects of decisions made during the design / planning process at different scales and planning phases: orientation towards cardinal points, prevailing wind direction, window-to-wall ratio, etc.

VERIFYING ENERGY PERFORMANCE IN USE

In order to verify the potential application of the selected building envelope systems at middle latitudes, the systems were evaluated with respect to the current Italian design regulations [5]. This standard defines an upper limit for the thermal transmittance of a façade based on the climatic zone of the building and imposes a minimum "superficial mass" (kg/m²) for the external vertical surfaces. According to the Italian design regulations, thermal transmittance [U] has to be lower than 0,33 W/m²K for the coldest climate zone in Italy and the superficial mass [M_S] has to exceed 230 g/m² for the warmer climate zones. In case the value for M_S falls below this limit, an experimental verification is necessary to prove that the thermal inertia is equivalent to that of an envelope characterised by the value required. As the selected building envelope systems show a very low value of thermal transmittance compared to the design standard - yet their kg/m^2 value is lower than the minimum required (Tables 1, 2 and 3) - it has been necessary to simulate their thermal inertia, here intended as phase delay and reduction of the amplitude of the heat transmission.

- Envelope type 1: U= 0,120 W/m^{2}K, M_s= 90 kg/m².
- Envelope type 2: U= 0,330 W/m^{2}K, M_s= 16 kg/m².
- Envelope type 3: U= 0,230 W/m^{2}K, M_s= 135,34 kg/m².

Given that the design standard does not define a methodology to verify the energetic performance in use, this research has developed an experimental procedure, which simulates the application of the selected building envelope systems in three different Italian cities located in diverse climatic zones: Milan (North Italy), Ancona (Central Italy) and Catania (South Italy) (Fig. 7, Table 4).

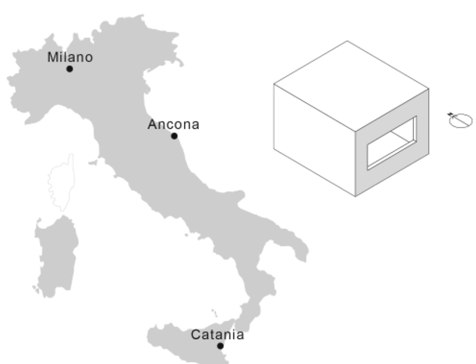

Figure 7: Three test locations and 3D view of the test-room.

Table 4. Climate data for the three Italian test locations. Data obtained from regulation UNI 10349:1994 and measurements of the weather stations of the local airports.

	Milano	Ancona	Catania
Latitude	45°27' E	43°36' E	37°30' E
Longitude	9°11' N	16°30'N	10°05' N
Altitude above sea level	122 m	16 m	7 m
Average max temperature in summer	29 °C	30,1 °C	33,6 °C
Average min temperature in winter	-2 °C	1 °C	5 °C
Average annual precipitation	944 mm	776 mm	556 mm
Average wind speed	1,1 m/s	3,2 m/s	4,4 m/s

The energy performance in use of the three selected building envelope systems has been verified by means of thermodynamic simulations using the software package "Energy Plus" applied to a virtual test room (Fig. 7) in those three cities. The virtual test room has a floor surface of 22,5 m² and a height of 3 m. The room has been simulated as an office space (internal thermal load of 380 W) oriented towards the south and with a window-to-wall ratio of 30% (Fig. 8).

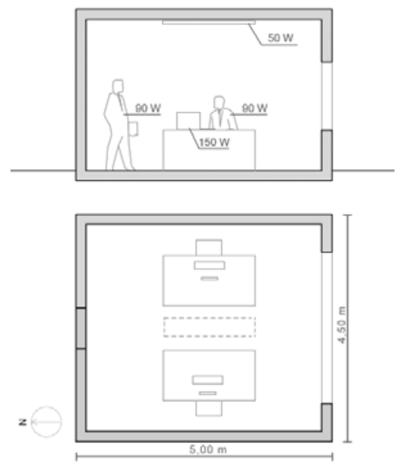

Figure 8: Section and floor plan of the virtual test-room.

By means of the simulations, not only the static energy performance parameters imposed by the Italian legislation (U and M_S) were checked, but also two dynamic energy performance parameters defined especially for non-massive structures [1] (time shift f_a and decrement factor ϕ) were calculated. The time shift is the period of time (hours) between the maximum amplitude of a cause and the maximum amplitude of its effect. In this case, the time shift is the period of time between the maximum value of external surface temperature and the maximum value of internal surface temperature. The decrement factor is the reduction of the amplitude of the heat transmission. Additionally, the annual energy demand necessary to ensure the internal comfort (21°C in winter and 26°C in summer [7]) was calculated assuming a heating system powered by natural gas and an electric cooling system. The annual energy demand is expressed in terms of kWh, € and CO_2 produced [8] (Table 5).

Table 5. Method of calculating costs and produced CO_2

efficiency of the heating system	90%
thermal energy produced per m³ of natural gas	9 kWh
price of natural gas per m^3	0,65 €
CO_2 emissions per kWh produced	0,20 kg CO_2
1 kWh for heating	0,08 € 0,20 kg CO_2

EER: Energy Efficiency Ratio	3,3 W/W
price of electric energy mix per kWh	0,19 €
CO_2 emissions per kWh produced	0,58 kg CO_2
1 kWh for cooling	0,05 € 0,16 kg CO_2

The numeric results of the simulation of these three systems were compared with those of a reference façade system (Fig. 9) that is commonly used in buildings in Italy.

- Reference envelope: U=0,33 W/m^{2}K and M_s= 31 kg/m² (Table 6).

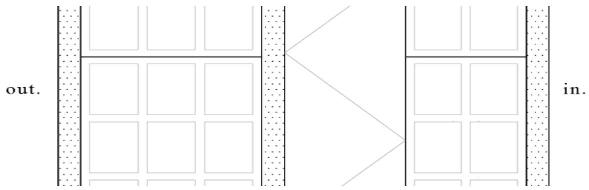

Figure 9: Section of reference envelope, scale 1:5.

Table 6: Technical data of the reference envelope.

	s [m]	λ [W/mK]	ρ [kg/m^3]	R [m^{2}k/W]	C J/kgK
h_e				0,043	
plaster	0,015	0,900	1800	0,016	910
big honeycomb brick	0,120	0,500	800	0,240	840
plaster	0,015	0,900	1800	0,016	910
insulation panel	0,070	0,30	100	2,300	670
small honeycomb brick	0,080	0,250	700	0,320	840
plaster	0,015	0,350	1200	0,042	1010
h_i				0,123	

Since this research was not only intended to verify the selected façade systems against the design standard, but also to simulate their energy performance, an in-depth analysis was performed, changing the orientation of the test room in the four orientations (north, west, south and east) and the window-to-wall ratio (20%, 30% and 50% respectively, corresponding to dimensions of 2,00 x 1,35 m, 3,00 x 1,35 m and 4,10 x 1,56 m respectively) of the tested façade. In all the simulations, the energy demand was compared to the one of the reference envelope and was evaluated in terms of energy demand [kWh], energy costs [€] and CO_2 produced, aiming at establishing also the economic and "environmental" applicability of the considered building envelope systems. The applied methodology comprises the following phases:

1. Climatic analysis of three Italian cities in three different climate zones.

2. First set of thermodynamic simulations: Monitoring of the thermal performance of a traditional façade and three innovative envelope systems in these cities during one year.

3. Calculation of the annual energy demand [kWh], costs [€] and CO_2 produced [kg] for heating and cooling - first set of simulations. Calculation of the annual energy demand [kWh],

4. Evaluation of the simulation results and comparison of the energy performance in use of the reference and the tested façade systems.

5. Second set of thermodynamic simulations - sensitivity analysis:
   - variation of orientation towards 4 cardinal points,
   - variation of the window-to-wall ratio for the test system.

6. Calculation of the annual energy demand [kWh], costs [€] and CO_2 produced [kg] for heating and cooling - second set of simulations.

7. Evaluation of the results of the second set of simulations.

8. Elaboration of proposals for improving the analysed building envelope systems.

9. Definition of design guidelines for the application of the analysed building envelope systems in buildings in Southern Europe (middle latitudes).

RESULTS OF THE SIMULATIONS

The simulations provide the possibility of determining the values of time shift (ϕ) and decrement factor (f_a) of the building envelopes as well as the overall annual energy demand during one year (winter and summer) (Fig. 10).

- Reference envelope: φ = 7 h, f_a =0,10.
- Envelope type 1: φ = 9,5 h, f_a = 0,02
- Envelope type 2: φ = 2,5 h, f_a = 0,11
- Envelope type 3: φ and f_a can not be determined due to the nature of PCM

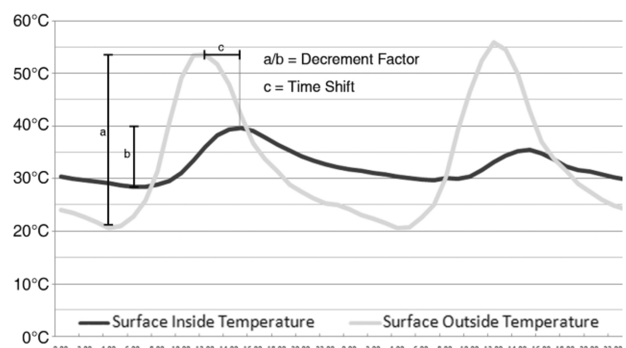

Figure 10: Example of the calculation of time shift and decrement factor of the reference envelope system.

The results of the thermodynamic simulations show not only a good thermal performance and energy saving potential of the new building envelopes, but also their liabilities, particularly when using those systems in buildings in Southern Europe. The tested building envelopes showed good results during the course of one year, especially in winter. During the summer period, on the other hand, only a minimum energy saving potential was detected (e.g. envelope type 2 in Catania was less efficient than the reference envelope) (Fig. 11).

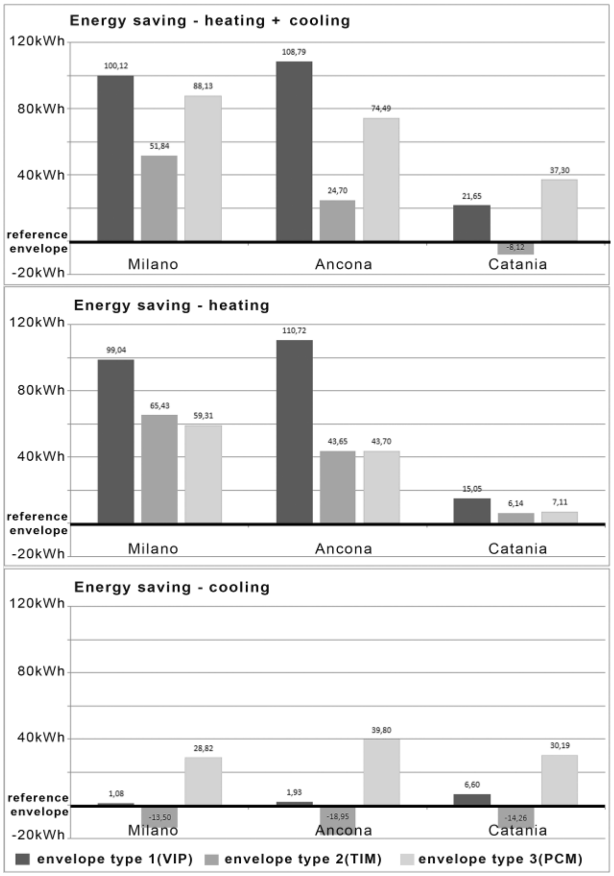

Figure 11: Energy saving potential for the new building envelope in comparison with the reference building envelope.

These results depend on two main factors:

- The analysed building envelopes were developed for the climatic conditions of central Europe (continental climate), where, in contrast to Italy, energy saving mainly means limiting the energy losses towards the surrounding environment during winter period.
- The used test room is considered to be an office room, meaning that significant internal thermal loads are present. In this case, also building envelope systems with a very good energy performance can not reduce the energy demand for cooling purposes during summer. The use of building envelopes with a big time shift and decrement factor contributes to limiting the impact of the external thermal load on the internal climate. At the same time, they can't influence the temperature increase due to the internal thermal load and the solar irradiation through the windows.

Based on the above considerations, two different approaches can be derived to solve the two problems:

- Proposals to improve the analysed building envelope systems for their application in southern Europe.
- Criteria for their application at middle latitudes considering not only the building envelope but the entire energy concept of the building in which the envelope is used.

PROPOSALS FOR IMPROVING

In order to improve the energy performance of the tested envelope systems for their application in the climate zones of Southern Europe suggestions for improvement were developed for manufactures as well as potential users.

Envelope type 1 (VIP): the VIP envelope system shows good energy performance and no further modifications are considered necessary. In order to further improve the energy performance of a building realized with this building envelope system, strategic-functional choices have to be approached during the design process rather than changing the stratification, thickness and materials of this system.

Envelope type 2 (TIM): a good energy performance was observed for this envelope type during winter. Nevertheless, excessive energy demand for cooling in summer was determined. This depends essentially on a reduced value of time shift of 2,5 hours, meaning that changes in external temperature arrive inside the room only 2,5 hours later. As a result, four suggestions for improvement were developed (Table 7), all of which include a new panel of various materials inserted between TIM and a PAVATEX panel.

Table 7: Proposal to improve the envelope type 2 (TIM).

		s [m]	λ [W/mK]	ρ [kg/m³]
Proposal **1**	concrete panel middle density	0,08	1,35	1000
Proposal **2**	concrete panel high density	0,12	1,50	2400
Proposal **3**	insulation panel	0,12	0,036	90
Proposal **4**	sandwich panel QASA (VIP)	0,051	0,010	200

The optimized envelope systems have the following characteristics:

- Proposal 1: U= 0,329 W/m^{2}K, M_s= 93 kg/m².
- Proposal 2: U= 0,327 W/m^{2}K, M_s= 301 kg/m².
- Proposal 3: U= 0,158 W/m^{2}K, M_s= 23,8 kg/m².
- Proposal 4: U= 0,124 W/m^{2}K, M_s= 23,2 kg/m².

The performance of the optimized building envelope systems were analyzed and verified in terms of thermodynamic simulations. The results of thermodynamic simulations did not reveal positive results for the first two proposals, but significant outcomes for the second two proposals (Table 8).

Table 8: Energy saving potential for the optimized building envelope in comparison with the reference system.

	Milano	Ancona	Catania
Envelope type 2	51,85 kWh	24,70 kWh	-8,12 kWh
Proposal **1**	50,90 kWh	25,48 kWh	-5,76 kWh
Proposal **2**	50,49 kWh	26,38 kWh	-3,56 kWh
Proposal **3**	80,88 kWh	46,20 kWh	1,19 kWh
Proposal **4**	91,76 kWh	55,15 kWh	6,57 kWh

These results highlight that a reduction of the thermal transmittance of the envelope corresponds directly to a reduction of the energy demand. An increased superficial mass, on the other hand, does not necessarily mean an improved energy performance, as proposed by the Italian design regulations [5].

Envelope type 3 (PCM): the envelope system containing PCM has a good energy performance during summer. In order to further improve its energy performance during the summer period in hotter climate zones two proposals for improvement were developed. Both of them utilize a PCM with a higher melting temperature (28°C and 30°C) in contrast to the original envelope type 3 (26°C). The simulation results (Table 9) of the optimized envelope system type 3 proved that an increasing melting temperature of the PCM has an energy saving effect only in the hottest of the three Italian cities considered.

Table 9: Energy saving potential for the optimized building envelope in comparison with the reference system.

	Milano	Ancona	Catania
Envelope type 3 (26°C)	88,13 kWh	74,49 kWh	37,30 kWh
Proposal 1 (28°C)	80,89 kWh	74,33 kWh	40,98 kWh
Proposal 2 (30°C)	79,90 kWh	66,54 kWh	43,01 kWh

The results further demonstrate that using materials that have the ability of changing their thermal performance with changing temperature (PCM) requires an a priori accurate climatic analysis of the desired construction site in order to optimize their energy performance. Using PCM without knowing the average daily and monthly temperature - and especially the range of temperature fluctuation during one day - can not be energetically and economically efficient.

DESIGN CRITERIA FOR THE APPLICATION AT MIDDLE LATITUDES

Based on the results of the simulation it was further possible to identify the reasons that determine the overall energy demand of a building (Fig. 12).

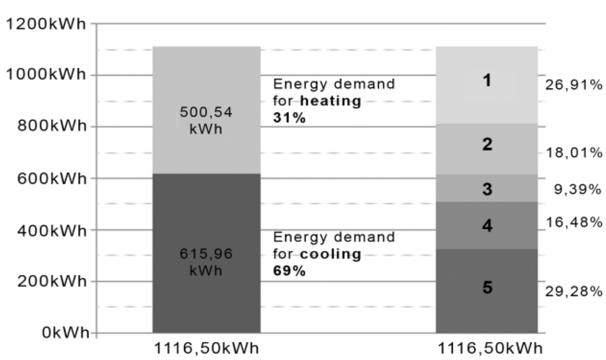

Figure 12: Reasons determining a building's energy demand in the case of Milan. 1-Heating loss through window, 2-Heating loss through wall, 3-Cooling demand due to heat transport through the wall, 4-Cooling demand due to solar irradiation through the window, 5-Cooling demand due to internal thermal load.

The orientation and the variation of the window-to-wall ratio of the test facade influence considerably the calculated annual energy demand (Fig. 13). Based on the sensitivity analysis, it can be stated that - e.g. for an office building at middle latitudes - the most energy efficient orientation is northwards and the window-to-wall ratio should not exceed 20%. Nevertheless, window size can be increased, if sufficient shading is provided. The potential user of these criteria are architects and engineers.

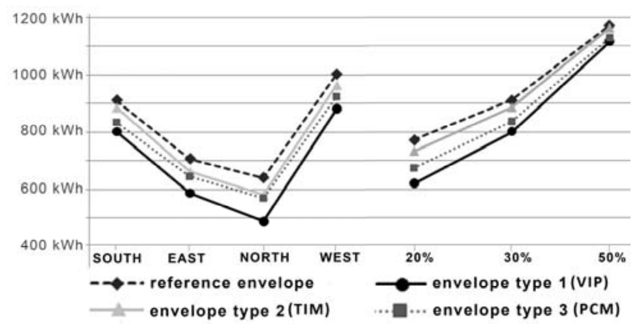

Figure 13: Diagram summarizing the results of the sensitivity analysis in the case of Ancona.

CONCLUSION

This research has demonstrated that non-massive building envelopes with a reduced superficial mass can have a lower energy demand compared to massive building envelopes, also if used at middle latitudes. However, in order to meet this goal it is necessary that the design of a building is based on a consistent energy concept that addresses all aspects of decisions during the design process at different scales.

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