Energy Performance of Vertical Extensions on Old Buildings: Comparison between Architectural Membranes and Conventional Building Technologies

Paulo Mendonça, Monica Macieira, and João Miranda Guedes

***Abstract*—This research aims evaluating in what measure the proposed refurbishment solutions with architectural membranes can benefit an existing building and provide an energy efficient alternative to conventional reference building technologies for vertical extensions. In order to do it, an old building from the 19th century, located in Porto (Portugal) is taken as case study. Both solutions are compared regarding thermal comfort, energy consumption for heating/cooling needs using numerical simulation, which allowed evaluating the project from the environmental point of view, based on the energy consumption. The proposed membrane alternatives include conventional and non-conventional thermal/acoustic insulation and a membrane envelope option with vegetation on its external skin. The paper argues that architectural membrane refurbishment solutions can constitute an energy efficient alternative to lightweight conventional ones.**

***Index Terms*—Architectural membrane materials, energy and thermal performance, old buildings, retrofitting.**

I. Introduction

In Europe, extension operations corresponded between 10 to 15% of the total building refurbishment interventions in 2010 [1]. In Portugal, according to INE [2], extension works accounted for 18% of the total completed building operations in 2010, while in 2015 they corresponded to 23%. Between 2010 and 2015, considering the different types of works that are within the group of refurbishment actions, the expansion works remained predominant, concentrating 68% of the total actions in 2015 [2]. Besides that, in Portugal, 56% of the extension operations finished in 2015 was intended for residential use [2].

Making extensions on existing building has impact on its functional performance (thermal and acoustic, spatial definition, useful area, etc.). However, many of the old buildings are located in areas with restricted access and physical constraints on the displacement of materials, components and equipment, which limit interventions and maintenance actions, demanding for alternative solutions. Furthermore, the increasing importance given today to the environmental compatibility leads designers to use energy efficient materials and technical solutions to maximize savings in buildings.

According to Bergsten [3] the adoption of lightweight building solutions to perform vertical extensions has already shown to have an economic advantage, especially in refurbishment interventions located at urban centres. Due to its lightness, resilience and flexibility, membranes are becoming common solutions in specific contexts of existing buildings' refurbishment [4]-[6] at the exterior [7] or interior [8] When inserted in lightweight building systems, architectural membrane materials have the potential to be used in extensions, renovations or alterations of buildings subject to functional [9], [10] or structural [11], [12] refurbishment, being interesting alternatives in cases where the use of conventional/traditional solutions is limited, especially for its weight.

The following section will study the application of membrane solutions to perform vertical extensions using as case study an old building from the 19th century, located in Porto, Portugal.

A. Motivations to Extend

Over the past 20 years the construction of buildings was irreversibly linked to the occupation of virgin soil, extending the cities horizontally and involving a great need to build additional infrastructure. One way to revert this model involves the rehabilitation of the building stock. In this context, vertical extension's operations, whenever they respect the existing built environment and the structural limitations of the intervening building, present some environmental advantages, such as: do not increase the consumption of natural soil; do not reduce biodiversity; optimize existing infrastructures (services and supply); decrease the ecological footprint (estimated to be at least 50% [13]) and the carbon footprint (estimated to be at least 30% [13]), relatively to build on virgin soil.

Currently, the main motivation to extend a building comes from the high demand for housing in urban areas and with a growing trend [14], giving rise to denser population areas, where any available living space is considered. Another motivation may derive from a strategy to reconfigure an interior space and optimize the use of adjacent spaces; the functional distribution of a building may need to be rearranged to accommodate programmatic changes in the lifestyle/usage patterns of its occupants [15].

On the other hand, considering its limits, vertical extensions could favour overcrowding and congestion, against quality of urban life [16], [17]. However, by adopting reversible and low carbon footprint building technologies, such the ones under study, it can contribute to get cities more adjustable to the changing requirements to achieve more sustainable environments.

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B. *Benefits to Environmental Impact/Energy Consumption Reduction*

In previous studies, based on the life cycle analysis methodology, Wald *et al.* [18] compared different energy refurbishment alternatives for old buildings that require thermal insulation in its envelope and efficient HVAC equipment. The analysis included the following scenarios: (a) no intervention (leaving the building in its current state); (b) light refurbishment (thermal insulation of the roof and floors); (c) deeply refurbishment (option (b) + facades and windows); (d) option (b) + vertical extension (incorporating renewable energy) and (e) demolish to rebuild (following current standards to achieve higher energy efficiency). From the analysis of these scenarios, according to Wald *et al.* [18], it is concluded that the best option is the combination of light refurbishment and vertical expansion, as it presents the lowest consumption of renewable energy and lower greenhouse gas emissions in the medium and long term.

II. Case Study

The old building taken as case study (Fig. 1(a)) presents a constructive system with similar characteristics of the majority of the houses built in Porto (Portugal) during the 19th century: single-pane granite walls with lime and granitic sand based mortar; timber floor structures; wooden window frames with single glass (3 mm); light timber frame partitions; plaster ceilings and sloping roof with timber structure and ceramic tiles. The slab of the last floor that serves as basement for the vertical extension is made of a timber structure, too. In the last 10 years, the building has suffered a significant degradation process; the lack of maintenance allowed water to enter inside the building, causing deterioration of the wooden structure of the roof and the top floor. Because of this, there was the need to demolish those two structures and perform a new rooftop/vertical extension. Fig. 1(b) presents the adopted refurbishment project using timber structures with design from Anarchlab [19].

Informations about the existing building			
Number of floors above the ground level:	4	Ceiling height:	3,00-3,50m
Constructed area:	367m^2		
Depth:	15m	Width:	6m

Fig. 1. Sections and exterior view of the building case study: (a) in its original state and with (b) the adopted refurbishment project using timber structure (designed by Anarchlab [19]).

III. Lightweight Building Solutions for Rooftop Extensions

The building in Fig. 1(a) was then used to evaluate and compare the efficiency of several lightweight vertical extension options, namely those presented in Fig. 2: one Traditional Solution (TS); two conventional reference models (CWood and CSteel) and four proposed alternatives (AMb, AMv1, AMv2 and AMv3). Because vertical extensions correspond to an increase of weight to the existing structure, especially when they will be misaligned from the facade walls, i.e. from the main load bearing walls, it is particularly important that they be conceived with lightweight structures. The next sections refer to the traditional solutions, the conventional refurbishment solutions and the alternative solutions using membranes that will be the focus of this research.

A. *Traditional Building Solution (TS)*

The building taken as case study presents a small rooftop extension volume, a type of dormer traditionally called “mirante” in Portuguese (Fig. 1(a) and Fig. 2 TS); it presents an external envelope with constructive characteristics of a traditional lightweight building solution: roof timber structure covered with ceramic tiles; exterior and interior light frame timber walls (exterior ones covered with corrugated metal sheet from the outside and with lime and sand based plaster from the inside).

B. *Conventional Refurbishment Building Solutions*

1) Conventional refurbishment building solution using Wood structures (CWood)

   The building taken as case study was refurbished with a rooftop extension - with a conventional building solution with wood structure (wood framing and OSB (Oriented Strand Board) panels) (Fig. 1(b) and Fig. 2). The exterior envelope is made of: ceramic tiles roof; exterior walls with corrugated metal sheet faced covering, thermal insulation, OSB in the middle and plasterboard in the inner side (Fig. 3).

2) Conventional refurbishment building solution using Steel structures (CSteel)

   CSteel is a variant of solution CWood: it had the same exterior envelope, but with a Light Steel Framing (LSF) structure. The main structural components of this system are cold-formed galvanized steel profiles (Fig. 2 and Fig. 3).

C. *Alternative Membrane Refurbishment Building Solutions (AM)*

The referred to as alternative solutions to the conventional ones (previously described) correspond to the use of architectural membrane materials in the construction system. Membranes are foils or textile reinforced composite materials that presents low self-weight (generally less than 1 kg/m^2) and high flexibility and resistance under tensile forces. In this study, a modular and prefabricated base constructive solution is proposed (AMb). However, as AMb is lightweight and, therefore, has reduced thermal mass, three variants, AMv1, AMv2 and AMv3, are proposed to overcome this limitation (Fig. 3), namely by adding materials with phase change and/or vegetation and that take advantage of the thermal mass of the building itself. All AM solutions present a modular multilayer envelope system, with membranes in both sides (with low emissivity and self-cleaning coating, combined with a thermal/acoustic insulation material), an insulated core and a wood structure (with modular and prefabricated elements (frames) connected with metal tubes, cables and fittings – all these elements are assembled in situ and easily transported by man work) (Fig. 2).

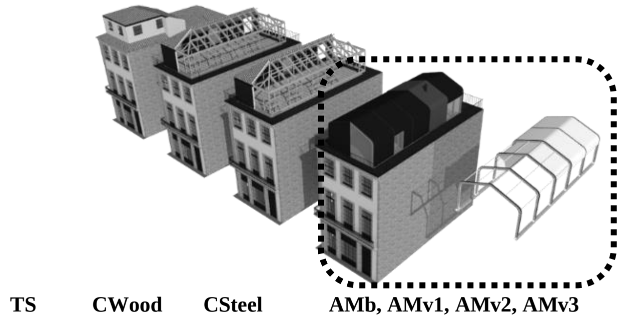


Fig. 2. Virtual views of the case study building with the different rooftop options.

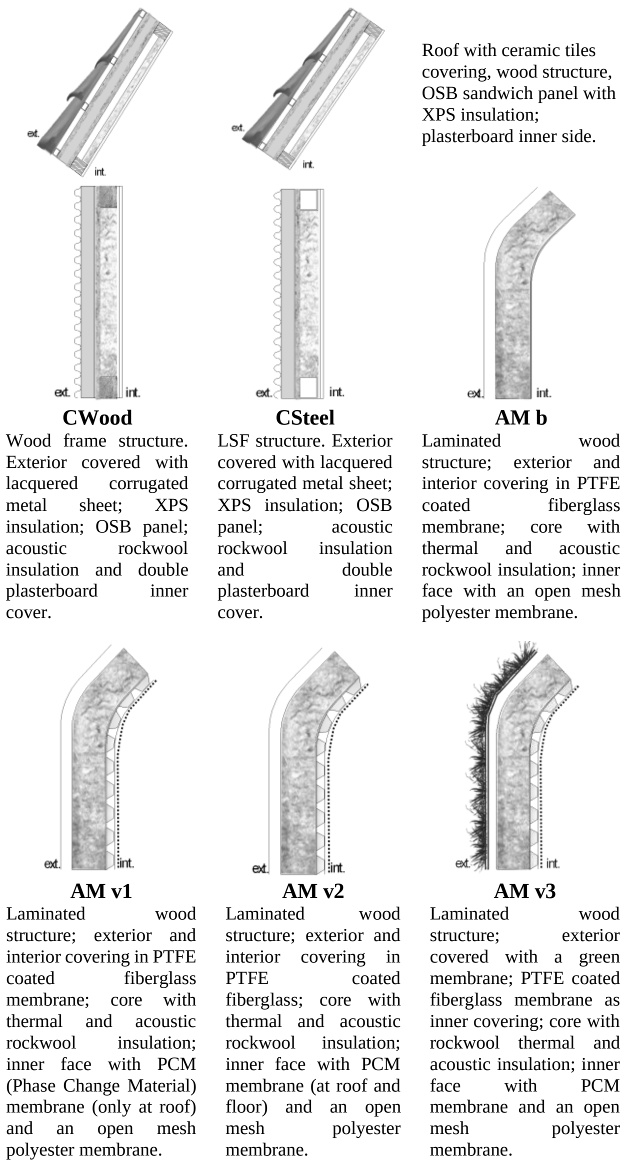


Fig. 3. Composition of conventional and alternative building solutions for the external envelope.

Examples of interventions involving vertical extensions using membrane building technologies can be found elsewhere, namely: Imagination Headquarters [20] (designed by Ron Herron, 1990); Shishiodoshi House [21] (designed by Avignon Clouet, 2010), Carnegie Hall [22] (an air tent placed at a rooftop, designed by Federal Fabrics) and the AirClad rooftop Pod [23] (designed by Inflate, 2008).

The rooftop extensions options under analysis are presented at Fig. 3. Knowing that heavy exterior envelope elements (walls and roof) present more than 500 kg/m^2, medium weight elements 25 < 500 kg/m^2 and lightweight ones approximately 100 < 250 kg/m^2, one may consider that building elements with membrane technologies, as those proposed in this study, which weight less than 100kg/m^2, are ultra-lightweight solutions [24]. Thus, the thermal/energy performance evaluation presented in this study compares lightweight conventional constructive solutions with ultra-lightweight alternative ones (Table 1). Considering the total weight of the rooftop extension, alternative membrane solutions weight less 38 to 85% than the conventional ones, for the same U value of its external envelope [24].

IV. Thermal and Energy Evaluation Model

A. Objectives and Methodology

This research derives from a previous research study, where economic and environmental impact aspects of conventional and membrane rooftops were assessed in order to determine the relative efficiency of membrane ones, where these were favored over conventional ones [24],[25]. The present paper gives a detailed analysis about the thermal performance of the six rooftop extensions during building's operational use phase.

It is intended to determine to what extent AMb and its variants regarding thermal mass (AMv1, AMv2 and AMv3), comparatively to CWood/CSteel, can: (1) take advantage of the thermal inertia of the existing building (due to the lack of thermal mass of the membrane materials) and (2) complement and benefit the existing building. For this purpose, a dynamic numerical simulation of the building, with and without the rooftop building solutions under comparison, was carried out with the EnergyPlus engine interface software Design Builder [26], on the basis of the energy consumption related to thermal performance.

B. Calculation Model

The building under study was modelled according to the geometric and constructive characteristics presented in Fig. 1, Tables I and II, as well as the building location/urban environment where it is inserted (Fig. 4). Fig. 5 highlights the building zones under evaluation; the interior dividing walls of the vertical extension's underlying floor have not been modelled to simplify the analysis of the results. However, its thermal mass was considered for calculation purposes. The existing stairs, which connects the three floors, were represented by a hole.

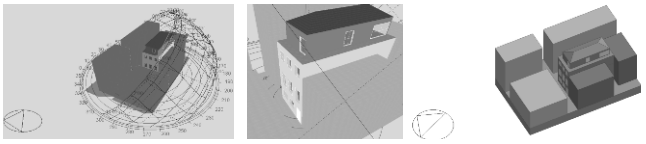


Fig. 4. Three-dimensional model used on numerical simulations.

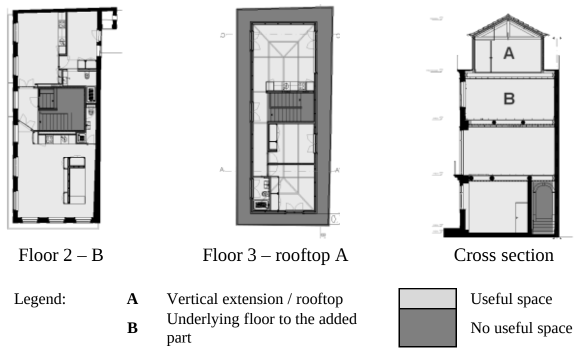


Fig. 5. Architectural drawings with identification of the case study floors under analysis, useful and non-useful spaces.

Table I presents an overview of Porto climate characteristics, as well as the heating, cooling and ventilation systems considered on the energy performance evaluation of the building. Table II presents the technical characteristics of the building envelope prior to the refurbishment intervention. Globally, Tables II, III and IV presents the most relevant thermal-physical characteristics of the building elements, considered the numerical model.

TABLE I: GENERAL INFORMATION ABOUT THE CASE STUDY BUILDING. MAIN CLIMATE CHARACTERISTICS OF PORTO CITY

General characteristics	
Location	Porto
Latitude	41º09'02.35'N
Longitude	8º36'51.23'O
Altitude	103
Use	Residential
Thermal inertia	Medium
Gross area of existing building/ rooftop area	367 m^2/ 60m^2
Climatic parameters [11]	
Winter climate zone	I2
Heating days (days)	1610
Conventional heating period (months)	6.7
Summer climate zone	V1
Incident radiation on a transparent south facing surface (kWh/m^2. month)	93
Outdoor air temperature in the project (ºC)	30
Mean air temperature daily thermal range (ºC)*	9

* Difference between the minimum and maximum daily average temperature for the warmest month of the cooling season.

TABLE II: THERMAL TRANSMISSION COEFFICIENT OF EXISTING BUILDING'S CONSTRUCTIVE ELEMENTS (WITHOUT ROOFTOP) AND CLIMATE SYSTEM CONSIDERED FOR THE BUILDING WITH AND WITHOUT ROOFTOP

Elements of existing building	
Exterior and adiabatic walls.	U= 2.50 W/(m^2.ºC)
Ceiling and interior walls	U= 1.70 W/(m^2.ºC)
Ground floor	U= 1.13 W/(m^2.ºC)
Thermal inertia	Medium
Notes on HVAC, lighting and DHW systems considered for the calculation of energy consumption:	Indoor air conditioning system: COP 3 direct expansion air conditioning terminal (connected only to ensure that the indoor air temperature does not exceed 25ºC and does not drop below 18ºC). Consumption for DHW or lighting was not considered.

TABLE III: CONSTITUTION AND THERMAL-PHYSICAL PROPERTIES OF THE ROOFTOP BUILDING ELEMENTS

Building element	**Constitution (see Fig.3) (from exterior to interior / top to bottom)**	**Thick. (m)**	**U value (W/m^{2o} C)**
CWood CSteel EXTERIOR WALLS	Corrugated and lacquered galvanized steel plate	0.03	0.23
	Extruded Polystyrene (XPS) insulation	0.06	
	Vapor barrier (Polypropylene) layer	0.002	
	Oriented Fibre Board (OSB) panel	0.02	
	Rockwool insulation	0.08	
	Plasterboard	0.025	
CWood CSteel ROOF	Ceramic roof tiles	0.015	0.20
	Air gap formed by profiles	0.03	
	Vapor barrier (Polypropylene) layer	0.002	
	OSB panel	0.02	
	Extruded Polystyrene (XPS) insulation	0.06	
	OSB panel	0.01	
	Air gap	0.04	
	Rockwool insulation	0.04	
	Plasterboard	0.013	
AMb EXTERIOR WALLS AND ROOF	PTFE coated fibreglass membrane	0.002	0.21
	Air gap	0.05	
	Rockwool insulation	0.15	
	Polyamide and polypropylene membrane - water vapor diffusion retardant (water tightness and condensation control)	0.002	
	PTFE coated fibreglass membrane	0.002	
AMv1 AMv2	AMv1 = AMb with Bio PCM® blanket type on the roof (from exterior to interior – positioned below the rockwool insulation). AMv2 = AMb with Bio PCM® blanket type on the roof and exterior walls (from exterior to interior - positioned below the rockwool insulation).	0.04	0.22
AMv3	AMv3 = AMv1+ green membrane VGTEX™ type (from exterior to interior – above the PTFE fiberglass membrane).	0.03	0.18
TS EXTERIOR WALLS	Corrugated and lacquered galvanized steel plate	0.03	3.70
	Pine wood lath	0.02	
	Lime and sand mortar	0.02	
	Traditional plaster stucco.	0.02	
TS ROOF	Ceramic roof tiles	0.015	3.70
	Air gap (attic space)	-	
	Pine wood plank.	0.030	
TS FLOOR	Wooden floor (pine)	0.03	1.09
	Air gap	0.30	
	Pine wood lath	0.02	
	Lime and sand mortar	0.02	
	Traditional plaster stucco.	0.02	
NEW ROOFTOP FLOOR for: CWood CSteel. AMb. AMv1. AMv2 AMv3	Wooden floor (pine)	0.025	0.16
	Cork granulate	0.015	
	Polyethylene membrane (impact noise reduction)	0.005	
	OSB panel	0.016	
	Air gap (formed by wooden beams)	0.26	
	OSB panel	0.016	
	Air gap	0.08	
	Rockwool insulation	0.04	
	Plasterboard	0.013	
Interior dividing walls	Plasterboard	0.015	0.43
	Rockwool insulation	0.06	
	Plasterboard	0.015	

Sources: [27]-[30]. **Note:** regarding the properties of the considered membrane for exterior and interior finishing. equivalent membrane datasheet available on the market and the data available in Knippers [31] were taken as references.

TABLE IV: THERMAL PHYSICAL AND OPTICAL PROPERTIES OF THE GLAZED ELEMENTS ACCORDING TO DESIGNBUILDER [26] DATABASE

Glazed elements	U value (W/(m². °C))	g (dimensionless)	Light transmission
6mm double glazing with 16mm air spacing and wood frame.	2.5	0.63 (winter) 0.25 (summer)	0.90

V. RESULTS AND DISCUSSION

A. *Thermal Performance Comparison – Influence of the Vertical Extension on the Existing Building*

The thermal performance of the models created according the previous section were numerically tested for a typical summer and winter week; the results are shown in Fig. 6 till Fig. 13.

Comparing the conventional solutions with the alternative base solution, it is verified that, in the winter week (Fig. 6) and in the summer week (Fig. 7), the alternative membrane base (AMb) solution presents higher thermal oscillations. This is due to the fact that AMb has lower thermal mass than conventional solutions and, consequently, its building has fewer comfort hours within the considered range (18-25 °C).

Fig. 6 shows that, in the summer week, there is a high number of hours within the comfort temperature, i.e. the need to use active climate control systems is very reduced. So, in order to prevent the interior rooftop space overheating, it is recommended to use passive cooling strategies such as natural ventilation in all rooftop solutions.

In both summer and winter weeks, the indoor space temperature of the underlying floor is slightly more stable after the refurbishment intervention, i.e. it has fewer temperature fluctuations with the addition of a rooftop/vertical extension (both with conventional or alternative solutions) to the existing building, being beneficial for the building as a whole.

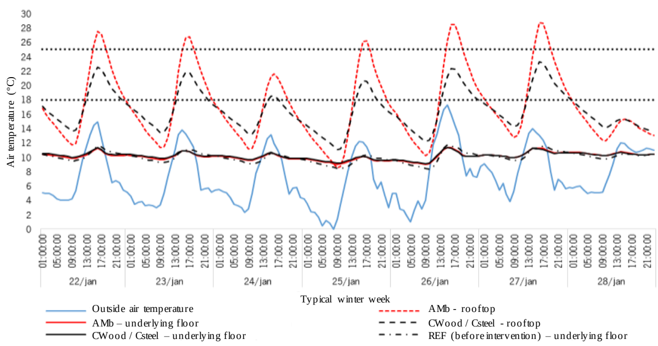


Fig. 6. Indoor temperature variation, in the rooftop and the floor below it, for a typical winter week.

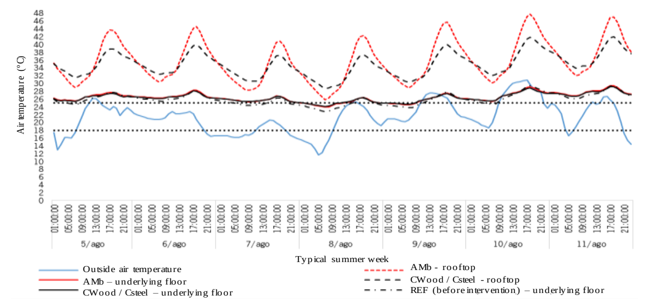


Fig. 7. Indoor temperature variation. in the rooftop and the floor below it, for a typical summer week.

Fig. 8 and Fig. 9 present the results of indoor thermal comfort feeling tests for a typical winter and summer week. According to Fanger [32], the thermal comfort feeling gathers air temperature, relative humidity, mean radiant temperature, surface temperature, indoor air velocity, and thermal resistance of clothing and metabolic activity parameters in an index - Predicted Mean Vote (PMV) - with a 7-9 point's thermal sensation. The nine-point scale is as follows: 4 = very hot; 3 = hot; 2 = warm; 1 = slightly warm; 0 = neutral; -1 = slightly cool; -2 = cool; -3 = cold and -4 = very cold. At Fig. 8 it is found that, on average, the thermal feeling comfort in the winter week is better in the rooftop floor with AMb solution (average of 0 = neutral) than in CWood/CSteel (average of -4 = very cold). On the other hand, the underlying floor without rooftop (hereinafter referred to REF, the floor B on Fig. 5) or with the AMb rooftop presents a very similar thermal feeling comfort (where the average is -1= slightly cool), which contrasts positively with the thermal feeling comfort on the CWood/CSteel underlying floor (the average is -4= very cold). Thus, in a typical winter week, the thermal comfort feeling at AMb rooftop is better than at CWood/CSteel one.

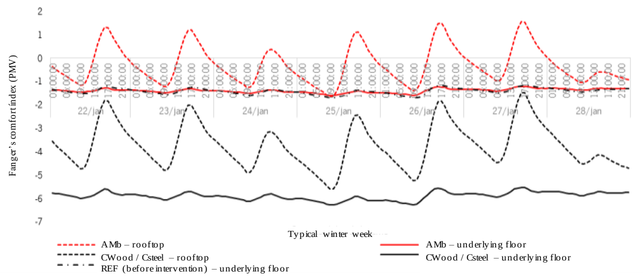


Fig. 8. Thermal comfort feeling's variation according PMV index – winter week.

However, in a typical summer week, the average thermal comfort feeling on the underlying REF floor is improved with the introduction of a CWood/CSteel rooftop/vertical extension as it goes from slightly temperate (REF) to slightly cool (CWood/CSteel) Fig. 9. On the other hand, the average thermal comfort feeling of the AMb and CWood/CSteel rooftops solution is hot. Thus, in a typical summer week, the thermal comfort feeling at AMb or CWood/CSteel rooftop is slightly overheated. However, the CWood/CSteel rooftop benefits more the thermal comfort feeling in the underlying floor than the AMb rooftop.

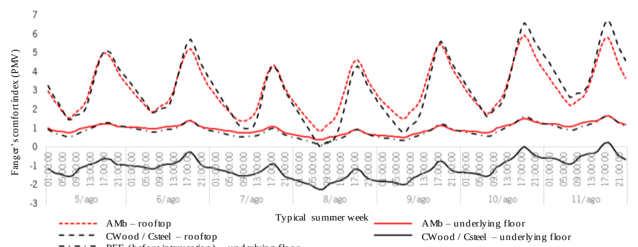


Fig. 9. Thermal comfort feeling's variation according PMV index – summer week.

B. *Thermal Performance - Comparative Analysis between Conventional Solutions and Alternative Membrane Variants with the Addition of Unconventional Thermal Mass*

Considering the results presented before, for the membrane based alternative solution were analysed three variants/proposals: AMv1, AMv2 and AMv3. In these variants the thermal mass is increased (with Phase Change Materials (PCM), such as BIOPCM^{TM} M51/Q29 type), in order to determine which of these variants presents a better or equivalent thermal behaviour, among other aspects, to conventional solutions.

To include the effect of phase change properties on numerical simulations, an advanced method using a finite-difference algorithm is used; the chosen software provides some PCM materials in its database, including the PCM selected for this study. Regarding the simulation of the AMv3 solution, with a green membrane envelope, it is adopted the advanced moisture diffusion calculation method that also uses finite-difference algorithms to divide the substrate/soil into nodes, according to the model described in [33]. The characteristics of green membrane considered in the numerical model are as follows: maximum plant height of 0.10m; leaf area index (LAI) of 2.7 (in 0.001 - 5.0 range. according [34]); leaves reflectivity of 0.22 (in 0.1 - 0.4 range); leaves emissivity of 0.95 (in 0.8 - 1.0 range, being 1 the equivalent of a black body); minimum stomatal resistance of 180 (in 50 - 300 e/m range - plant transpiration); minimum residual soil moisture volume of 0.01; maximum soil moisture volume of 0.5; initial soil moisture volume of 0.15.

Fig. 10 till Fig. 11 presents the numerical simulation results of the model's thermal behaviour. for a typical winter and summer week, adding to this comparison the AMv1, AMv2 and AMv3 solutions and considering the same conditions of the previous simulations (for REF, CWood/CSteel and AMb models).

It is observed in Fig. 10, Fig. 12 and Tables V and VI that, for a typical winter week, the rooftop variants of the base membrane alternative solution are those that present the best thermal behaviour, especially AMv3, with smaller temperature variations and thermal comfort feeling (presenting the highest number of comfort hours in the 18ºC≤25°C range). However, regarding rooftop's underlying floor, all models exhibit similar thermal behaviour, except for the model with TS rooftop solution, that is worst, i.e. presents more unstable interior air temperature.

At Fig. 11, Fig. 13, Tables V and VI, it can be seen that in a typical summer week, all the rooftop solutions under study overheat, which is justified by the fact that natural space ventilation was not considered on the numerical simulation model. However, since, on average, the daily maximum outdoor temperature is 23°C, a passive cooling strategy - such as natural ventilation - will help to mitigate this problem in the summer season.

Comparing the alternative solutions with the conventional ones, regarding the presented results, it is concluded that: (1) AMv3 rooftop solution presents the best thermal behaviour in the winter season; (2) considering that the overheating problem is overcome by adopting natural ventilation, in the summer, all solutions present similar thermal behaviour; (3) all AMb variant solutions, with thermal mass increase, have a more stable thermal behaviour, with smaller oscillations than the remaining options. In summary, all rooftop solutions under analysis: (1) do not significantly prejudice or improve the thermal behaviour of the case study building; (2) present a similar influence/benefit on the thermal behaviour of the rooftop underlying floor.

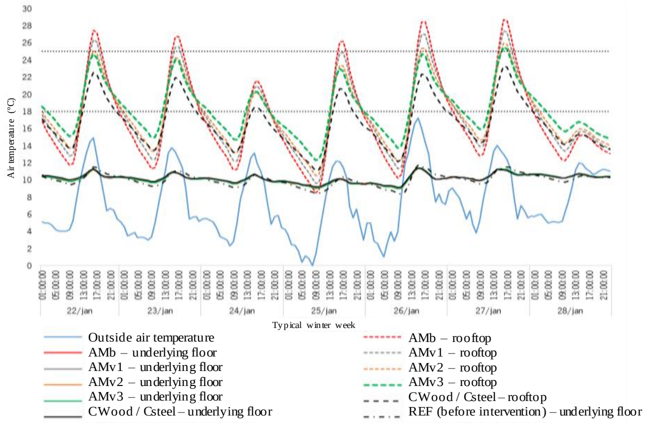


Fig. 10. Indoor temperature variation, in the rooftop and the floor below it, for a typical winter week.

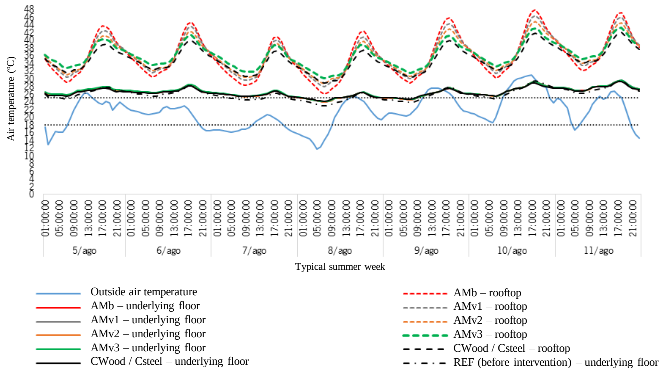


Fig. 11. Indoor temperature variation, in the rooftop and the floor below it, for a typical summer week.

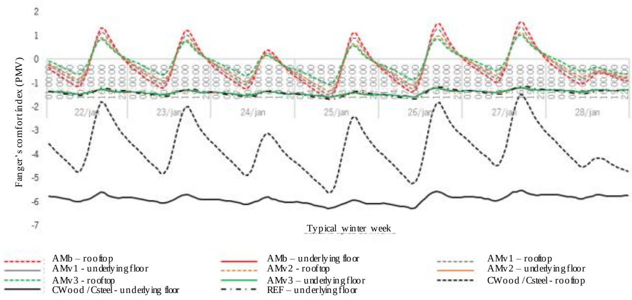


Fig. 12. Thermal comfort feeling's variation according PMV index – typical winter week.

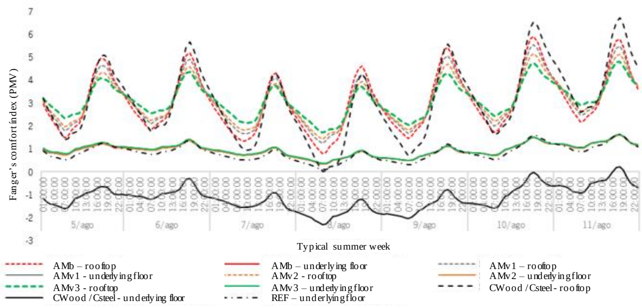


Fig. 13. Thermal comfort feeling's variation according PMV index – summer week.

Table V and Table VI show the statistical analysis of the thermal behaviour and the thermal comfort sensation of the considered models.

TABLE V: STATISTICAL ANALYSIS OF AIR TEMPERATURE VARIATIONS DURING A TYPICAL WINTER AND SUMMER WEEK

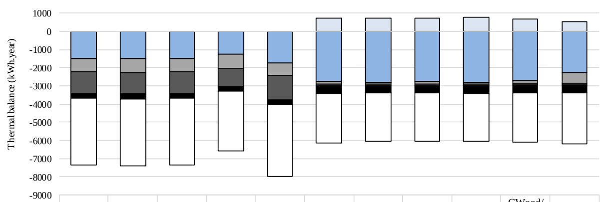
		Rooftop floor					Underlying floor					
	Outside air temperature	**AMb**	**AMv1**	**AMv2**	**AMv3**	**CWood CSteel**	**AMb**	**AMv1**	**AMv2**	**AMv3**	**CWood CSteel**	**REF**
Air temperature:	**Typical winter week (°C)**											
Daily average	**6.9**	**17.90**	**18.16**	**18.24**	**18.89**	**17.23**	**10.17**	**10.19**	**10.18**	**10.19**	**10.28**	**10.12**
Daily minimum	3.00	11.31	12.41	13.34	14.96	13.46	9.67	9.70	9.67	9.68	9.81	9.24
Daily maximum	13.8	26.72	25.52	24.26	24.06	21.91	10.85	10.87	10.87	10.88	10.92	11.06
≠ Max. and Min.	10.8	15.41	13.11	10.92	9.10	8.45	1.18	1.17	1.20	1.20	1.11	1.82
N. hours 18 ≤ 25°C	**0**	**43**	**53**	**62**	**75**	**48**	**0**	**0**	**0**	**0**	**0**	**0**
	Typical summer week (°C)											
Daily average	**20.83**	**36.12**	**36.37**	**36.17**	**36.51**	**35.34**	**26.81**	**26.84**	**26.81**	**26.97**	**26.65**	**26.35**
Daily minimum	16.46	30.37	31.54	32.09	33.43	32.25	26.17	26.19	26.17	26.34	26.07	25.38
Daily maximum	22.83	44.53	43.46	42.12	41.19	39.92	28.27	28.31	28.27	28.42	28.04	28.09
≠ Max. and Min.	6.37	14.16	11.92	10.03	7.76	7.67	2.10	2.12	2.10	2.08	1.97	2.71
Number of hours 18 ≤ 25°C	**95**	**0**	**0**	**0**	**0**	**0**	**24**	**23**	**24**	**22**	**21**	**50**

TABLE VI: STATISTICAL ANALYSIS OF COMFORT FEELING ´S VARIATION. ACCORDING PMV INDEX IN A TYPICAL WINTER AND SUMMER WEEK

	Rooftop floor					Underlying floor					
	AMb	**AMv1**	**AMv2**	**AMv3**	**CWood CSteel**	**AMb**	**AMv1**	**AMv2**	**AMv3**	**CWood CSteel**	**REF**
Comfort index:	**Typical winter week (Fanger's PMV)**										
Daily average	-0.20	-0.16	-0.15	-0.05	-3.55	-1.42	-1.41	-1.41	-1.41	-5.90	-1.43
Number of hours equal to 0 PMV	53	55	53	59	0	0	0	0	0	0	0
Ranking (1 = best)	**3º**	**2º**	**3º**	**1º**	**4º**	**2º**	**1º**	**1º**	**1º**	**3º**	**2º**
	Typical summer week (Fanger's PMV)										
Daily average	3.18	3.23	3.19	3.26	3.34	1.07	1.07	1.07	1.11	-0.91	0.98
Number of hours 0 ≤ 2 PMV	38	25	20	7	47	167	167	167	167	3	167
Ranking (1 = best)	**2º**	**3º**	**4º**	**5º**	**1º**	**2º**	**3º**	**3º**	**3º**	**1º**	**2º**

C. Energy Consumption – Comparison between Conventional and Alternative Membrane Solutions

The graph of Fig. 14 shows the annual thermal balance of the building for the various solutions under study, through the building elements. In particular, it shows that all the vertical extension interventions under study benefit the existing building, as thermal gains are observed in the underlying floor, through the ceilings. In addition, the greatest energy losses occur by through the outside envelope, especially on the walls. By incorporating PCMs and green membrane on rooftop solutions, there is a positive impact on energy consumption, which is higher in AMv3 than in AMb options; in the AMv1, AMv2 and AMv3 options. the interior surface of the exterior walls presents lower temperature than AMb, leading to heat loses reduction through the exterior walls (Fig. 14).



	AMb - rooftop	AMv1 - rooftop	AMv2 - rooftop	AMv3 - rooftop	CWood/ CSteel - rooftop	AMb - underlying floor	AMv1 - underlying floor	AMv2 - underlying floor	AMv3 - underlying floor	CWood/ Csteel - underlying floor	REF - underlying floor
Total	-3687	-3707	-3683	-3286	-3997	-2700	-2647	-2652	-2649	-2713	-2832
Nat Vent + Infiltration	-252	-255	-253	-259	-219	-439	-388	-405	-409	-437	-441
Roof	-1198	-1183	-1189	-982	-1352	-93	-90	-89	-90	-91	-70
Pavements	-728	-757	-748	-770	-672	-142	-129	-133	-134	-136	-580
Ceilings	0	0	0	0	0	722	752	743	765	677	549
Exterior walls	-1509	-1512	-1492	-1275	-1753	-2749	-2792	-2767	-2781	-2727	-2289

Fig. 14. Annual thermal balance of the various rooftop solutions and existing building (in its original state), through its building elements and air infiltration.

The energy amount required for cooling (not exceeding 25 °C) and heating (not dropping below 18 °C) was calculated using an air-conditioning system (specified in Table II) for the interior useful spaces in the building numerical model in its original state and with the considered vertical extension options.

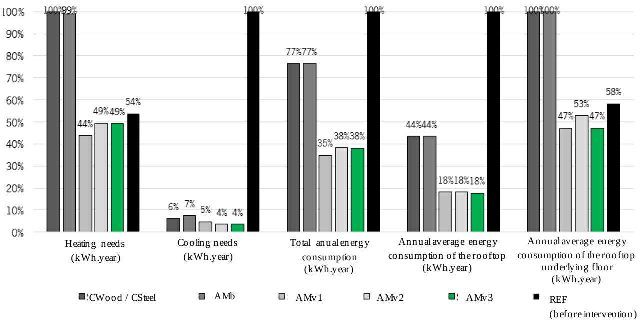


Fig. 15. Energy consumption of rooftop solutions compared to each other and with the existing building.

Looking at the energy performance results in Fig. 15 and Table VII, it can be seen that: (1) the annual consumption of the AMv1 solution is the lowest, by 65% in relation to REF with TS and 42% to the CWood/CSteel options, mainly due to the 96% decrease in energy heating consumption; (2) among all considered solutions under analysis, the alternatives AMv1, AMv2 and AMv3 are those with lower energy consumption in the rooftop useful area (less 82% than TS and 26% than AMb. CWood/CSteel) and in the rooftop underlying floor area (less 11% than TS and 53% than AMb and CWood/CSteel). It should be noted that on the results of the REF model are only included on Fig. 15 and 16 graphs for referential purposes. The TS rooftop that exists on REF solution, i.e. the building in its original state/before the intervention, does not have the same floor area of the remaining solutions; it only appears in Table VII to compare the behaviour of the rooftop underlying floor before the vertical extension intervention with Conventional and Alternative Membrane solutions. In any case, the useful area of the TS rooftop of REF model is so small, when compared to the C or AM solutions, that it was considered as an attic, without occupation.

TABLE VII: OPERATIONAL ENERGY CONSUMPTION OF THE BUILDING WITH THE SOLUTIONS UNDER ANALYSIS. RESULTS OBTAINED BY NUMERICAL SIMULATION

Rooftop solutions:	**Energy for heating needs** (kWh.year)	**Energy for cooling needs** (kWh.year)	**Annual total energy consumption** (kWh.year)	**Energy consumption by Total building area** (kWh/m^2.year)	**Annual average energy consumption of rooftop useful area** (kWh/m^2.year)	**Annual average energy consumption of rooftop's under floor useful area**	**Ranking** (1st =best)
REF with (existing building in its original state)	14480	22427	36907	145	-	93	-
TS	17480	27227	44707	138	170	63	**5**
CWood/ CSteel	32574	1662	34236	105	74	108	**4**
AMb	32200	2040	34240	105	74	108	**4**
AMv1	14279	1283	15561	48	31	51	**1**
AMv2	16106	1000	17107	53	31	57	**3**
AMv3	16070	959	17029	52	30	51	**2**

In an overall and comparative view of all vertical extensions' solutions under study, AMv1 (with the PCM addition on the membrane roof envelope) is the best in terms of energy consumption (Fig. 16) and thermal comfort behaviour.

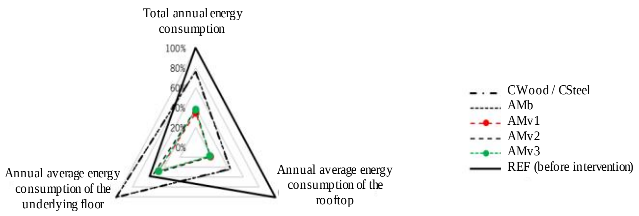


Fig. 16. Comparison of operational energy consumption aspects between conventional and alternative solutions under analysis for vertical extensions (percentage values). The best solution is the one with the smallest polygon area.

D. Energy Consumption – Comparing Different Climatic Zones

To promote more efficient buildings, it is important to know the environment in which they operate in order to get the most out of it, namely, to reduce the use of active HVAC systems. In the previous results it was found that alternative solutions with membranes and unconventional thermal mass are sensitive to climate variations and it is not recommended to assume general assumptions only based on the previous case study's climate zone – where Porto is located. Therefore, each scenario should be studied to evaluate the performance of all refurbishment solutions, especially the membrane options, in order to evaluate their efficiency in terms of energy performance.

Portugal presents three winter climatic zones (I1, I2, I3) and three summer climate zones (V1, V2, V3) regarding thermal quality requirements of the building envelope, as can be seen in Fig 17.

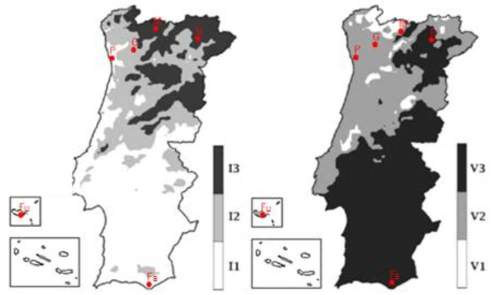


Fig. 17. Portuguese climatic zones for the winter and summer seasons (decree-law no. 15793-F / 2013) pointing out cities under study.

By using the same protocol and calculation model described on Section IV, only changing the climatic data, it was possible to generate results that allow comparing the behaviour of the refurbishment solutions under study in other national climatic zones. The weather data of the following Portuguese cities were used: Porto, Funchal (that belongs to Autonomous Region of Madeira, where there is the highest percentage of refurbishment interventions with extensions in Portugal [33]), Guimarães, Bragança, Faro and Montalegre. Table VIII presents in detail the climatic parameters associated to these cities and the respective climate scenario classification.

TABLE VIII: CLIMATE REFERENCE PARAMETERS FOR DYNAMIC SIMULATION OF THE CITIES UNDER STUDY [25]

Scenery designation/ city	**Case study**	**Island scenario**	**Mid scenario**	**Extreme scenario**		
Climatic parameters	**Porto**	**Funchal**	**Guimarães**	**1 Bragança**	**2 Montalegre**	**3 Faro**
Altitude	86	35	196	900	948	145
Climatic Winter zone	**I1**	**I1**	**I2**	**I3**	**I3**	**I1**
Heating days (ºC days)	1250	818	1653	2015	2015	987
Conventional heating period (months)	7.3	3.2	7.2	7.3	7.3	4.8
Climatic summer zone	**V2**	**V2**	**V2**	**V3**	**V2**	**V3**
Winter average exterio air temperature (ºC)	9.9	14.8	7.8	5.5	5.5	11.3
Summer average exterior air temperature (ºC)	20.9	20.2	20.8	21.5	21.5	23.1
Summer average daily temperature range (ºC)*	10.1	6.4	11.8	15.2	11.3	10.6
Winter average daily temperature range (ºC)**	8.1	5.7	7.8	7.6	6.5	8.2

Notes: * Difference between minimum and maximum daily average temperature for the hottest month of the cooling season; ** Difference between the minimum and maximum daily average temperature for the warmest month of the heating season.

The graphic of Fig. 18 presents the energy consumption results of the building for all scenarios presented at Table 8.

Generally, despite alternative solutions presenting the lowest energy consumption, it is also verified that the existing building (REF), with and without intervention, presents lower energy consumption in the climate zones represented by Faro and Funchal, and higher consumption in the climate zones represented by Montalegre and Bragança (Fig. 18). The graphic of Fig. 18 shows that, generally and in relation to the REF building, climatic zones with higher energy needs present higher percentages of consumption reduction after the extension intervention (from 24% for CWood/CSteel and 57% for AMv3 options). Moreover, alternative membrane solutions have greater reductions in scenarios with lower energy needs. In particular, it is found that AMv3 has the largest reduction in energy consumption for all climate zones, particularly in the case study (Porto) and island scenarios. In general, despite presenting reductions very close to AMv3, in the case study (Porto) AMv1 is the one with the largest reduction of consumption (65%). In this case, in terms of actual savings in absolute numbers, the energy consumption with AMv1 is 18675kW/h less than with CWood/CSteel.

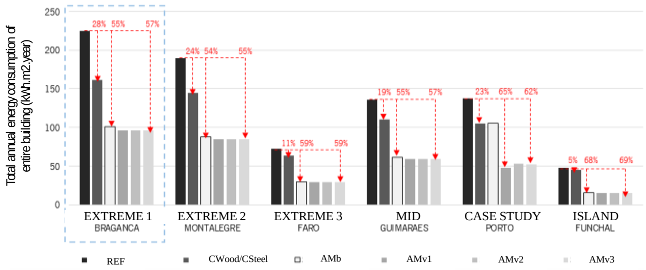


Fig. 18. Annual energy consumption per floor useful area for the entire building with different vertical extension solutions, located in different Portuguese climatic zones.

To determine the impact of different operational energy consumptions, a detailed analysis including heating and cooling energy consumption was performed. This analysis indicates that in all climate zones under study the majority of the operational consumption, 73%, is produced for building heating and only 27% for cooling.

The comparison between the performance of the building with and without intervention shows (Fig. 19): 1) the REF building has the highest percentage of cooling consumption; 2) the building with any alternative membrane variant solution has the lowest percentage of energy consumption for cooling and heating.

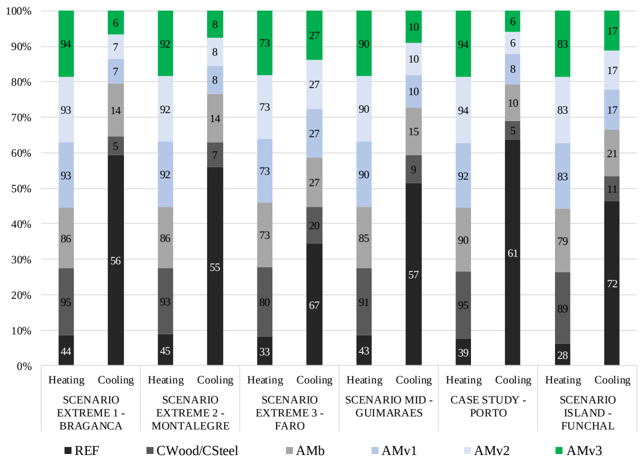


Fig. 19. Percentage of energy consumption for heating and cooling.

As the present study focus on vertical extension interventions, this analysis becomes particularly relevant in an island scenario (such as R.A. Madeira - Funchal), due to the limited resources and land area available to construct new buildings. Thus, focusing attention on the islands scenario, it is verified that this climate zone, with reduced daily and seasonal temperature range, is favourable to the adoption of lightweight construction solutions, in particular of AMv3 (Fig. 20). Overall, operational energy consumption in this climatic zone, namely in Faro and Funchal, accounts for 5 to 9% of total energy compared to the other climate zones under study (Fig. 20). Most of this consumption corresponds to cooling needs (64 to 67%).

The results show that the refurbishment solutions under study benefits the existing building, as the energy consumption at the underlying floor and at the total building is reduced (Fig. 20). In particular, AMb has the highest consumption reduction for most climate zones (from 19 to 25%). In any case, the remaining alternative solutions show very close reductions for both underlying floor and rooftop, even when compared to the conventional solution (Fig. 20).

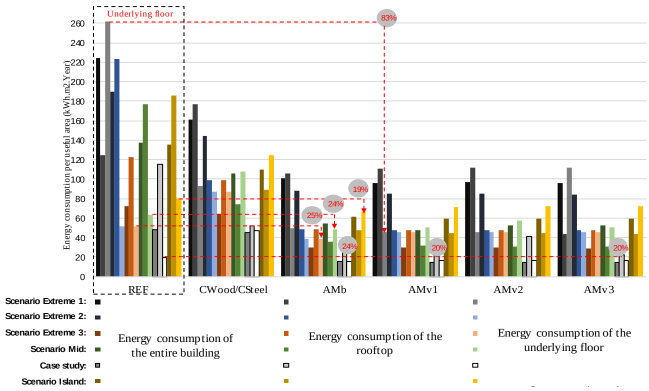


Fig. 20. Energy consumption of the rooftop and the underlying floor with all building technologies and all climate scenarios under study.

Therefore, the use of solutions with unconventional thermal mass, especially AMv3, favours the reduction of: 1) total energy consumption from 57% to 69% (island scenario, in comparison with REF building); 2) heating needs from 5% to 10% (on average and compared to CWood/CSteel building option) to all climate scenarios.

VI. Conclusion

This study focused on a relevant area of textile architecture: functional/energetic building's refurbishment using architectural membranes (textile composites) technologies.

By itself, membranes, because of its low thermal mass and insulation, when forming the outer envelope of a space, cannot provide the required conditions to achieve interior stable thermal conditions. Typically, architectural membranes have about one millimetre thick, around 1 kg/m² of weight and approximately 5 W/(m² °C) of heat transfer coefficient. As a result, architectural membranes are particularly sensitive to weather changing conditions, being affected much faster/significantly than the majority of other building materials. Therefore, it needs to be complemented with other materials.

In this case, if, on the one hand, it is necessary to reduce the weight of the vertical extension elements, on the other hand, to obtain good thermal/energy performance, it is necessary to have a building solution with high thermal mass, which is generally associated with heavy building solutions. To solve this problem, this study proposed lightweight and alternative solutions with unconventional thermal mass.

Architectural membrane materials/technologies, when integrated into a building system, serves as baseline surfaces for the addition of other materials, in multilayer building technologies - with thermal/acoustic insulation and unconventional thermal mass – in order to allow more permanent constructive solution, but with a high deconstructive degree. This study shows that the thermal/energy improvements achieved in alternative membrane solutions are due to the addition of other materials. However, even so, the amount of employed resources is smaller than the conventional reference building solutions and, at least, the same thermal/energy performance can be achieved with a much lower weight per square meter. This is the main advantage of using membrane alternative solutions in vertical extensions, for refurbishment interventions. In a scenario without HVAC, vertical extensions do not change the thermal behaviour of its underlying floor, either in winter or summer. But, when the spaces are air-conditioned, the situation changes and vertical expansion benefits the existing building, reducing its energy consumption to meet heating and cooling needs.

As general conclusion, the presence of a vertical extension can mitigate and improve the indoor comfort of the lower storeys and, consequently, is efficient for the general energy saving of the multi-storey building.

In a near future, it will be possible to integrate water and air insulation layers into membrane multilayer compositions, to allow the increase of thermal and acoustic insulation of transparent/translucent membrane (foils) building solutions. Other properties, such as electrical conductivity and electroluminescence, or the possibility of nanostructures integration, will also be relevant aspects that will positively change membrane functional properties. Considering this, the properties of the building envelope can be specifically adapted to climate parameters, meeting current and future demands for solutions to solve climate change's related problems.

Even with the increasing evolution that membrane materials have made in the recent past, there is still a long way to go before they can be accepted and considered sustainable, especially with regard to social and cultural resistance when it comes to housing. Therefore, in future works, full-scale prototypes of the analysed solutions should be constructed, and experimental tests should be made to increase knowledge and confidence in the use of membrane solutions in specific refurbishment interventions, as vertical extensions.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Paulo Mendonça supervised the research; Mónica Macieira carried out the research and wrote the paper; João Miranda Guedes co-supervised the research; all authors had approved the final version.

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