Development of Prefabricated Retrofit Module towards Nearly Zero Energy Buildings

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Abstract: The building sector is an energy intensive sector, with great potential to reduce energy needs and environmental pollution. Several measures are being taken to increase the energy efficiency and avoid energy consumption in this sector. A recent trend is the nearly zero energy buildings, which was already adopted by some of the latest regulations, such as the 2010 recast of the European Performance of Buildings Directive (EPBD). However, to reach these goals, especially considering the existing building stock, new retrofit solutions are required, which must be well adapted to the specific building stock needs, and ensure that the building retrofit can achieve the nearly zero energy buildings standards. This paper presents a new prefabricated retrofit module solution for the façades of existing buildings, and also the steps taken to optimise its performance, which includes a judicious choice of materials, 3D modelling, cost-benefit analysis, use of different simulation tools for performance optimisation and prototyping. It is also shown the implementation of the retrofit module within an integrated retrofit approach, whose final goal was to obtain a building with the minimum possible energy consumption and greenhouse gas emissions.

Keywords: *Prefabricated retrofit, nearly zero energy buildings, 3D modelling, simulation tools, case study*

1 Introduction

Climate changes are one of the main challenges that modern civilisation has to face. There is a clear association between climate changes and greenhouse gas emissions, whose main sources are the use and production of energy. The international communities are taking strong actions to tackle this problem, namely through public awareness, new standards / regulations and other measures [1,2].

One of the most important sectors to act upon is the building sector, especially considering that, for example in the European panorama, the existing building stock is responsible for the consumption of 33% of raw materials, 50% of electricity use, 16% of final energy in residential buildings and 10% in office buildings [3,4,5].

In line with the international energy awareness, several standards have emerged in the last decade, with increasing levels of exigency. As an example, the newly recast European Performance of Buildings Directive [6] defines the 20-20-20 strategy, establishing goals that all EU member states must comply with by 2020. Member states must also prepare national plans to ensure that new buildings are nearly zero energy buildings (NZEB) by 2020, i.e. buildings that have a very high energy performance. The nearly zero or very low amount of energy still required (exactly targets are not yet defined) must be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. The EU recommends a two-step approach, i.e. application of energy efficiency measures to a cost optimal level and suppression of the remaining energy needs through on-site renewable energy production [7, 8, 9].

Currently there is a lack of building regulations, or even appropriate, well-known and advertised technologies, specifically developed for massive and cost-effective rehabilitation, since, when considering most of the buildings regulations in force, they present simplified methodologies [10] that do not allow the correct assessment of the buildings retrofit interventions. But it is urgent to act on these buildings since they are very large energy consumers in spite of all the efforts made by many states to refurbish the existing building stock.

In Portugal, the existing building stock is responsible for 30.5% of the total energy consumption [11,12]. The reduction of this energy consumption share is a major objective of the national authorities due to the excessive energy dependence - 79.2% of all energy consumed in Portugal is imported [13].

On the other hand, the degradation state of a huge part of the Portuguese building stock assumes proportions that can be considered alarming, with 40% of the building stock presenting repair needs [14]. This causes a reduction in the quality of life of the citizens and a deterioration of the built heritage, as collective memory. In view of these new events, a study on the potential of the retrofit market was recently conducted which predicted that the Portuguese building retrofit market in 2010 would rise up to 74,617 million euro, having in mind the high retrofit needs, especially considering that only after 1990 the use of insulation was widespread, although with very low thickness (2 to 4 cm). Due to the global market crisis in general and to the Portuguese construction sector crisis in particular, this goal has not yet been reached. Even thought, the retrofit market increased its share of the construction sector market from 20% on 2008 to 35% on the first trimester of 2012 [15, 16]. However, in spite of this growth, retrofit is many times considered too expensive or ineffective and, therefore, the current practice is limited to executing building envelope maintenance or simply demolishing and rebuilding.

In order to reverse this trend, some prefabricated solutions have been developed lately to facilitate the buildings retrofit and also to provide more attractive solutions with simpler and quicker application methods [17]. Although still a weak sector in Portugal, industrialisation, rather than on-site construction, is already a reality all over the world. Currently, prefabrication is widely used in the construction of new buildings, with the application of precast concrete façades and staircases, aluminium windows, panel walls for internal partitions and other components [18]. Nowadays it is also possible to use prefabricated brick walls, with advantages over the in-situ constructions, such as independence from weather conditions, high quality and rapid assembly on site [19,20]. However, the introduction of prefabrication in the retrofit market is more difficult given the greater challenges at technical level. Several studies are still needed for the technical and economic characterisation of existing solutions in order to obtain a massive use of this technique.

In this sense, this paper presents the development of a Prefabricated Retrofit Module (PRM) for building façades adapted to the Portuguese reality, developed within the framework of the IEA ECBCS Annex 50 project and the Portuguese national project FCOMP-01-0124-FEDER-007189. This paper includes the PRM solution description as well as its optimisation process in terms of economic performance, thermal performance and moisture presence. It is also shown the results obtained in terms of thermal performance for a case study that was submitted to a complete integrated retrofit intervention, which included the application of the PRM panels.

2 Prefabricated Retrofit Module - PRM

The concept behind the prefabricated retrofit module (PRM) development is that the PRM should be simple, easy to apply, ensure high quality and have economic viability. The module was developed considering the following guidelines:

- Increase the energy efficiency of residential buildings, contributing to the achievement of NZEB standards;
- Be an integrated solution capable of including hot water, ventilation, heating and/or cooling ducts inside the module;
- Apply materials with high potential for reuse/ recycling and incorporate materials with low embodied energy;
- Reduce the execution/application time with lower financial investment;
- Comply with the Portuguese building regulations, particularly the regulation on the thermal performance of buildings [21];

The materials incorporated into the module were chosen considering the optimum balance between the energy performance and environmental impact and are the following:

- Agglomerated black cork insulation (ABC) – industrial production without additives; 100% recyclable material, lightweight, very abundant in Portugal;
- Extruded polystyrene (XPS) – technical possibility of moulding or creating cavities to lodge ducts; competitive price;
- Aluminium finishing - 100% recycled material; easy to manipulate with traditional working tools;

Based on the previously selected materials, a 3D CAD tool (Google SketchUp® [22]) was employed in order to test different module designs and to allow for solutions (Figure 1) with good aesthetics and duct integration.

The prefabricated retrofit module is a panel with one-metre length and one-metre height and 17.8 cm thickness, resulting in a panel with a weight of 12 kg/m^2. The panel materials composition (from the inside to the outside) is the following: aluminium composite exterior finishing (6mm); agglomerated black cork insulation (20mm); smart vapour retardant; steel U-profiles (1.5mm); extruded polystyrene insulation (XPS – 120mm) with or without moulded ducts or cavities for ducts and cables; agglomerated black cork insulation (30mm); aluminium composite exterior finishing (6mm).

The connection between the modules is based on two steel U-profiles on each side of the modules, with a system of pins and holes to be fitted into a support structure that is bolted to the existing wall.

This connection system will help the module fit into the metal support structure and also to connect the modules side by side. The fitting system of the modules, placed on their sides, is a steel U-profile with a thickness of 1.5 mm (Figure 2).

3 Methodology of Module Optimisation

In order to be effective, the module should be adapted to the building stock, have optimal energy performance and the mounting system has to work as designed.

3.1 Optimise the module performance

To ensure that the use of the developed retrofit module has no unpleasant side effects, it was considered essential to verify the potential existence of thermal bridges and to assess the risk of moisture. The software THERM – 2D heat transfer model [23], which is based on the finite element method, was applied to analyse the thermal bridges of the retrofit module. The moisture problems inside the module were studied with the application of WUFI®, which is a tool designed to calculate the simultaneous heat and moisture transfer in a building component [24]. The simulations carried out on WUFI were made for a whole year, applying a climatic file from Lisbon (only Portuguese location available by the tool at the time) which considers the average climatic conditions over the last 20 years. Also the interior conditions considered were: interior temperature of 22.5ºC (average value between the recommended heating and cooling set point by the Portuguese regulation); and a relative humidity of 50% (value recommended by the Portuguese regulation). To simulate the PRM solution, each material layer and its properties were introduced in the tool.

3.2 Optimise the insulation thickness

The strategy followed to optimise the insulation level was to select a typical building with repair needs (Figure 3, left), use a dynamic energy simulation tool – eQuest [25] – to obtain the building model (Figure 3, right), apply the PRM to the building envelope with different insulation thicknesses – from 7 to 18 cm – and thus obtain the energy needs and the associated final energy consumption of the original building and of all the proposed alternatives.

The case study chosen was a single-family house from the 1980s with an area of 55 m^2, a structure of steel reinforced concrete pillars and beams, single pane CMU (Concrete Masonry Unit) exterior walls (U-value of 1.9 $W/m^2 \cdot K$) and single glazing windows with aluminium frame (U-value of 4.1 $W/m^2.K$).

With the costs of the intervention and the respective energy savings associated with the different alternatives, a parametric study was carried out to ascertain the present net value (PNV) and the modified internal rate of return (MIRR) for different interest rates and thus obtain the optimal insulation thickness in a cost-benefit perspective.

3.3 Retrofit Module Prototypes

The prototype implementation and monitoring are essential steps to validate the performance of the developed prefabricated retrofit module.

The two major indicators that require *in-situ* evaluation are the U-value of the PRM module (determined by measuring its thermal resistance) and the thermal bridges associated with the application of the module (identified by using an infrared camera).

With this objective, several prototypes of each PRM design have been produced. The installation of the prototypes and the corresponding monitoring system was carried out in a test building at the School of Engineering campus, University of Minho.

The test buildings are a group of three buildings with a rectangular shape, as shown in Figure 4, and are the following: the sustainable test building (STB), the conventional test building (CTB) and the adiabatic test building (ATB), which is a highly insulated test building.

In this study, the PRM modules were applied to the ATB, specifically to a brick partition wall which was built for this purpose at the centre of the ATB, as shown in Figure 4.

The thermal resistances of PRM modules were measured by applying the ASTM Sum Technique from the Standard C1155–95 [26]. This method requires the measurement of the heat flux and both interior and exterior surface temperatures of all the envelope elements. Afterwards, the thermal resistance (R_e) for a time interval of 100 hours was obtained with the help of Equation (1):

$$R_e = \frac{\sum_{k=1}^{M} (T_{isk} - T_{esk})}{\sum_{k=1}^{M} q_{ik}} \quad (1)$$

With:

q_i	heat flux (W/m^2)
T_{is}	interior surface temperature (ºC)
T_{es}	exterior surface temperature (ºC)
M	thermal resistance measuring time interval (h)

However, it was necessary to carry out convergence and variance tests in order to guarantee the integrity of the data applied to calculate the thermal resistance of the walls. The convergence of two consecutive time intervals must be less than 0.1 and the variance must be inferior to 10%, as shown in Equations (2) and (3):

$$CR_n = \frac{R_e(t) - R_e(t-n)}{R_e(t)} \quad (2)$$

$$V(R_e) = [s(R_e) / Mean(R_e)] * 100 \quad (3)$$

With:

N	number of Re values (N≥3)
t	convergence test time interval (h)
n	time lag interval (h)

For this case study, the time lag applied in the convergence test was 12h (as recommended by the ASTM). Also, the confidence interval of the results was obtained by applying the accuracy of the heat flux meter [27], ±2% of daily totals, and the calibration of the thermocouples, ±0.5ºC.

The thermal bridge analysis of the PRM prototype was executed with the help of an infrared camera.

4 Integrated Retrofit with PRM

One of the main objectives intended with the development of the PRM is to achieve an effective product that can be applied to a building retrofit process, and thus contribute to increase the energy efficiency of the Portuguese building stock, in line with the EU targets.

To test this approach, two integrated building retrofits were simulated: a single-family building previously presented (chapter 3.2); and a multi-family building with retrofit needs (Figure 5). This approach was based on the EPBD recast [6] two-step approach, and by using a dynamic energy simulation tool [25].

The multi-family building chosen was a building with four floors, 14 apartments, with an area of 452 m², a structure of steel reinforced concrete pillars and beams, double pane brick masonry exterior walls (U-value of 1.19 W/m²·K) and double glazing windows with aluminium frame (U-value of 2.9 W/m².K).

The first step of the building retrofit - energy measures - was based on:

- Case Study 1 (single-family building) - application of the PRM on all exterior walls, replacement of the existing windows by double glazing windows with metallic frames with thermal break, application of 10 cm of XPS insulation on the floor, roof and walls in contact with non-heated spaces (the floor was insulated to maintain the same level of insulation on all building envelope and prevent some possible pathologies like the occurrence of condensations), application of a mechanical ventilation system with heat recovery with efficiency of 80% (in order to drastically reduce the heat losses/gains by infiltration) and replacement of the domestic hot water gas heater (efficiency of 50%) by a condensation gas boiler (efficiency of 102%);
- Case Study 2 (multi-family building) - application of the PRM on all exterior walls, application of 10 cm of XPS insulation on roof and floors in contact with non-heated spaces, application of a mechanical ventilation system with heat recovery with efficiency of 55%.

The second step was the application of on-site renewable energy sources:

- Case Study 1 (single-family building) - installation of solar collector panels for domestic hot water with 3.8 m^2 of effective area, south oriented, and the installation of photovoltaic panels with 8.3 m^2 of effective area with a nominal power of 1.05 kW;
- Case Study 2 (multi-family building) - installation of solar collector panels for domestic hot water with 27.9 m^2 of effective area, south oriented, and the installation of photovoltaic panels with 8.3 m^2 of effective area with a nominal power of 1.05 kW;

The area of PV panels considered was the maximum area allowed by the Portuguese government according to the incentives program for renewable energy, in which all the energy produced by the PV panels must be sold to the electric company at 0.325€/kWh, that is almost three times the energy price paid by the final consumer – 0.131€/kWh[1].

The input conditions of each case study were:

- Heating setpoint: 20ºC;
- Cooling setpoint: 25ºC;
- Climatic file: Guimarães (average climatic conditions);
- Lighting, equipment and occupancy power density: 4 W/m^2;
- Lighting, equipment and occupancy schedule: tool default schedule for a residential building,

5 Results

5.1 Optimise module performance

To study possible thermal bridges in the retrofit module, several sections were analysed: connection between module and support structure; steel U-profiles section; docking area between modules; standard zone; cavity zone. Figure 6 shows the module section (a) and the results obtained with THERM software tool regarding the flux magnitude (b), coloured infrared diagram of the temperature (c) and isotherm lines (d).

With the help of the heat flux tool, a significant thermal bridge was identified on the docking area of the PRM. To reduce this thermal bridge, a new insulation distribution was considered, i.e. all the agglomerated black cork insulation was moved to the exterior surface of the PRM leading to a single layer of cork with a thickness of 6 cm. This solution is called the optimised solution (Figure 7, right). Figure 8 shows the results obtained with this new insulation distribution.

The calculated U-Values of all the PRM sections analysed are the following:

- Connection section for the original solution – simulated U-Value = 1.1 W/(m²·K);
- Connection section for the optimised solution – simulated U-Value = 0.7 W/(m²·K);
- Middle section for both solutions – simulated U-Value = 0.21 W/(m²·K);
- Cavity section for both solutions – simulated U-Value = 0.33 W/(m²·K).

[1] prices in force in September 2012. Source: Edp, 2012

The critical zones regarding the possible presence of moisture inside the retrofit module occur in the connections between different materials, and between the module and the existing wall. Several different sections of the PRM panel were analysed by applying the transient heat and moisture transport tool.

With this tool it was possible to study the hygrothermal behaviour of the PRM solutions during a period of one year. The results are presented in Figure 9, where it is shown the temperature inside the module (dark grey), the variation of relative humidity (light grey) and water accumulated due to condensation (black).

The absence of black areas in either module solutions results graph indicates that there is no risk of moisture build-up.

5.2 Insulation thickness

To optimise the insulation thickness in a cost-benefit perspective, a parametric study was conducted. In this study, nine different insulation thicknesses were applied, as presented in table 1.

A dynamic energy simulation was applied to the case study considering the original situation and the nine PRM solutions. The main objective of this study was to determine the building heating needs. The average price of the diesel fuel considered in this study was 0.098 €/kWh. Table 1 shows the results obtained by simulation.

Also, a detailed economical analysis was carried out for an investment period of 20 years (building design service life – 50 years; building age – 30 years), where the net present value (NPV) and the modified internal return rate (MIRR) of each solution were calculated. Considering that the NPV of a time series of cash flows (inflows and outflows) is defined as the sum of the present values of the cash flows of the same individual entity and the MIRR is the refresh rate that the NPV of costs (negative cash flows) of the investment equals the NPV of benefits (positive cash flows) of the investment. For the calculation of the parameters mentioned above were applied the equations 4 and 5 [28,29]:

$$NPV = \sum_{t=0}^{N} \frac{R_t}{(1+i)} \qquad (4)$$

$$MIRR = \sqrt[n]{\frac{Positive\_Cash\_Flow}{Negative\_Cash\_Flow}} - 1 \qquad (5)$$

With:

i – Interest rate;
R_t – Cash flow of a given period of time (t);
t – Cash flow of the analysis period;
N – Total number of periods in analysis.

Figure 10 presents the average values of NPV and MIRR for the different PRM solutions studied in terms of the different insulation thicknesses. The interest rates used in this study varied from 0.5% to 6% (in order to take into account the current market instability), and the results presented in Figure 10 are an average of the results obtained for all the different interest rates considered.

5.3 Retrofit Module Prototypes

The construction of the retrofit module prototypes comprises the following steps:

- Production of the steel U-profiles and support structure;
- Application of the XPS insulation in the steel U-profiles;
- Production of the aluminium finishing with box shape;
- Application of the smart vapour retardant and cork insulation in the aluminium finishing;
- Connection of the aluminium finishing to steel U-profiles.

With the construction of the base prototypes finished, the next step was to place them on the partition wall of the test building to perform in-situ measurements. To this end, it was only necessary to mount the support structure on the wall and the consequent placing of the PRM modules in the support structure, as shown in Figure 11.

The measured U-value for the standard PRM section was 0.19 ± 0.004 W/m^2.ºK, and for the cavity section (duct area) it was 0.30 ± 0.016 W/m^2.ºK. This resulted in an overall U-value for the PRM solution of 0.23 ± 0.007 W/m^2.K, as previously foreseen.

With the use of a thermography camera, several infrared pictures were taken showing the temperature variation between different sections of the PRM module (Figure 12).

5.4 Integrated Retrofit with PRM

The two-step approach suggested by the EPBD recast was applied to two building retrofit case studies with the aim of achieving a nearly zero energy building.

The first step was the application of several building envelope improvement measures and substitution of mechanical systems.

Through dynamic simulation it was possible to determine the influence of the energy measures regarding the overall building energy performance, as shown in Table 2 (case study 1) and Table 3 (case study 2).

The second step was the use of two on-site renewable sources, in order to suppress the remaining energy needs of the retrofitted building:

Case Study 1 (single-family building)

- Solar collector panels for domestic hot water (DHW): collector area of 3.8 m^2 associated with a 300 l deposit, which resulted in the supply of 2058 kWh/year of energy for DHW;
- Photovoltaic panels: collector area of 8.3 m^2 and a nominal power of 1.05 kW, which resulted in the production of 1312 kWh/year of electrical energy.

Case Study 2 (multi-family building)

- Solar collector panels for domestic hot water (DHW): collector area of 27.9 m^2 associated with a 1500l deposit, which resulted in the supply of 13540 kWh/year of energy for DHW;
- Photovoltaic panels: collector area of 8.3 m^2 and a nominal power of 1.05 kW, which resulted in the production of 1312 kWh/year of electrical energy.

Considering the solar collector panel contribution, the DHW needs of the retrofitted building are of only 3.5 kWh/m^2.y for case study 1 and 16.6 kWh/m^2.y for case study 2. The original and retrofitted building energy balances were executed in relation to the final energy consumption, i.e. energy needs with associated systems efficiency. The results are shown in Table 4 (case study 1) and Table 5 (case study 2).

Additionally, several suppliers were consulted in order to obtain estimates for the implementation of the retrofit measures for each case study, as shown in Table 6 (case study 1) and Table 8 (case study 2).

With the retrofit measures estimates it was possible to obtain the payback periods, i,e,, the period necessary to assure the return of the investment on the retrofit measures (Table 7 and Table 9, for case study 1 and 2, respectively).

6 Discussion

With the proposed prefabricated retrofit module design, it was possible to obtain a product with a high recycling potential, based on the use of low embodied energy materials, on the deconstruction and on the improvement of the energy efficiency.

Regarding the module optimisation process, the thermal bridges study showed that the critical heat flux occurs on the docking area between the modules. Thus, the corrective measure applied was a new distribution of the agglomerated black cork insulation, which led to an 80% reduction in heat flux, drastically reducing the thermal bridge. In terms of moisture build-up it was verified that none of the solutions were problematic.

To optimise the PRM system to the Portuguese building stock, a cost-benefit analysis of the insulation thickness was carried out. It was concluded that the thickness that leads to a smaller payback period (6.9 years) with the best return rate of the investment is that with 12 cm of XPS and 5 cm of ABC, a U-value of 0.23 $W/m^2.K$ and a cost of application of 46.9 €/m^2.

Through the extensive measurement campaign performed on the PRM prototypes, it was possible to observe that the U- values measured were similar to the ones predicted ($U_{measured}$ = 0.230 ± 0.007 $W/m^2.K$; $U_{predicted}$ = 0.228 $W/m^2.K$), and that small thermal bridges were detected as predicted by simulation. Also PRM module (final solution) was optimised regarding the reduction of thermal bridges that resulted on a one-metre length by one-metre height panel with a thickness of 18.8 cm, a weight of 13 kg/m^2 and a U-value of 0.208 W/m^2.K. Figure 13 shows the optimised PRM solution.

The application of an integrated retrofit strategy to a single-family and to a multi-family building, based on the PRM system, resulted in:

- A retrofitted single-family building with 83% reduction of the overall energy needs, although with a small increase of the cooling needs. This fact can be explained due to the high level of envelope insulation in combination with the low infiltration rate and high building thermal inertia that results on a longer period necessary to cool the building during the night time (or in periods when the exterior temperature is under 25ºC) and thus increasing the cooling needs. Since these cooling needs are not significant, the global building energy balance after the retrofit still result on a building that has almost no energy needs. The amortization period of these measures was 6 years;
- A retrofitted multi-family building with 76% reduction of the overall energy needs. The amortization period of this situation was 4,6years,

7 Conclusions

A prefabricated retrofit module was developed and optimised having in mind the Portuguese building stock and their retrofit needs, considering the use of solutions with cost-effective insulation thicknesses, within the frame of the international project IEA ECBCS Annex 50 and the national Project - FCOMP-01-0124-FEDER-007189. The developed PRM solution has a measured overall thermal resistance of 4.35 m^2·K/W and a U-Value of 0.23 W/(m^2·K). It presents a small thermal bridge in the docking area section, between modules, and no significant thermal bridges occur in any other sections. The module shows no risk of moisture build-up.

A major advantage of this module is the type of connection to the existing wall that can greatly reduce the installation time. Another advantage is the simplicity of the fabrication method that can guarantee the quality of the solution.

As an example, the application of this solution to a test building resulted in the reduction of the U-value of the exterior opaque envelope from 1.7 to 0.2 $W/(m^2 \cdot K)$. When an integrated retrofit strategy has been implemented, also based on the PRM module and on-site renewable energy sources, the single-family retrofitted building presents a reduction of 83% of the total energy needs, 14% of which is due to the application of the PRM solution, and the multi-family building, presents a reduction of 76% of the total energy needs, 16% of which is due to the application of the PRM solution.

Therefore, this is a solution with good performance indicators, showing great potential for use in high-quality low energy building retrofit. It should be noted that this solution has been developed and optimised for the Portuguese reality. However, this solution can also be a valid option for the realities of other countries, using different materials but maintaining the same concept. Just as an example, table 10 shows alternative solutions considering different materials for the PRM module that are more widespread worldwide but that can lead to very similar energy performances rather than the original solution. However, previously to the application of these alternative solutions an extensive validation of the final solution is always necessary.

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TABLES WITH CAPTIONS

Table 1 – Simulated heating needs and associated Payback period of evaluated PRM solutions.

Solution	**Insulation Thickness** [cm]	**Heating Needs** [kWh/m^2.y]	**Heating final Energy** [kWh/m^2.y]	**Energy bill for Heating** (€/year)	**Savings** (€/year)	**Payback Period** (years)
Original	0	267.4	351.9	1874.1	-	-
PRM 1	18	219.0	288.2	1534.7	339.4	7.3
PRM 2	**17**	**219.8**	**289.2**	**1540.3**	**333.8**	**6.9**
PRM 3	15	225.6	296.8	1580.9	293.2	7.2
PRM 4	14	228.2	300.3	1599.1	275.0	7.3
PRM 5	13	231.5	304.6	1622.3	251.9	7.6
PRM 6	11	236.1	310.7	1654.5	219.6	7.9
PRM 7	9	240.5	316.4	1685.3	188.8	8.2
PRM 8	8	243.9	320.9	1709.1	165.0	8.8
PRM 9	7	246.3	324.1	1726.0	148.1	9.2

Table 2 – Case Study 1: Energy needs of original and retrofitted building

Solution	**Energy Needs** [kWh/m^2.y]			**Energy Reduction** [%]			
	Heating	Cooling	DHW	Heating	Cooling	DHW	Total
Original	267.4	0.4	83.7	-	-	-	-
Integrated Retrofit	16.1	2.3	41.0	-94	+83	-51	-83
Only with PRM	219.8	0.04	83.7	-18	-90	0	-14

Table 3 – Case Study 2: Energy needs of original and retrofitted building

Solution	**Energy Needs** [kWh/m^2.y]			**Energy Reduction** [%]			
	Heating	Cooling	DHW	Heating	Cooling	DHW	Total
Original	81.3	18.9	52.3	-	-	-	-
Integrated Retrofit	4.5	15.6	16.6	-94	-17	-68	-76
Only with PRM	57.6	18.7	52.3	-29	-1	0	-16

Table 4 – Case Study 1: Energy balance of original and retrofitted building

Solution		Heating	Cooling	DHW	Total	PV	Energy Balance
Final Energy ($kWh/m^2.y$)	Original	371.4	0.1	83.7	455.3	0.0	455.3
	Integrated Retrofit	22.3	0.6	3.5	26.4	24.1	2.3

Table 5 – Case Study 2: Energy balance of original and retrofitted building

Solution		Heating	Cooling	DHW	Total	PV	Energy Balance
Final Energy ($kWh/m^2.y$)	Original	101.6	6.3	52.3	160.2	0.0	160.2
	Integrated Retrofit	5.0	5.2	16.6	26.8	24.1	2.7

Table 6 – Case study 1 - Retrofit total cost estimation (€).

PRM	Roof slab insulation	Ground slab insulation	Glazings	Boiler	Solar collector	Mechanical ventilation
2466	1041.2	1041.2	1200	2000	2728	2469

Table 7 – Case study 1 - Simulated total final energy (heating, cooling and DHW) and associated Payback period of retrofit solutions.

Solution	Total final Energy [kWh/y]	Energy bill (€/year)	Savings (€/year)	Investment (€)	Payback Period (years)
Original	24762.9	2254.6	-	-	-
Integrated Retrofit	1436.2	89.3	2165.3	12945	6.0
Only with PRM	21163.1	2165.3	333.8	2466	7.0

Table 8 – Case study 2 - Retrofit total cost estimation (€).

Solution	Equipments	Glazings	Frames	Doors	Ventilation	PRM
Original – maintenance	2080	4075	31380	19862	-	-
Retrofit	7079	8032	51025	16081	8000	29467

Table 9 – Case study 2 - Simulated total final energy (heating, cooling and DHW) and associated Payback period of retrofit solutions.

Solution	Total final Energy [kWh/y]	Energy bill (€/year)	Savings (€/year)	Investment (€)	Payback Period (years)
Original	149490	17254	-	58062	-
Integrated Retrofit	25004	3903	13351	119660	4.6
Only with PRM	121788	12593	4661	29467	6.3

Table 10 – Alternative solutions in terms of materials for the retrofit module

Thickness (mm)	Original Retrofit Module Materials	Alternative retrofit module Materials		
6	Aluminium composite finishing	Aluminium composite finishing	Aluminium composite finishing	Aluminium composite finishing
60	Agglomerated black cork insulation	Rock wool insulation	Glass wool insulation	Rock wool insulation
1.5	Steel U-Profile	Steel U-Profile	Steel U-Profile	Steel U-Profile
120	Extruded Polystyrene insulation	Rock wool insulation	Polyurethane panel insulation	Expanded polystyrene insulation
1	Vapour retardant	Vapour retardant	Vapour retardant	Vapour retardant
U-Value $W/(m^2 \cdot K)$	**0.23**	**0.23**	**0.24**	**0.24**

FIGURE CAPTIONS

Figure 1: 3D model of the PRM solution – a) without duct integration; b) molded ducts; c) cavity for necessary additional wiring.

Figure 2: Retrofit module fitting system

Figure 3: Case study with retrofit needs. Left - photograph; Right – simulation model

Figure 4: Test buildings south façade (left) and partition wall for prototypes application (right).

Figure 5: Prefabricated retrofit module original solution - docking area section

Figure 6: Original and optimized PRM solution composition

Figure 7: Prefabricated retrofit module optimized solution - docking area section

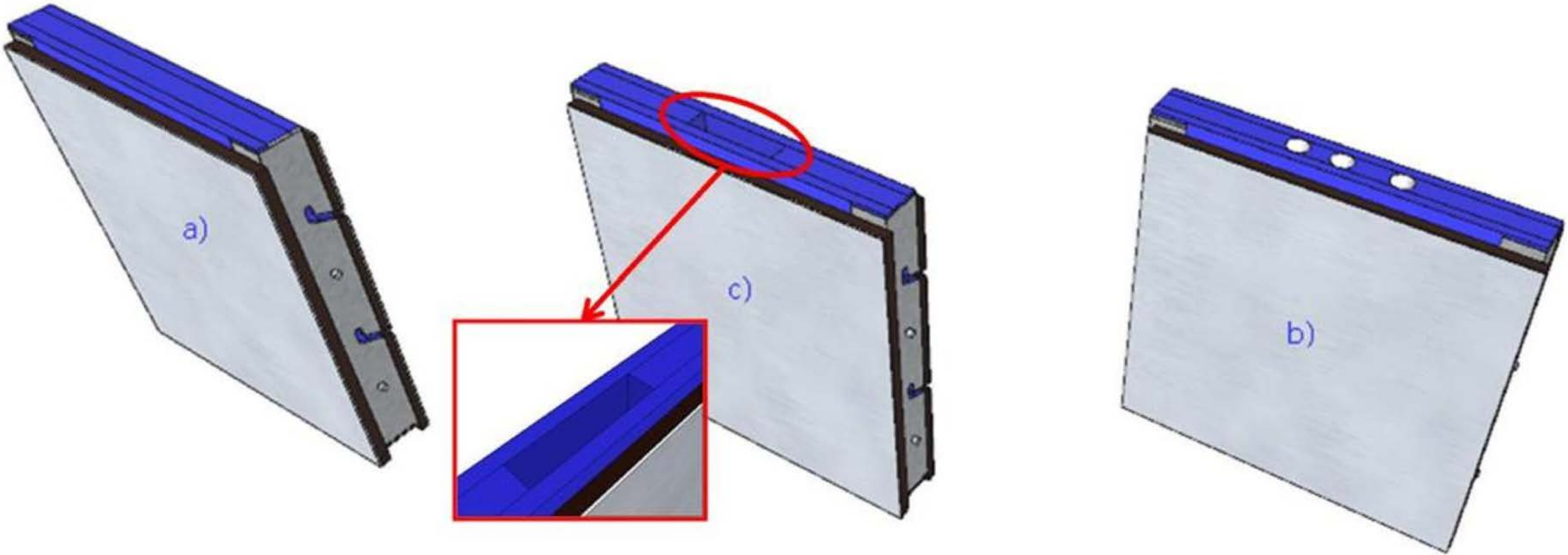
Figure 8: Original (top) and optimized (bottom) prefabricated retrofit module moisture analysis

Figure 9: NPV and MIRR for different PRM solutions applied to case study

Figure 10: PRM prototypes applied on the test building

Figure 11: Infrared pictures of the PRM prototypes applied on the test building

Figure 12: PRM optimized design – a) without ducts or cables; b) with ducts and cables cavities; c) with moulded ducts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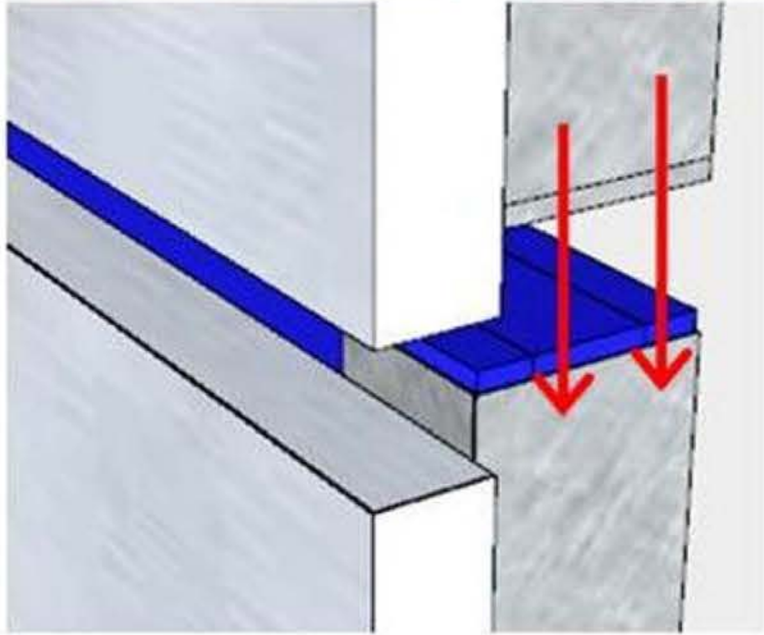

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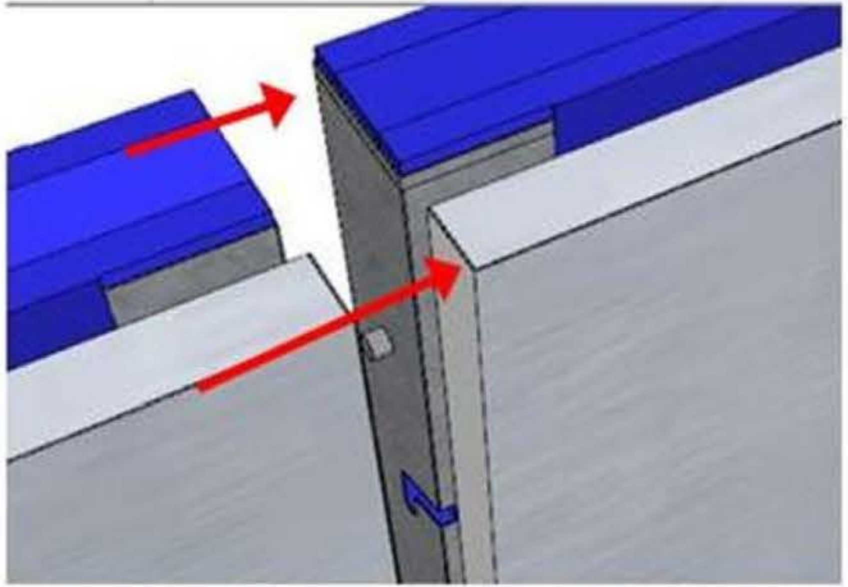

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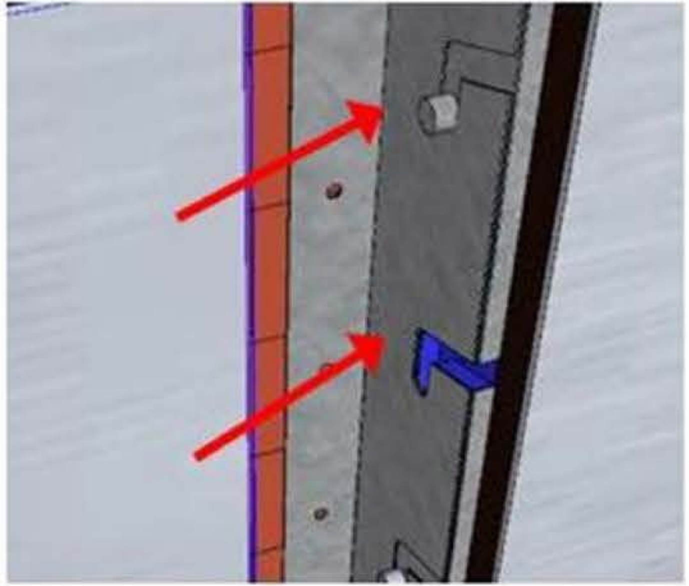

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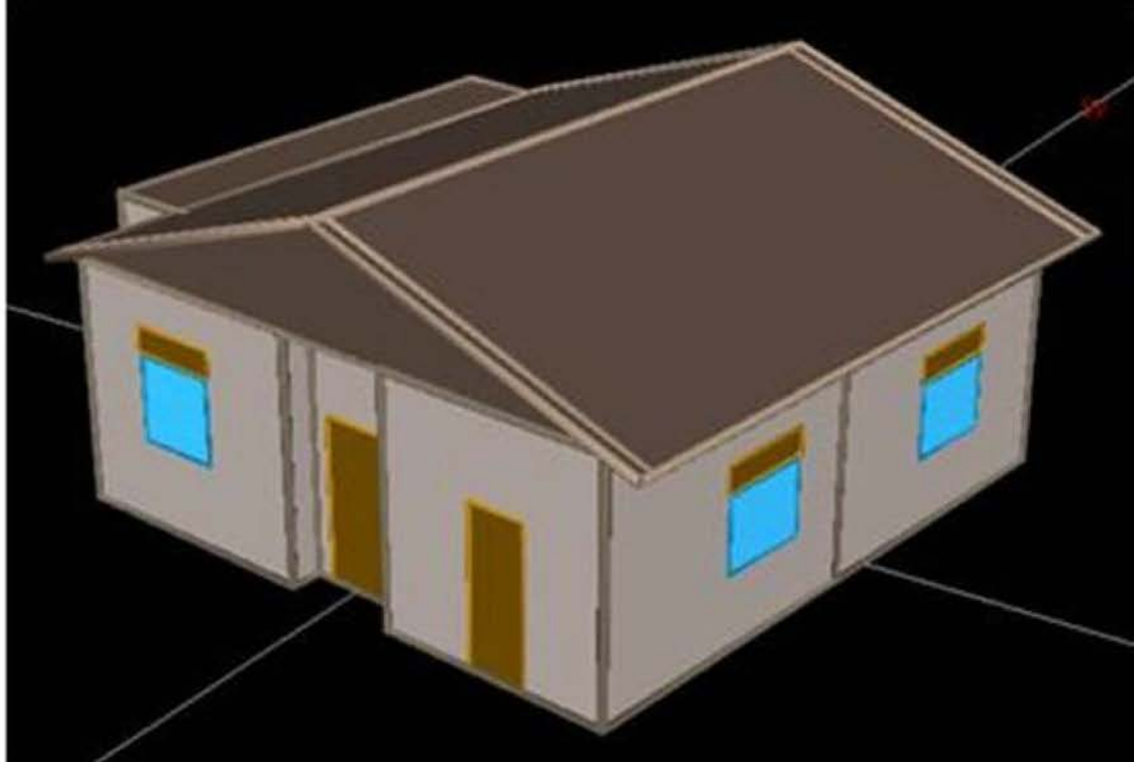

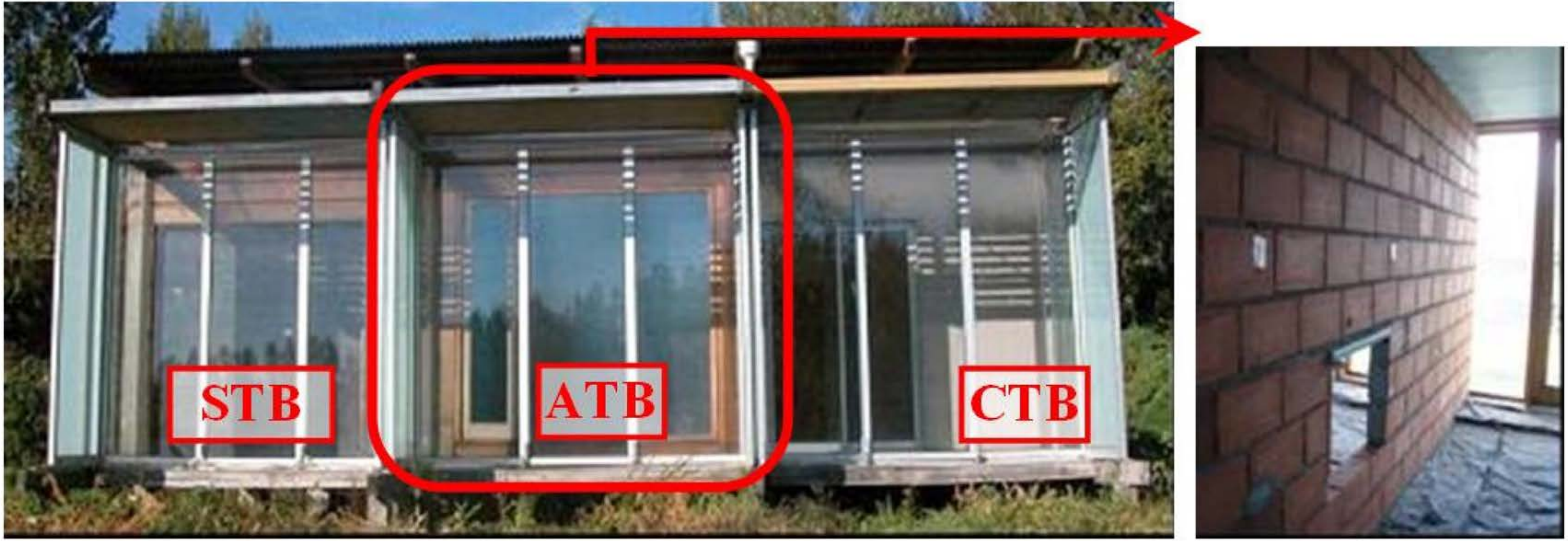
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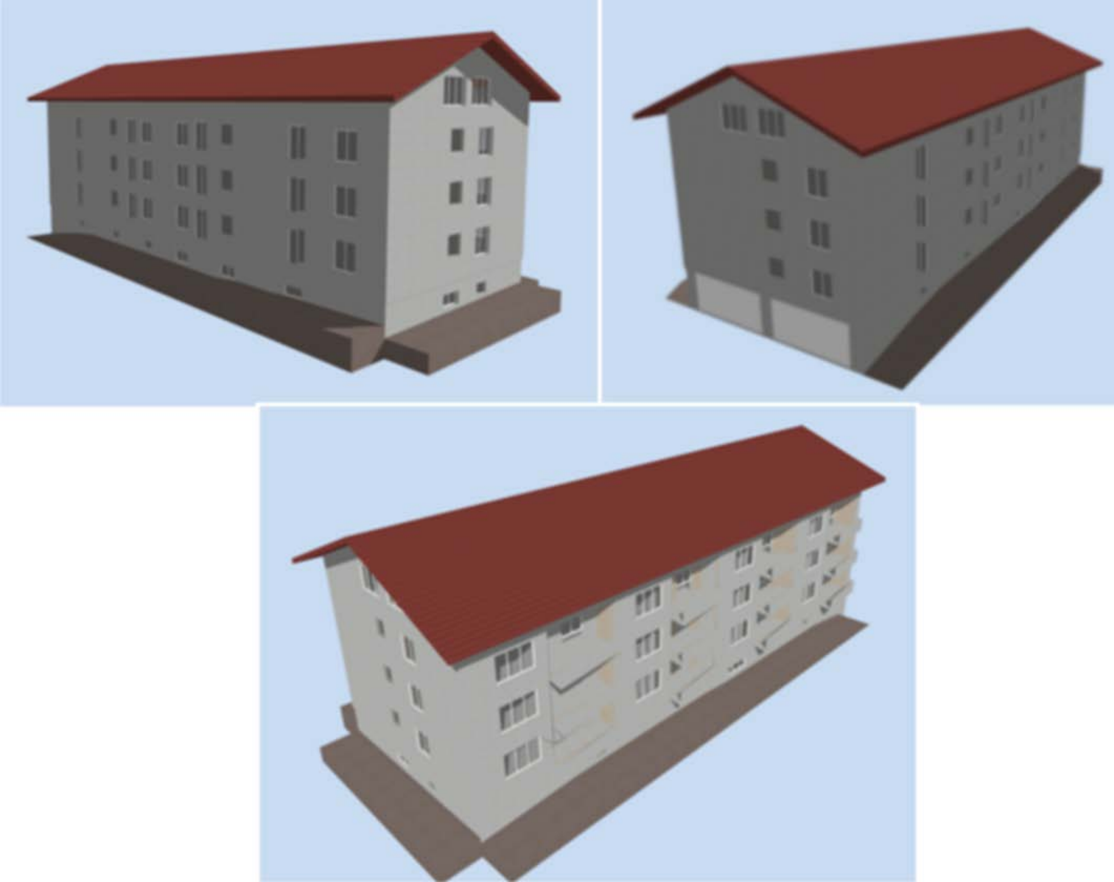
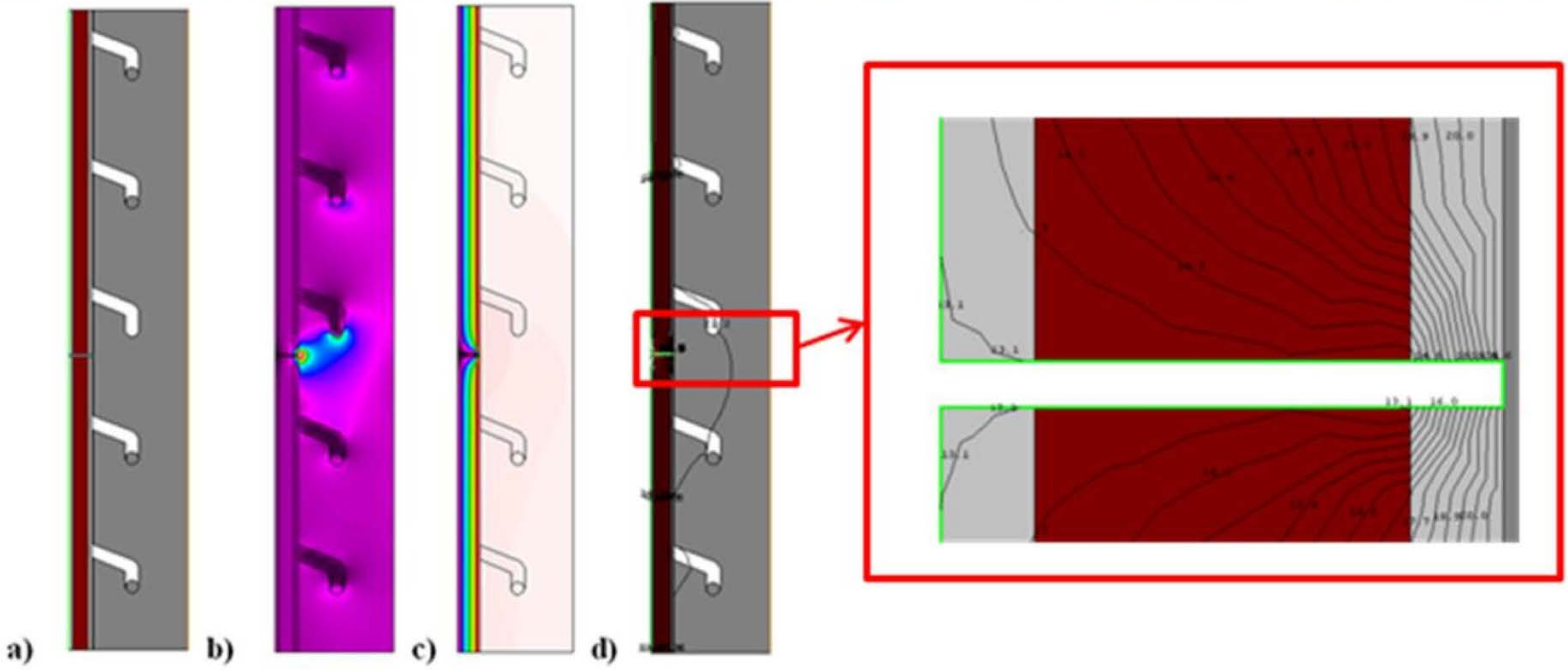
ATB
CTB




a)
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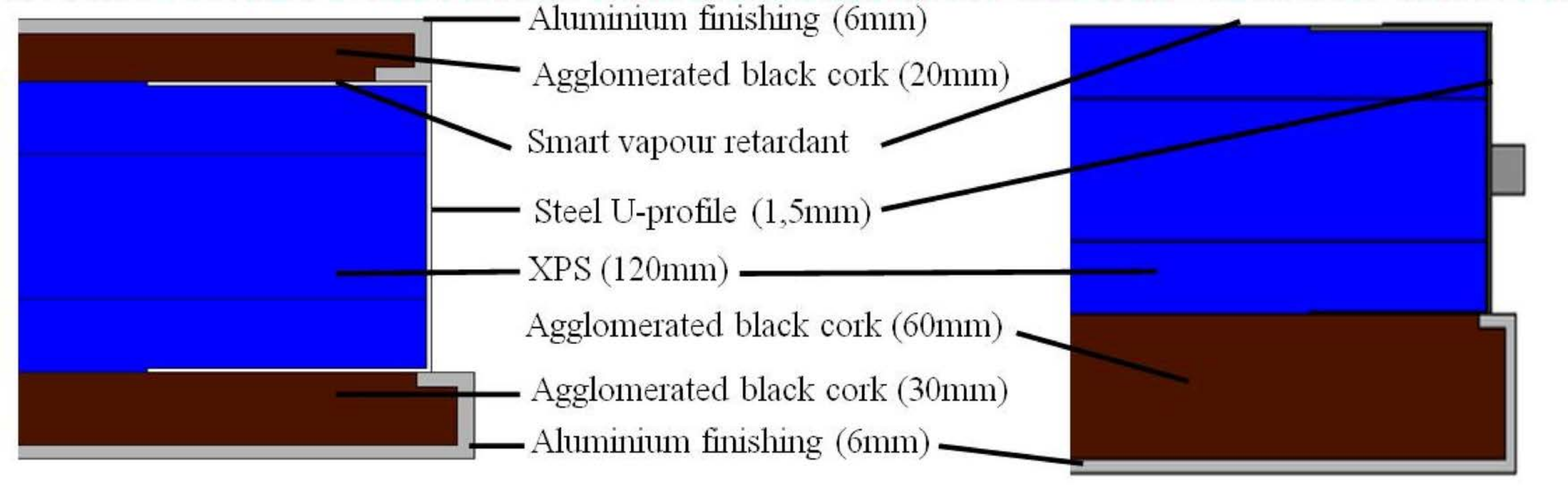
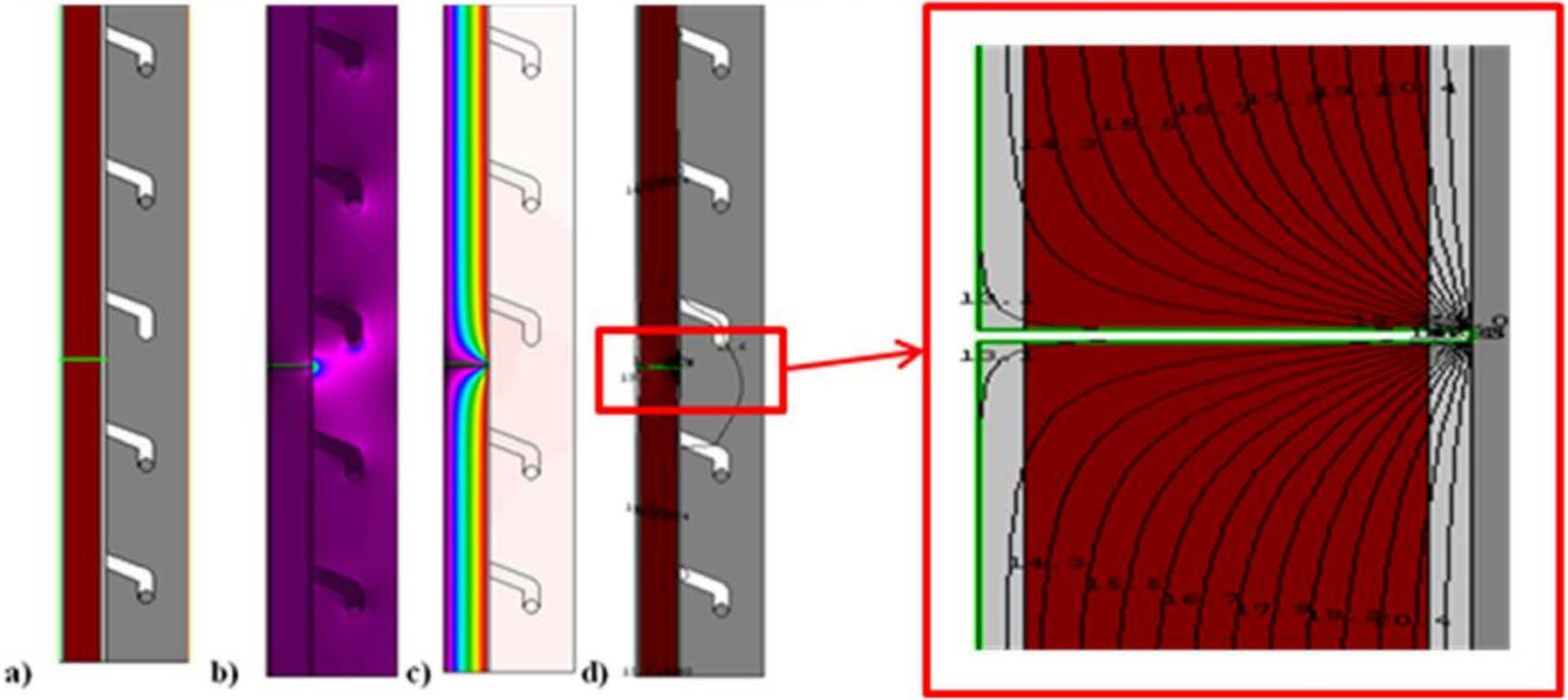

Aluminium finishing (6mm)
Agglomerated black cork (20mm)
Smart vapour retardant
Steel U-profile (1,5mm)
XPS (120mm)
Agglomerated black cork (60mm)
Agglomerated black cork (30mm)
Aluminium finishing (6mm)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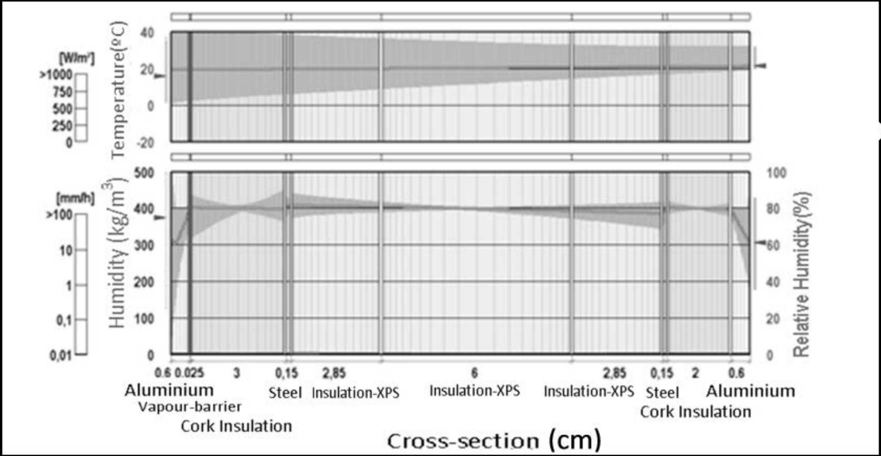
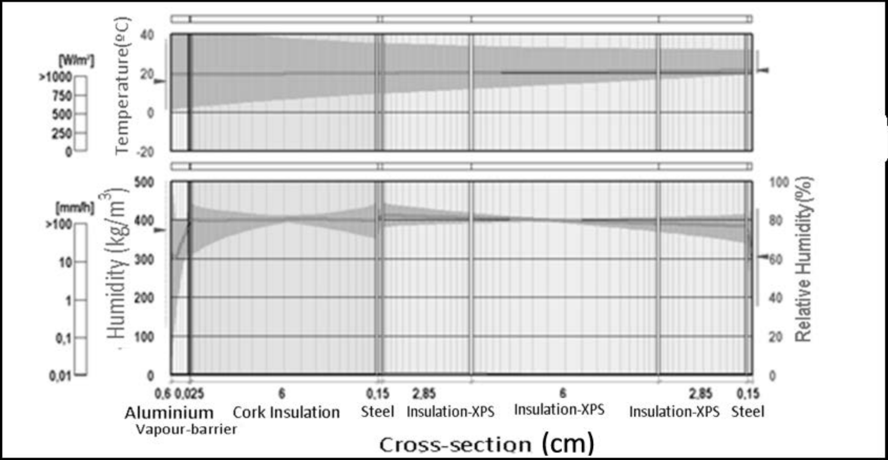


[W/m²]
>1000
750
500
250
0
Temperature(ºC)
40
20
0
-20
[mm/h]
>100
10
1
0,1
0,01
Humidity (kg/m³)
500
400
300
200
100
0
Relative Humidity(%)
100
80
60
40
20
0
0.6 0.025 3 0,15 2,85 6 2,85 0,15 2 0.6
Aluminium
Vapour-barrier
Cork Insulation
Steel
Insulation-XPS
Insulation-XPS
Insulation-XPS
Steel
Cork Insulation
Aluminium
Cross-section (cm)



[W/m²]
>1000
750
500
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Temperature(ºC)
40
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-20
[mm/h]
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1
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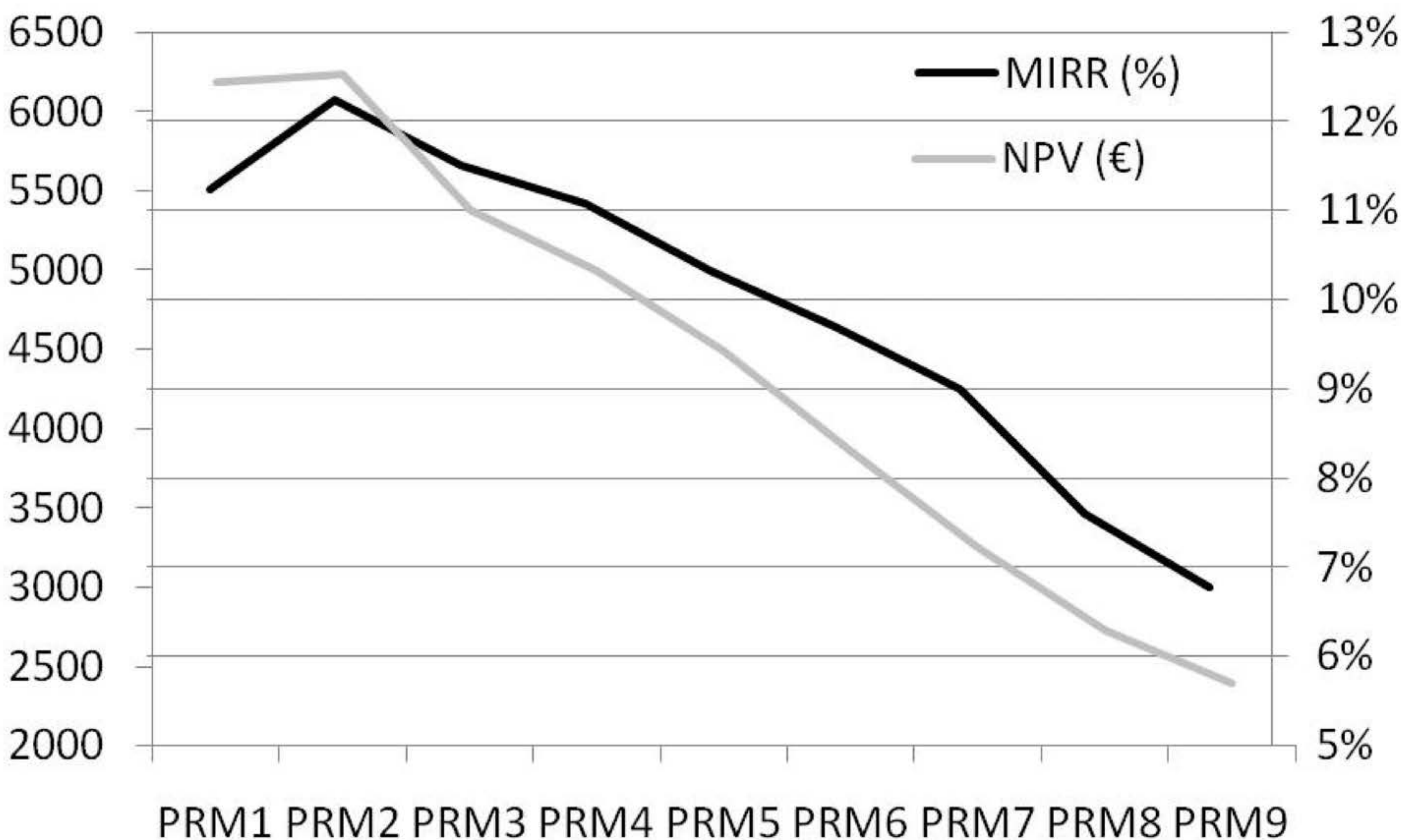
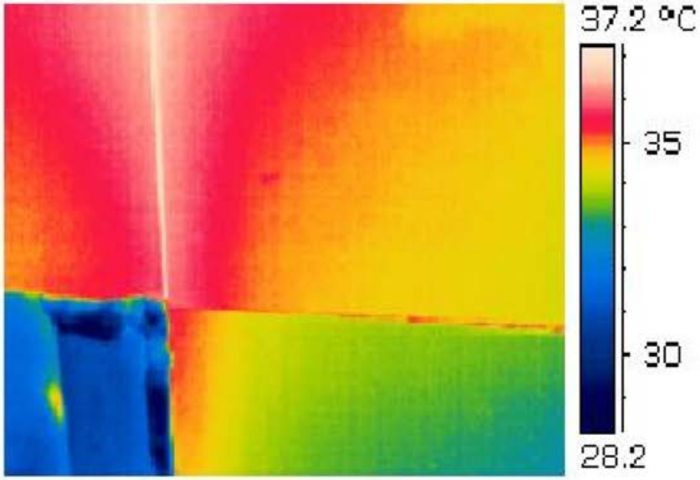
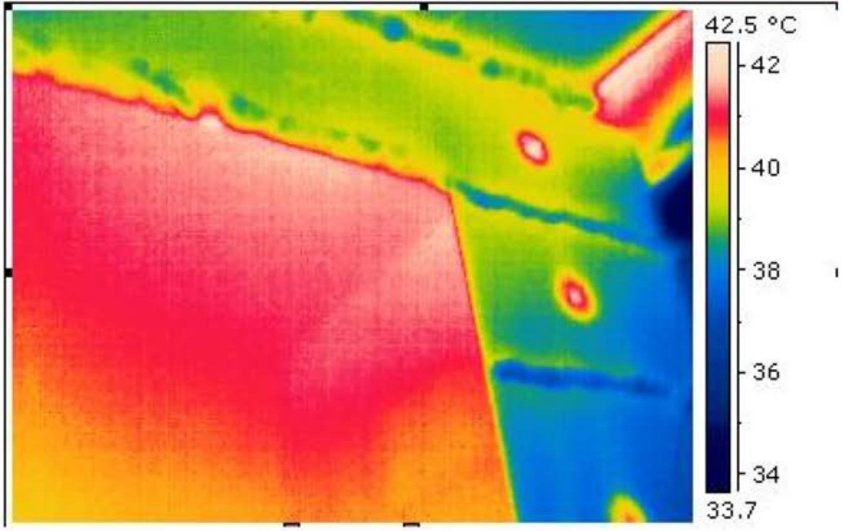
0,01
Humidity (kg/m³)
500
400
300
200
100
0
Relative Humidity(%)
100
80
60
40
20
0
0,6 0,025 6 0,15 2,85 6 2,85 0,15
Aluminium
Vapour-barrier
Cork Insulation
Steel
Insulation-XPS
Insulation-XPS
Insulation-XPS
Steel
Cross-section (cm)

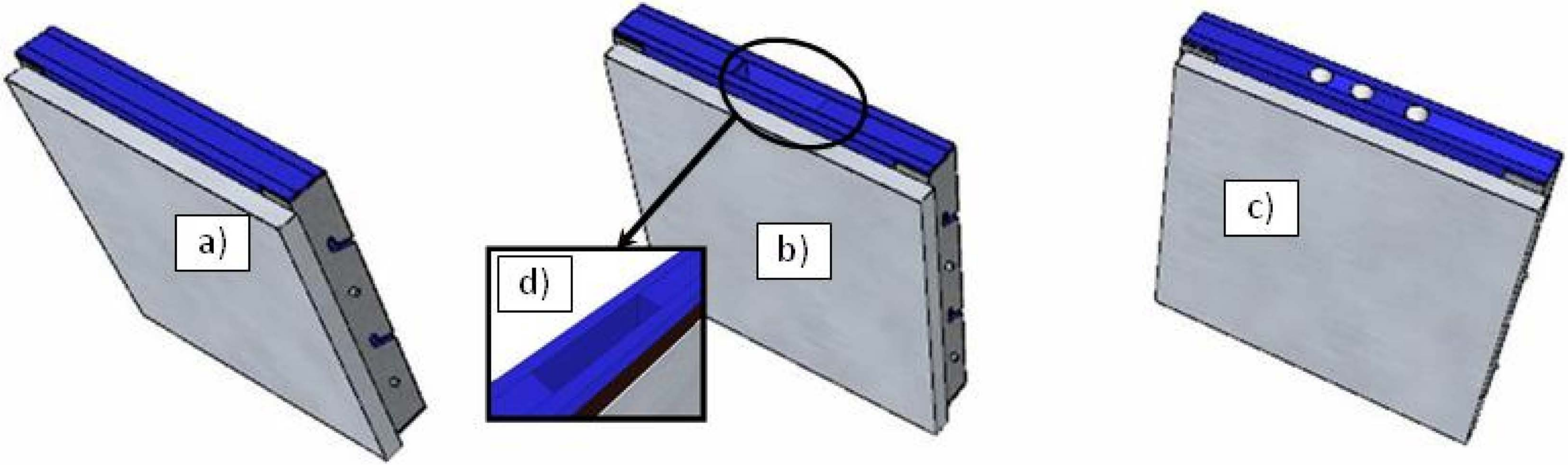


6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
13%
12%
11%
10%
9%
8%
7%
6%
5%
MIRR (%)
NPV (€)
PRM1 PRM2 PRM3 PRM4 PRM5 PRM6 PRM7 PRM8 PRM9





37.2 °C
35
30
28.2


42.5 °C
42
40
38
36
34
33.7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