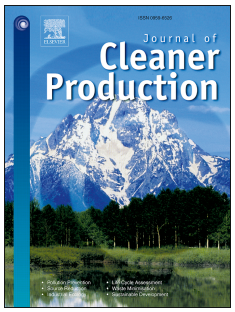
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Wall and roof solutions for a retail building considering cost investment and life cycle approach: A case study in Portugal

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Wall and roof solutions for a retail building considering cost investment and life cycle approach: a case study in Portugal

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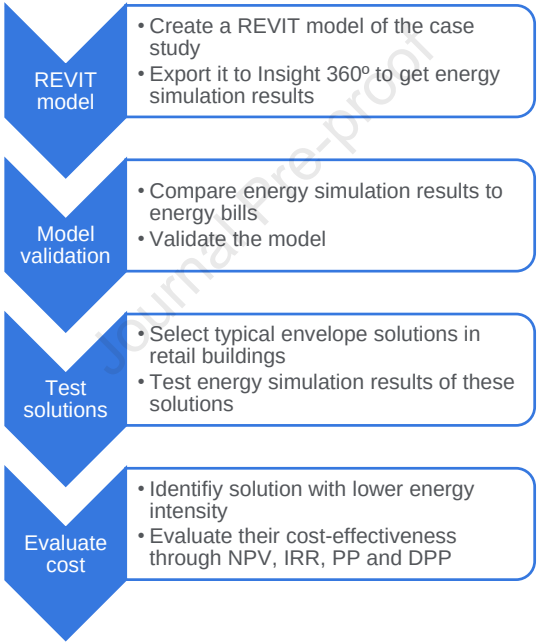
Wall and roof solutions for a retail building considering cost investment and life cycle approach: a case study in Portugal

The U-values of walls and roofs for retail buildings according to the transposition of the EPBD to Portugal, could be lower and still be cost-effective

This study set out to explore how does standard practice in the retail construction industry compare to EPBD codes in terms of energy and cost-effectiveness.

Additionally, envelope retrofitting solutions that retailers can resort to in stores behind current building codes demands were discussed.

A large retail store in Algarve, Portugal, was selected as a case study to analyze the impact of different typical envelope solutions in the annual energy performance of the building.



Results indicate that the envelope solution that constitutes the case study is at a near cost-optimal level. Under an estimated economic lifecycle of 50 years, as pointed by the EPDB, several solutions can offer energy savings, namely vacuum insulation panels of 2,5cm, and sandwich panels of 8, 10 or 12 cm. This leads to the conclusion that the U-values of walls and roofs mentioned in the legal instruments that transpose the EPBD to Portugal could be lower and still be cost-effective.

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Wall and roof solutions for a retail building considering cost investment and life cycle approach: a case study in Portugal

Abstract

This study explored which envelope solutions in retail buildings led to cost-optimal levels considering the Energy Performance of Building Directive and Portuguese regulation. For such, energy simulations were run in BIM software based on the analysis of a case study in Portugal. Typical alternative solutions were tested against the original case study, and solutions with considerably lower U-value considering the code for commercial buildings (0,7 W/m^2.°K for walls and 0,5 W/m2.°K for roofs). To assess the cost-effectiveness of alternative envelope solutions, the Payback Period, the Net Present Value and the Internal Rate of Return at 15 years and 50 years were assessed. Results indicate that solutions with lower U-values are related to 2-5% savings in energy consumption and can be cost-effective at 15 and 50 years, namely vacuum insulation panels of 2.5 cm and sandwich panels of 8-12 cm. This leads to the conclusion that lowering present code U-values can be cost-effective, but it will result in additional initial costs.

Keywords

Retail buildings, U-value, envelope, EPBD, energy simulation, REVIT plugin Insight 360º

1. Introduction

Buildings are the single largest energy consumer in Europe, representing approximately 40% of the European Union's (EU) energy consumption and 36% of the EU's energy-related greenhouse gas (GHG) emissions [1]. To accelerate the energy performance of buildings, the EU has established a legislative framework that includes the European Directive for the Energy Performance of Buildings (EPBD) [2] and the Energy Efficiency Directive [3], as policies that help member states promote a highly energy efficient and decarbonized building stock by 2050, and as such, to mitigate the effects of climate change.

Nevertheless, not all industry sectors consume energy equally. Indeed, retail buildings have one of the highest Energy Use Intensities (EUI) [4], which makes them an important sector to target for the improvement of energy efficiency in buildings. EUI values in retail buildings are three times higher than those of office buildings and five times higher than residential ones. The average EUI values are around

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548 kWh/m²/year for food retailers and 238 kWh/m²/year for nonfood retailers [5]. In addition, retail buildings have high energy consumption at the same time as energy utility peak demands [6] as they operate when most businesses and services do, which further attests to the significance of this segment of buildings for increased energy performance. Therefore, decreasing energy demand in retail buildings could also reduce energy supply pressure from the grid at critical periods.

Most of the energy consumed in nonfood retail buildings is for HVAC systems and refrigeration and HVAC systems in food retail buildings [4]. Thus, the choice of materials that constitute the envelope of retail buildings is of the utmost importance to improve the overall energy performance of this typology of buildings. Envelope materials with high thermal resistance (Rt) or low thermal transmittance (U-value) enable the reduction of energy losses, as they function as powerful thermal insulators and therefore reduce heat transfer between outside and inside, which in Mediterranean climates such as Portugal, leads to low energy consumption in HVAC systems [7]. Recognizing the importance of the envelope in the energy performance of buildings (as 25% of the energy consumption of buildings depends on the envelope) [8], the 2018 amendment to the EPBD requires member states to set cost-optimal minimum energy performance requirements for new and refurbished buildings, and for the replacement of building elements like roofs and walls [3]. The EPBD also requires member states to provide numerical indicators for buildings' energy performance, such as EUI, which normalizes the annual energy consumption per m² of floor area per year [3], with the goal of assisting consumers and business owners in informed decision-making with regards to saving energy and lower expenditure costs.

As defined by the EPBD, the building envelope is made of the integrated elements of a building which separate its interior from the outdoor environment [3]. Previous studies identified the influence of the envelope on the energy performance of buildings. However, few of those studies addressed retail buildings in specific: Jiang and O'Meara [14] explored the thermal resistance of envelope elements of commercial buildings in Florida; Balaji *et al*. [15] investigated the thermal performance of six different masonry walls used in commercial and residential buildings in India, Ooteghem and Xu [16] studied structural and envelope building materials in a single-story retail unit in Canada from a Life Cycle Assessment (LCA) perspective, Chau *et al.* [17] investigated the environmental impact of building materials for commercial buildings in Hong Kong, Huang *et al.* [7] investigated retrofitting thermal insulation and high-reflectivity wall coatings in commercial buildings and Dowd and Murshed [18]

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investigated the sensitivity of 36 multi-layered wall types in a commercial building.

In parallel, some studies examined energy-efficiency measures for building services as a means of decreasing life cycle energy consumption in commercial buildings, such as Galvez-Martos *et al*. [19] by identifying best practices to improve the energy performance of the retail sector, and Tassou *et al.* [20] by reviewing emerging technologies for refrigeration systems. Other studies assessed the impacts of building envelope airtightness in retail buildings: Emmerich and McDowell [21], Bartko *et al*. [22], and Bhandari *et al.* [23] estimated energy savings in commercial buildings resulting from improvements in airtightness, while Ng *et al.* [24] analyzed the interior air quality and energy impacts of ventilation strategies and building envelope airtightness in a big box retail building. In addition, an array of authors studied new developments for alternative envelope materials in commercial buildings. Atinafu *et al.* [25] assessed the thermal properties of composite organic phase change materials (PCMs), Silva *et al.* [26] reviewed the use of PCMs in glazing and shading solutions, Pasupathy *et al.* [27] investigated the application of PCMs for thermal management in residential and commercial establishments and Hu and Yu [28] simulated an energy analysis of thermal and light-responsive building envelope under different climate conditions. Gonçalves *et al.* and Alam *et al*. [29,30] investigated the use of Vacuum Insulation Panels (VIPs) in external insulation finishing systems and non-domestic buildings, while other authors researched thin-walled fibre-cement elements [31], cool walls [32], cool roofs [33], reflective materials applied to exterior building components [34,35], thermally efficient precast concrete sandwich panels [36], or solar walls [37]. All these studies focus mainly on energy and environmental analysis but do not address the cost-benefit analysis of implementing strategies to reduce energy consumption, mainly in retail buildings. Current knowledge about what makes for best practices amongst retailers in terms of envelope solutions to reduce EUI at a cost-effective level, as proposed by the EPBD, is extremely limited. The call for applied research on this subject via the investigation of case studies has been identified by Omer and Noguchi [38], which could also better understand the part that building materials can play in the Agenda 2030 goals [39].

In addition, most building solutions used by retailers typically focus on their energy performance and solutions with shorter payback time [40]. This is mostly due to commercial buildings being considered assets that should yield the greatest return on investment with minimum financial risk. Hence, investors seek to obtain adequate performance at the lowest cost [40]. However, the disclosure of environmental

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impacts in LCA studies provides data to support informed decision-making in business sectors. In this way, retailers may choose a costlier solution that has better environmental performance, more aligned with their corporate social responsibility strategy [41]. It is in this way that Life Cycle Cost (LCC) and LCA studies are increasingly being incorporated in decisions towards the choice of building solutions, as several studies support the use of these tools in decision-making processes: Gluch and Baumann [42] studied the usefulness of LCC for environmental decision-making, Ding [43] analyzed the role of environmental assessment tools in sustainable construction, Malmqvist *et al.* [44] introduced a simplified methodology to conduct LCA studies, Forsberg and Malmborg [45] compared five different tools for quantitative environmental assessment and Zabalza *et al.* [46] presented a state-of-the-art and simplified LCA methodology as a complement for building certification. Studies in the literature regarding LCA and LCC in retail stores are missing, despite their importance in minimizing the impacts caused by the continuous growth of this sector.

This study is innovative by providing insight into how building codes could be pushed further in terms of the U-value for retail buildings at a cost-effective level. Two specific questions were tested: i) "*How does standard practice in the retail construction industry compare to EPBD codes in terms of energy and cost-effectiveness*?" and ii) *"What envelope retrofitting solutions can retailers resort to when standard building practice can be behind building codes demands?* A large retail standalone building in Algarve, Portugal, was selected as a case study to analyze the impact of envelope solutions on annual energy performance. Choosing a real retail building as a case study allows identifying how new national building codes under the EPBD compare to standard practice in the retail construction industry. If new building codes require insulation levels that are already nearly standard practice, they have no real impact on fostering continuous improvement. By comparing the thermal characteristics of the envelope required by new building codes to recently built retail stores, the baseline that is used for assessing the energy impacts of these building codes can be further validated. In addition, by considering a longer period of analysis and by setting the life cycle of envelope materials at 50 years, the array of envelope solutions that can be considered cost-effective is widened, thus conferring value to long-term return-on-investments, in turn inverting the focus on short to medium-term paybacks. Figure 1 depicts the graphical abstract of the conducted study.

Hence, the findings of this study can assist project teams, property owners and asset managers of retail

buildings in quantifying the cost-effectiveness of the tested envelope solutions. Additionally, this study's findings can inform policymakers about the effectiveness of existing national regulations supporting the EPBD quest for increased energy performance of buildings and net-zero-energy buildings as a future reference in the building stock [49].

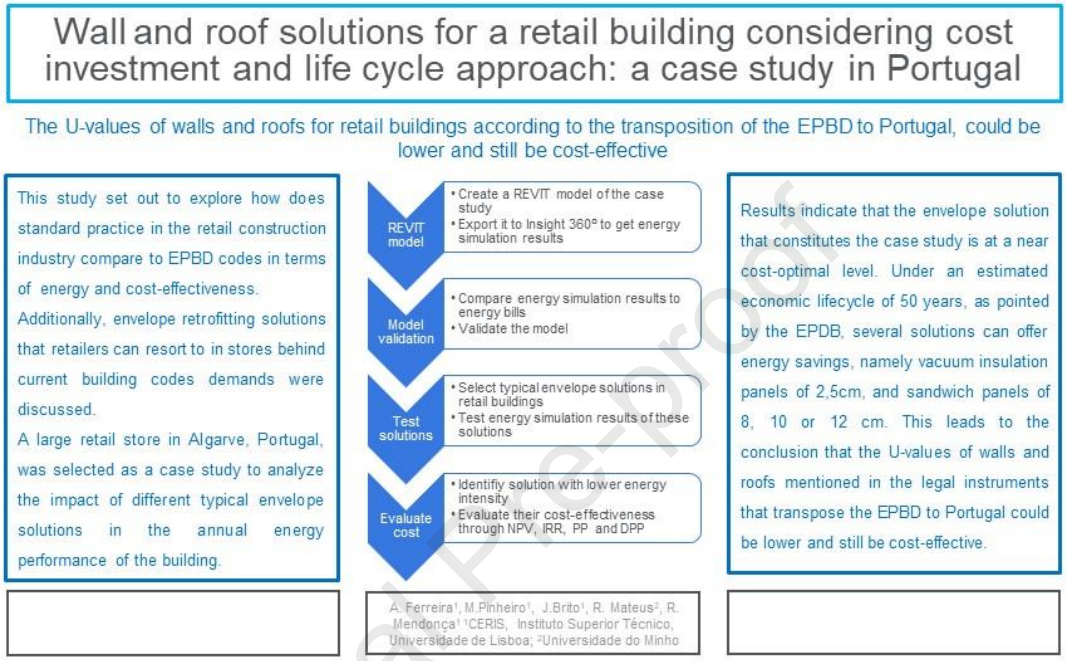


Figure 1 - Graphical abstract

2. Materials and methods

For the present case study, a 3D model of the retail store was produced, a Building Information Modeling (BIM) software - REVIT® -, which served as the basis to carry out energy simulations according to changes in materials in the building's envelope. Typical solutions found in the retail group's existing buildings were tested to assess the energy performance of standard practice envelope materials, as well as solutions with lower U-value currently not used by the retail group in Portugal, to assess their cost-effectiveness in terms of energy consumption. Energy simulation results were analyzed according to Portuguese regulations, which stipulate parameters for the thermal behaviour of commercial buildings, in line with the EPBD requests: the decree-law 101-D/2020 [47] and Ordinance 138-I/2021 [48].

2.1 Description of the case study

A retail store located in the South of Portugal, in the Algarve region, was selected as a case study (Figure 2). The store is part of one of the top global Do-it-yourself (DIY) and home improvement retail

groups, operating in Europe, South America, and China.

This store was selected as a case study because it is one of the group's most recent stores in Portugal (opening in 2017). Nonetheless, it has been in operation for four years, which is enough to establish an energy consumption profile of the store, as pointed out by Kelsey [50]. Typical alternative envelope-building solutions found in the group's property portfolio were tested against the original case study (solutions 1 to 15) to analyse their potential differences in energy consumption. Additionally, envelope solutions with lower U-value currently not used by the retail group in Portugal were also tested to evaluate whether new materials can offer more cost-effective solutions than the ones that are currently standard practice (solutions 16 to 20). These solutions were comprised of either typical envelope materials available in the market that can be readily used (solutions 17, 18 and 20) or represent new developments for alternative envelope materials in commercial buildings, such as vacuum-insulated panels (solutions 16 and 19).

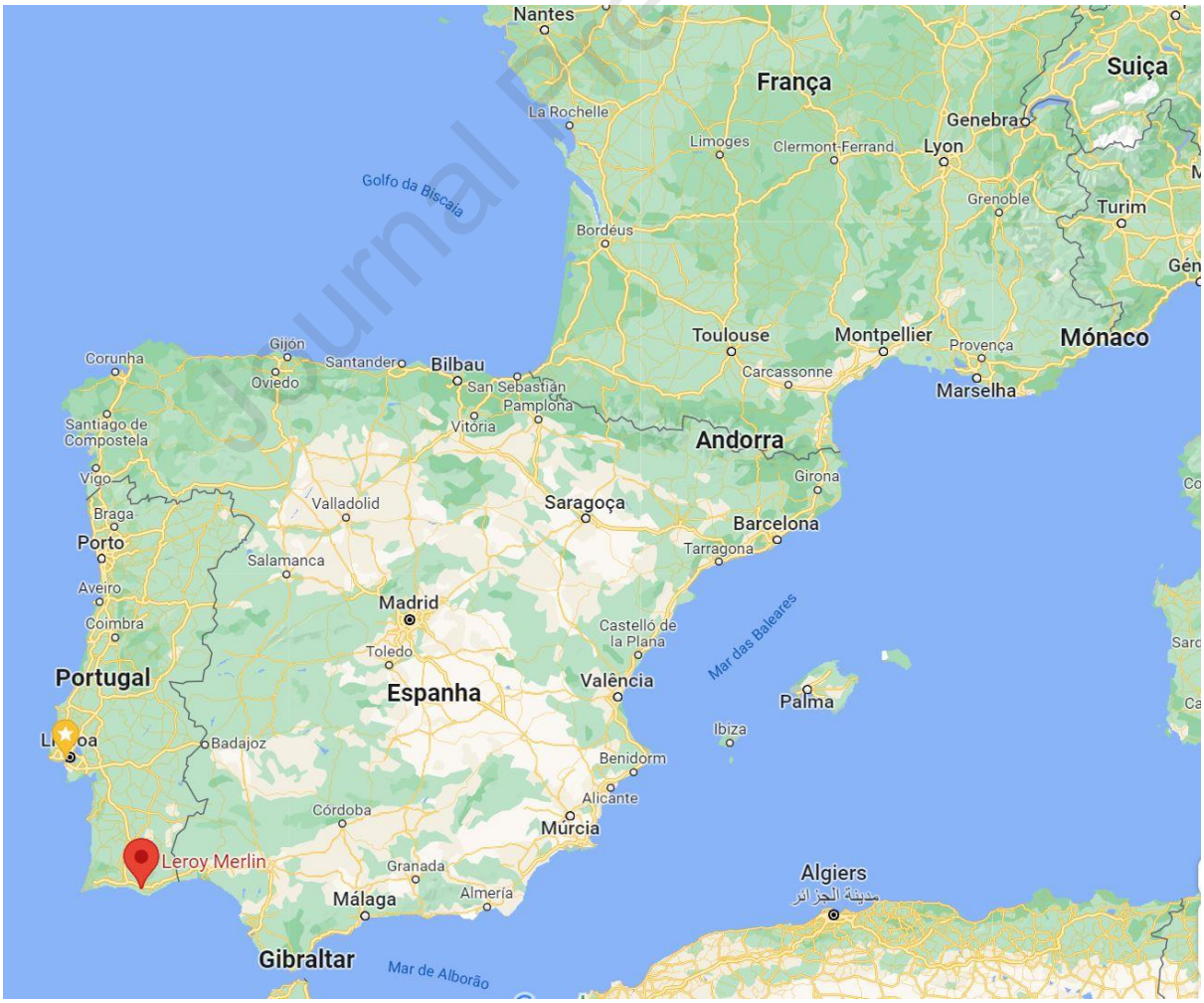


Figure 2 - Approximate location of the retail store in Algarve, Portugal

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The case study store consists of two ventilated parking floors in the basement plan, the sales area floor, a mezzanine for staff facilities, and a roof with limited access, where photovoltaic panels are installed. The retail building has a total gross floor area of 16473.90 m² and a sales area of 8799 m², which was the value considered to calculate EUI and annual energy costs per m². The main facade of the building is faced in the southeast direction, and the window-to-wall ratio is about 5%, with southeast exposure. The store is open 12 hours a day, seven days a week. The store is located in the winter climate zone I1 (less than 1300 Celsius degree-days in the heating season) and summer climate zone V3 (average outdoor temperature greater than 22 ºC in the cooling season) [51]. The selected case study is a typical big-box nonfood store. It is representative of a large nonfood store from an international retailer in Portugal due to its peripherical urban location, store size (< 9.000 m² in sales area), and store layout (sales floor comprising cashiers, cafeteria, and restrooms, goods receiving area in the back of the store and a mezzanine with offices and staff rooms on the first floor). The choice of building solutions and building materials is also typical of retail buildings: the underground floors are made of concrete superstructural elements, while the sales floor is made of a conventional hot-rolled steel structure. The facades are comprised of sandwich panels, while the roof is comprised of ceramic blocks covered by rock wool and a flexible waterproofing bitumen membrane (Table 1).

Table 1- Building materials used in the envelope of the case study

Envelope element	Building element detailed composition	Building element abbreviation
Walls	Exterior wall in white colour with the following composition: i) rigid polyurethane foam (PUR) sandwich panels, 6cm thickness, density= 35-50 kg/ m³	Sandwich panels in rigid polyurethane foam (PUR) 6cm
Roofs	The external surface of the roof is white and with a total thickness of 34cm, with the following composition: i) a lightened slab of ceramic blocks 21 to 28cm in height (2 rows of holes), 30 cm in width, 23cm thickness, thermal resistance = 0,23 m²°C/ W; ii) rock wool, density= 35-100 kg/ m³, 10cm thickness, thermal resistance=2.50 m²°C/W; iii) flexible waterproofing membrane impregnated with bitumen, 1cm thickness	flexible waterproofing bitumen membrane 1cm + rock wool 10cm + ceramic blocks 23cm

In terms of equipment, the store has LED lighting, two elevators, and two escalators. The HVAC systems are comprised of two heat pumps for the sales area and a VRF system for the staff rooms. The breakdown of the annual energy consumption of the main building systems is indicated in Table 2.

Table 2 - Breakdown of the annual energy consumption of the case study's main building systems

	Energy consumption per building system	Energy consumption in kWh/y
HVAC	0,17	221 274
Lighting	0,41	533 661
Equipment (elevators and escalators)	0,42	546 677
Total annual energy consumption		1 301 612

2.2 Data collection and assessment

The data required were obtained from two sources: i) the group's technical department provided ACAD projects of the store, bills of quantities, energy bills and the energy certificate of the store; and ii) REVIT®'s Plug-in Insight 360º provided results of energy simulations of the envelope solutions in terms of EUI, once the building model was created.

The modelling of the exterior walls, interior walls, floor slabs and glazing was carried out based on the information on the construction materials contained in the store's energy certificate in a BIM methodology software (REVIT®), as shown in Figure 3.

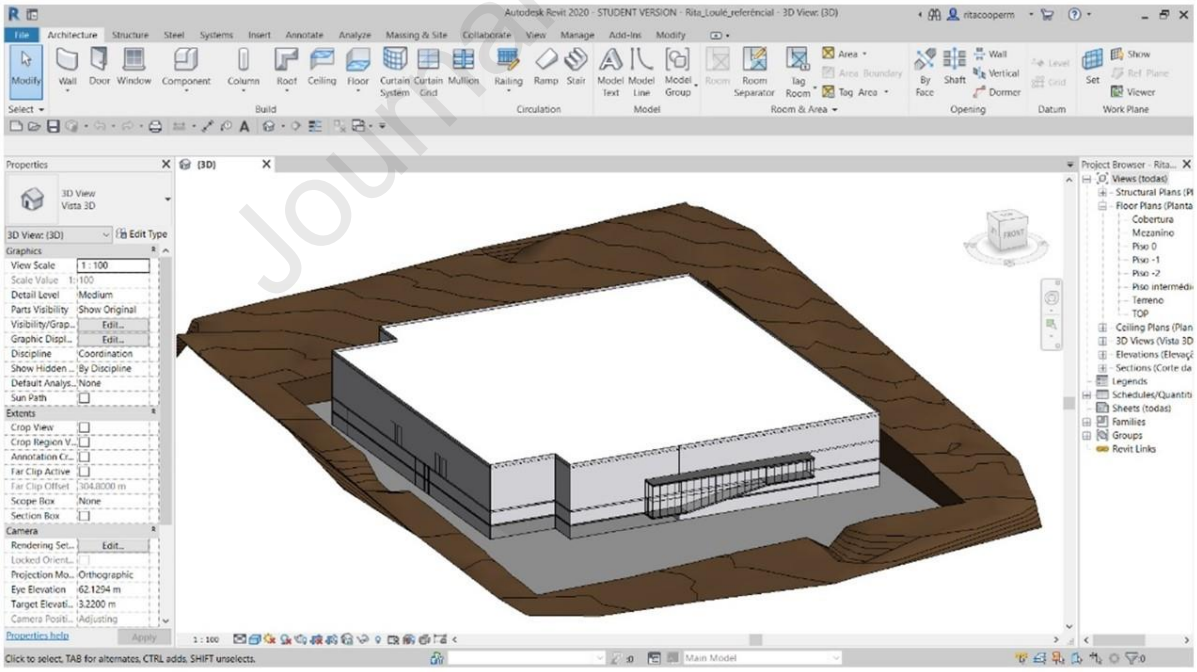


Figure 3 - Case study's building modelling in software REVIT®

An energy model was created in REVIT® (Figure 4) according to the U-value of the building elements selected. This model was later exported to Autodesk's plugin Insight 360º, which simulates the

building's annual energy consumption according to assumptions defined for the energy analysis in REVIT® (Appendix 1). The energy simulation results presented are generated by Green Building Studio (GBS), the cloud-based service that powers the energy analysis features in REVIT®. The plugin Insight 360º links GBS into the REVIT® environment, sending the 3D models created in REVIT® to GBS, where it is converted into an energy model. Next, GBS uses the DOE-2 simulation engine for calculating the whole building energy usage of the project, and results are shown on the website "insight360.autodesk.com", where they can be exported as DOE2, gbXML or Energy Plus file formats. These files will contain the energy simulation results from GBS, as well as the values for any missing data for energy simulation that GBS has applied to the model.

Energy simulation was performed with Revit®'s plugin Insight 360º as a fast, intuitive, outcome-driven tool that can provide designers guidance in early design stages about the impact of design choices in terms of future energy consumption of buildings and their environmental performance without extensive workload.

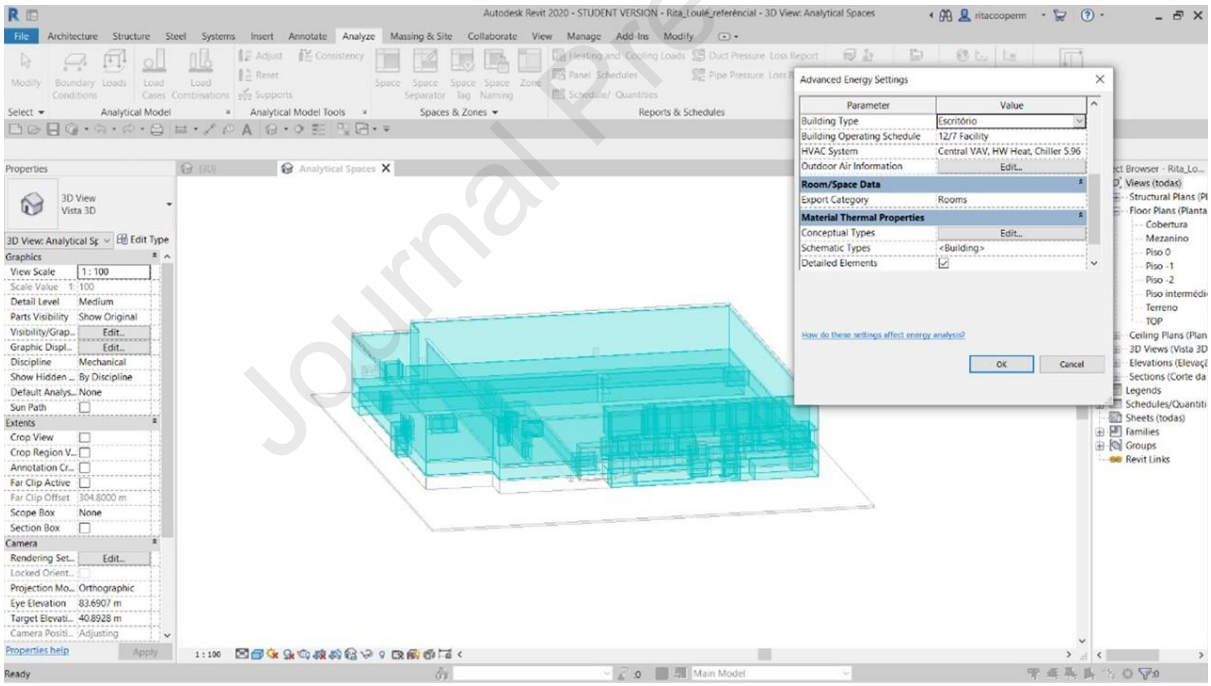


Figure 4 - Case study's energy model in software REVIT®

The energy simulation of the store's model with envelope materials as built provided an annual energy consumption equal to 1 302 252 kWh per 8799 m², which consists of a EUI of 148 kWh/m²/year. The energy bills of the retail store were consulted to validate this value. The year chosen was 2018 because the following year, the store installed photovoltaic panels, thus making energy metering analysis less straightforward. Hence, during 2018, the store's energy consumption was 1 301 612 kWh, which corresponds to a deviation

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of 0,05% regarding the simulated energy model, thus validating the model calibration. Nevertheless, the total annual energy consumption expected for the store according to its energy certificate of 1 211 233 kWh [dataset 1], which accounts for a deviation of 7% in terms of the energy certificate expectations and shows how much user preferences can impact energy consumption results.

Next, typical alternative envelope-building solutions found in the group's property portfolio were simulated in REVIT®, and their energy results were compared against the original store's energy simulations' results to analyse potential differences in terms of energy consumption. These solutions (solutions 1 to 15) were the most frequent ones found in the 40 energy certificates of the group's stores in Portugal for walls and roofs to analyse potential differences in terms of energy consumption due to opaque envelope materials. Additionally, five solutions with lower U-value currently not used by the retail group in Portugal were tested (solutions 16 to 20) to ascertain whether these envelope materials could represent viable, cost-effective solutions for future new stores. To evaluate the different types of walls, the original roof was considered in each simulation and to evaluate the different types of roofs, the original walls were considered in each simulation.

The building costs of alternative envelope solutions that resulted in less energy consumption were assessed through the Portuguese price estimation website [52]. Differential costs between the original envelope solution and the alternative solutions were calculated, as well as the Cash Flow (CF) generated from correspondent energy savings over 15 years. The maintenance cycle and total life cycle cost of the alternative envelope solutions have not been studied at this stage. Economic indicators were then estimated to assess the cost-effectiveness of the analyzed alternative envelope solutions, namely the Net Present Value (NPV), the Internal Rate of Return (IRR), the Payback Period (PP) and the Discounted Payback (DPP). The following equation was used to calculate the PP (1).

$$PP = \frac{I_v}{CF} \quad (1)$$

The NPV corresponds to the difference between the sum of the CF and the initial investment costs. A constant discount rate (r) equal to 3.4% was assumed. The following equation was used to calculate the NPF (2):

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} - I_\vartheta \quad (2)$$

where *t* is the time frame considered.

The IRR corresponds to the rate that allows the sum of the updated CF to be equalled to the initial

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investment, i.e. the rate that allows the NPV to be equal to zero. The following equation was used to calculate the IRR (3):

$$Iv + \sum_{t=0}^{n} \frac{CF_t}{(1+TIR)^t} = 0 \quad (3)$$

The PP corresponds to the number of years needed to recover the initial investment, that is, the number of years needed for the NPV to be equal to zero. The DPP is like PP but calculated with the discounted NPV at a rate of 3.4%. The following equation was used to calculate the DPP (4):

$$DPP = \frac{1-(1+NPV)^{-15}}{NPV} \quad (4)$$

The NPV and IRR were calculated for 15 years and 50 years. A period of 15 years was selected as it is an average timeframe between major refurbishments in retail buildings [53]. It also corresponds to the minimal expected lifetime of certain envelope components evaluated in this study, such as bitumen or PVC waterproofing membranes and coatings on metal sheets [17]. A period of 50 years corresponds to the estimated economic life cycle of the building, mentioned in the EPDB as a basis for cost-optimal calculations [3]. The EPBD defines 'cost-optimal level' as the energy performance level which leads to the lowest cost during the estimated economic life cycle, considering the investment costs, maintenance, operating and disposal costs (where applicable), and the estimated economic life cycle of the building, or of a building element. In parallel, a solution is cost-effective when its investment cost is lower than the benefits resulting from it under a given time frame. The NPV can assess the cost-effectiveness of building solutions by discounting future costs and savings. If the NPV is positive, the solution is cost-effective for the set of assumptions used in the calculation. The cost-optimal solution is a special case of cost-effectiveness, as it is the solution that maximizes the NPV [54]. In the case of multiple envelope solutions with positive NPV, the IRR may help to determine the best solution, as the higher the IRR, the higher the profitability of the investment. PPs and DPPs, as the number of years needed to recover the initial investment, are, in practical terms, the first economic indicator that assesses the feasibility of a solution. A simple PP is the only indicator considered in the Energy Certification Manual for Portuguese Buildings [51] when evaluating alternative energy-efficiency measures.

Thus, the assumptions used for the economic calculations in the present study were the following: i) annual inflation rate of 3,4%. This was the average inflation rate between January 2021 and January 2022 in Portugal [55]; ii) electricity rate of €0.10/kWh. This was the average cost of electricity in 2021, excluding tax, according to the store's energy bills, and iii) an annual electricity cost escalation rate of 2.4%. This

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was the average rate increase between 2021 and 2022 in Portugal [56]. It was also assumed that no capital was required from the bank to fund the investments; hence there, no “discount rate” was applied.

3. Results and Discussion

This study set out to explore which envelope-building solutions in retail buildings lead to cost-optimal levels considering the EPBD and Portuguese correspondent thermal code.

To find which envelope-building solutions lead to increased energy performance, 21 energy simulations were carried out with alternative building materials for exterior walls and roofs. Table 3 presents the results of the energy simulations of these solutions in terms of EUI, total annual energy consumption, energy costs per m² per year and total annual energy costs. The Rt and the U-value of the envelope solutions tested are also provided. In this table, typical alternative envelope-building solutions found in the group’s property portfolio were tested against the original case study (solutions 1 to 15), as well as solutions with lower U-value currently not used by the retail group in Portugal (solutions 16 to 20).

The energy simulation of different envelope alternative solutions provided results in annual energy consumption that ranged from 141 to 181 kWh/m²/year, which resulted in differences in annual energy costs of over 35 000€. Only one of the typical wall solutions found in the group’s property portfolio led to lower annual energy consumption than the original solution of the case study (solution 4). As for roofs, three typical wall solutions found in the group’s stores led to lower annual energy consumption: solutions 8, 12 and 14. Nevertheless, all solutions with lower U-value currently not applied in the analysed retail group's existing buildings (solutions 16 to 20) led to lower annual energy consumption.

In Table 4, the economic analysis of the nine solutions that led to energy savings was conducted to assess their cost-effectiveness.

Only one solution provided positive NPV at 15 years (solution 12), which makes it the cost-optimal solution for roofing considering this time frame. Nevertheless, two other solutions with lower U-value currently not used by the retail group have positive IRR at 15 years, which makes them cost-effective considering this time frame (solutions 17 and 18). Considering the estimated economic life cycle of the building in 50 years, more solutions have positive NPV and IRR and are therefore cost-effective: solution 4, solution 14 and solutions 16-20.

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Table 3 - Energy simulations results of different envelop solutions, energy consumption and cost according to Rt and U-value

Envelope Element	Solution number	Envelope composition	Energy Use Intensity (kWh/m²/y)	Total energy consumption (kWh/m²/y)	Total energy cost (€/y)*	Rt value (m².K/W)	U value (W/m2.°K)
Walls	Original solution	Sandwich panels in rigid polyurethane foam (PUR) 6cm	148	1 302 252	130 225,20 €	1,62	0,62
	1	concrete block 25cm	157	1 381 443	138 144,30 €	0,59	1,69
	2	sandwich panel 5cm	150	1 319 850	131 985,00 €	1,35	0,74
	3	metal sheet + rock wool 4,6cm+ metal sheet	151	1 328 649	132 864,90 €	1,02	0,98
	4	sandwich panel 8cm	147	1 293 453	129 345,30 €	1,79	0,56
	5	concrete 25cm + air cavity 4cm + rockwool 4cm + plasterboard 2,5cm	167	1 469 433	146 943,30 €	0,46	2,17
	6	metal sheet + air cavity 6,8cm + rock wool 3cm+ metal sheet	151	1 328 649	132 864,90 €	1,10	0,91
	7	mortar 2cm + concrete block 25cm + mortar 2cm	160	1 407 840	140 784,00 €	0,47	2,12
Roofs	Original solution	flexible waterproofing bitumen membrane 1cm + rock wool 10cm + ceramic blocks 23cm	148	1 302 252	130 225,20 €	1,62	0,62
	8	sandwich panel 5cm + air cavity 5cm + plasterboard 2cm	147	1 293 453	129 345,30 €	2,13	0,47
	9	waterproofing membrane + thermal insulation 4cm + ceramic block lightened slab 15cm	181	1 592 619	159 261,90 €	0,59	1,69
	10	waterproofing membrane + metal sheet + rock wool 6cm+ metal sheet	152	1 337 448	133 744,80 €	1,35	0,74
	11	flexible membrane impregnated with bitumen + metal sheet + rigid polyurethane foam (PUR) 5cm+ metal sheet	151	1 328 649	132 864,90 €	1,53	0,65
	12	polyvinyl chloride (PVC) + rock wool 6cm+ metal sheet	145	1 275 855	127 585,50 €	1,64	0,61
	13	pure asphalt mesh + rock wool 8cm+ metal sheet	150	1 319 850	131 985,00 €	1,58	0,63
	14	sandwich panel rigid polyurethane foam (PUR) 10cm	147	1 293 453	129 345,30 €	2,38	0,42
	15	reinforced concrete 20cm + thermal insulation 3cm + screed 10cm	156	1 372 644	137 264,40 €	0,99	1,01

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Solutions with lower U-value currently not used in the analysed retail group's existing buildings							
Walls	16	vacuum insulation panels 2,5cm	141	1 240 659	124 065,90 €	3,5	0,29
	17	sandwich panel 10 cm	144	1 267 056	126 705,60 €	2,38	0,42
	18	sandwich panel 12 cm	143	1 258 257	125 825,70 €	2,86	0,35
Roofs	19	vacuum insulation panels 2,5cm	143	1 258 257	125 825,70 €	3,5	0,29
	20	sandwich panel 12 cm	145	1 275 855	127 585,50 €	2,86	0,35

*kWh price of 0,10€ used in simulations, in accordance to Leroy Merlin energy bills

** Store area of 8799 m²

Table 4 - Investment cost of the envelope solutions that led to lower annual energy costs, their Net Present Value (NPV) and Internal Rate of Return (IRR) at 15 years and 50 years, Payback period (PBP) and discounted payback (DPB)

Envelope Element**	**Solution number**	**Envelope composition**	**Total energy cost (€/y)***	**Energy savings (€)**	**Investment cost (€)**	**Investment cost Δ (€)**	**NPV (15y)**	**IRR (15 y)**	**NPV (50 y)**	**IRR (50 y)**	**PBP (y)**	**DPB (y)**
Walls	Original solution	sandwich panels in rigid polyurethane foam (PUR) 6 cm	130 225 €		246 960 €							
	1	concrete block 25 cm	138 144 €	- 7 919 €								
	2	sandwich panel 5 cm	131 985 €	- 1 760 €								
	3	metal sheet + rock wool 4,6cm+ metal sheet	132 865 €	- 2 640 €								
	4	sandwich panel 8 cm	129 345 €	880 €	276 360 €	- 29 400 €	-17 463,09 €	-7%	4 468,06 €	4%	33	42
	5	concrete 25 cm + air cavity 4 cm + rockwool 4 cm + plasterboard 2.5 cm	146 943 €	- 16 718 €								
	6	metal sheet + air cavity 6.8 cm + rock wool 3 cm+ metal sheet	132 865 €	- 2 640 €								
	7	mortar 2 cm + concrete block 25 cm + mortar 2 cm	140 784 €	- 10 559 €								
Roofs	Original solution	flexible waterproofing membrane impregnated with bitumen 1 cm + rock wool 10 cm + ceramic blocks 23 cm	130 225 €		484 464 €							
	8	sandwich panel 5 cm + air cavity 5 cm + plasterboard 2 cm	129 345 €	880 €	524 836 €	- 40 372 €	-28 435,09 €	-10%	-6 503,94 €	3%	46	<50

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	9	waterproofing membrane + thermal insulation 4 cm + ceramic block lightened slab 15 cm	159 262 €	- 29 037 €								
	10	waterproofing membrane + metal sheet + rock wool 6 cm+ metal sheet	133 745 €	- 3 520 €								
	11	flexible membrane impregnated with bitumen + metal sheet + rigid polyurethane foam (PUR) 5 cm+ metal sheet	132 865 €	- 2 640 €								
	12	polyvinyl chloride (PVC) + rock wool 6 cm+ metal sheet	127 586 €	2 640 €	514 743 €	- 30 279 €	5 527,67 €	6%	71 313,64 €	11%	11	15
	13	pure asphalt mesh + rock wool 8 cm+ metal sheet	131 985 €	- 1 760 €								
	14	sandwich panel rigid polyurethane foam (PUR) 10 cm	129 345 €	880 €	509 697 €	- 25 233 €	-13 296,09 €	-5%	8 635,06 €	5%	29	35
	15	reinforced concrete 20 cm + thermal insulation 3 cm + screed 10 cm	137 264 €	- 7 039 €								
Solutions with lower U-value are currently not used in the analysed retail group's existing buildings												
Walls	16	vacuum insulation panels 2.5 cm	124 066 €	6 159 €	446 880 €	- 199 920 €	-116 371,10 €	-6%	37 129,50 €	4%	32	41
	17	sandwich panel 10 cm	126 706 €	3 520 €	296 940 €	- 49 980 €	-2 237,77 €	3%	85 476,86 €	9%	14	16
	18	sandwich panel 12 cm	125 826 €	4 400 €	317 520 €	- 70 560 €	-10 882,21 €	1%	98 761,07 €	8%	16	18
Roofs	19	vacuum insulation panels 2.5 cm	125 826 €	4 400 €	767 068 €	- 282 604 €	-222 926,21 €	-12%	-113 282,93 €	1%	64	<50
	20	sandwich panel 12 cm	127 586 €	2 640 €	545 022 €	- 60 558 €	-24 751,33 €	-3%	41 034,64 €	6%	23	27

*kWh price of 0,10€ used in simulations, in accordance with Leroy Merlin energy bills

** Roof area of 5880 m² and external walls area of 10093 m²

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3.1 Compliance with Portuguese thermal building codes

The Portuguese decree-law 101-D/2020 and the Ordinance 138-I/2021, as the legal instruments that transpose the EPBD to Portugal, set commercial buildings' U-values at 0,7 W/m^2.°K for walls and 0,5 W/m^2.°K for roofs, considering the climate zone where the case study store is located. Therefore, out of the eight envelope solutions typically used in the group's retail stores for walls, four complied with the new building code: the original case study solution, solution 2, solution 4 and solution 6. In terms of envelope solutions for roofs, four of the analysed solutions met the new building code: solution 8, solution 12, solution 13 and solution 14. All the solutions with lower U-value currently not used by the retail group (solutions 16-20) have U-values significantly lower than threshold code values, from 0.29-0.42 W/m^2.°K for walls and 0.29-0.35 W/m^2.°Kfor roofs, as to access the cost-optimal performance of the current U-vales imposed by the code.

3.2 Cost-effectiveness of the tested solutions

In the analysed case study, cost-efficient envelope solutions are found at a near-optimal level, as only one typical roof solution found in the group's property portfolio (solution 12) led to lower annual energy consumption. Two other typical solutions could be considered cost-effective within the estimated life building life of 50 years: solution 4 for walls and solution 14 for roofs, as well as all solutions with lower U-value currently not used in the analysed retail group's existing buildings (solutions 17-21). Solution 8 and solution 19 have a PP longer than 50 years and are, therefore, economically unviable. Figure 5 shows the envelope solutions that obtained positive NPV / IRR values, showing the PP and DPP of each one.

The results also showed that the simple PP of envelope solutions with U-values in compliance with the Portuguese code varied over a wide range, from 15 to over 50 years. These findings corroborate those of Kelsey [50], as levels of wall and roof insulation greater than those required by the code, could be beneficial to building owners, especially from a life cycle perspective. The solutions with envelope materials with lower U-value save more energy, as they decrease heating loads inside the building, therefore minimizing HVAC systems sizing and energy consumption.

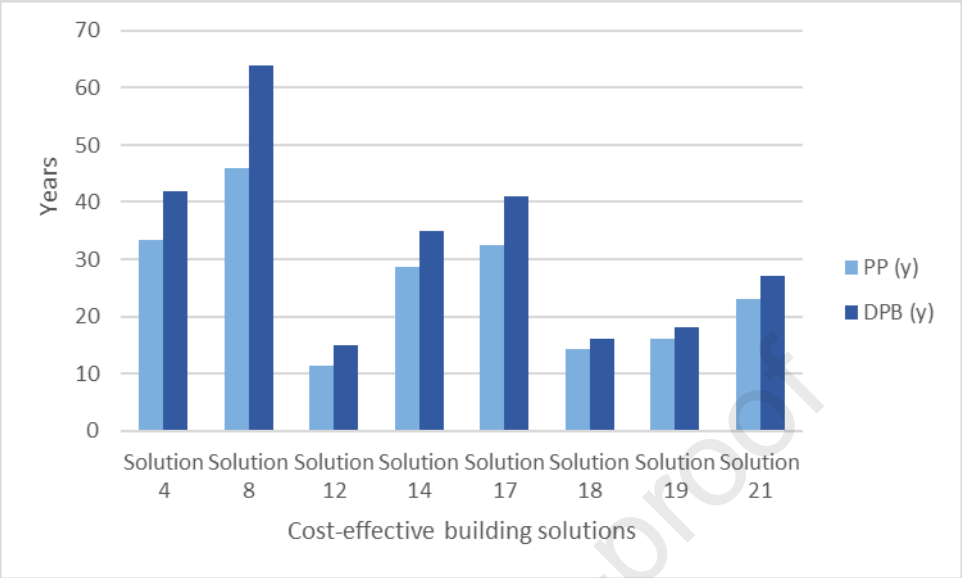


Figure 5 - Payback Period (PP) and Discounted Payback Period (DPP) of envelope solutions with positive Net Present Value (NPV) and positive Internal Rate of Return (IRR)

Our results also corroborate those of Huang *et al.* [57] in the sense that more insulation could decrease envelope heat gain, despite its contribution to overall energy savings being relatively small. In the present case study, decreasing the U-values of envelope materials significantly would only bring about 2-5% annual energy savings. As such, the economic profitability of wall solutions with more than 50mm of insulation material is limited, as pointed out by Huang *et al*. [57].

Our findings also support those of Jiang and O'Meara [58] regarding the cost of increased insulation in envelope materials: since in a number of the tested solutions, the energy savings over the life cycle of 50 years are higher than the additional building cost, current thermal transmittance codes for the U-value of opaque envelope materials could be revised. None was withstanding, and as advocated by Almeida *et al*. [59], policymakers must then determine whether the social gain is worth the economic effort. If so, the introduction of legal or financial incentives to push private stakeholders in that direction may be necessary.

As pointed out by Vasconcelos *et al*. [10], buildings could benefit thermally from different envelope solutions in walls and roofs: an approach that studies combinations of solutions incrementally can yield greater results. In this sense, expedited building simulation methods, such as the one used in the present study, can be useful to explore the synergies obtained by different solutions in the overall

building's energy performance, which is also the suggestion of Xie and Gou [60].

In opaque envelope elements that constituted the present case study, energy savings are higher by decreasing the U-value of walls than that of roofs since they have more overall surface area in the building. This is in line with the findings of Jiang and O'Meara [58] for commercial buildings, and opposite to those of Vasconcelos *et al*. [10], regarding residential buildings.

The findings of this study also indicate that about half of the typical envelope solutions that constitute standard practice in the retail construction industry meet current building codes, possibly implying that they were ahead of existing building codes at the time they were built. Withal, it clearly indicates that an important percentage of stores with envelope solutions that do not meet present codes could benefit from envelope retrofitting. Article 4 of the EPBD encourages member states to implement measures to increase the energy performance of envelope elements when they are replaced or retrofitted, to achieve cost-optimal levels [2]. Thus, the large stock of existing retail buildings that need retrofitting is both a persistent problem and an opportunity to attain increased energy performance in the retail sector and to share the lessons learned with competitors [40] since most of the building solutions in the retail construction industry are similar. The envelope solutions typically found in this group's real estate portfolio are in line with the most prevalent envelope solutions referred to in the literature for retail stores, namely External Thermal Insulation Composite Systems (ETICS) on concrete block or brick masonry, built-up double skin cladding and sandwich panels [61].

3.3 Options for the envelope retrofitting of existing retail buildings

When considering envelope retrofitting solutions for retail buildings, the use of ETICS on masonry walls could be technically viable and added to some of the studied wall solutions that currently are not up to code standards, namely solutions 1, 5 and 7. The retrofit of built-up double skin cladding systems, such as in solution 3 is less attractive, as it requires the stripping and replacement/addition of insulation materials, which may not be economically viable, and functionally difficult, as it may compromise the sales operation of retail stores, especially when complete replacement of materials is necessary. As for roofs in layers, thermal retrofitting could

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be timely when outer weatherproofing membranes of built-up double skin cladding systems are replaced, such as bitumen or PVC membranes, usually around the 15-year mark. In practical terms, the retrofitting of single-layer envelope elements in roofs and walls, like sandwich panels or fibrocement elements, requires the complete replacement of the envelope material for more thermally efficient ones, in turn implying the interdiction of use of the adjacent sales area. Given these scenarios, the retrofitting of the envelope of a retail building presents challenges in operational terms that may not be overcome by the potential economic gain. Moreover, retrofitting decision-making in retail tends to be associated with market factors, keeping up with the competition, functionality factors, reversing the obsolescence of systems and equipment, and complying with existing regulations. Most investment decisions in retail are considered in a cost-effective way, and envelope retrofitting may thus be postponed as an energy-efficiency strategy when other solutions offer better payback periods, such as the installation of photovoltaic panels or the replacement of lighting and HVAC systems. Despite being consensual for most retailers that energy is the top priority regarding investment decisions in their buildings, largely because of the potentially high cost-savings, according to Evans *et al.* [62], priorities mentioned by retailers were lighting, refrigeration, and HVAC systems. Envelope retrofitting is not referenced possibility due to the low financial gain implied and to the perceived risk that replacing façade elements poses on customers and sales. In addition, retail property is not always owned by retailers, which hinders investment in energy-efficiency measures. Developers who rent the property to tenants may not be able to reap the benefits of such investments, as energy savings favour the occupier. Owner-occupier retailers are in the best position to make long-term investment decisions about their property [63]. However, market uncertainties, such as variations in inflation rates, energy costs and sales profitability, contribute to a greater attraction to shorter payback periods in investments, thus limiting the range of high-performance solutions that could be considered to upgrade the energy performance of retail buildings. Investment solutions with long-term payback periods, in the mark of 25-50 years, have very little chance of being considered by retailers even with positive NPV and IRR, as they pose too much risk on investment return.

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3.4 Implications for Portuguese thermal building codes

Thus, according to the results of our study and at present energy cost and inflation rate, it would be possible to push existing codes further in terms of decreasing the U-value of opaque envelope elements within the cost-effectiveness range. This is, even more, the case if the assumptions used for the economic calculations in the present study vary, as it is expected that energy costs will become higher. Like so, incentives to accelerate the implementation of energy-efficiency measures are necessary, namely to facilitate envelope retrofitting, as acknowledged by the EU [1]. As a result, more solutions to encourage the decarbonisation of buildings were promised in the future revised version of the EPBD, and the revised Energy Efficiency Directive [3] will set more ambitious targets for the decrease of energy consumption by 2030, introduce legal requirements to prioritise energy efficiency in investment decisions and encourage the use of Energy Performance Contracts for the renovation of large non-residential buildings [1].

As suggested by Li *et al.* and Juang *et al.* [64,65], in the path towards net zero energy buildings, an integrated approach is necessary that combines passive building solutions and technologies that maximize energy efficiency and minimize GHG emissions, such as the use of renewable energy. A combined approach of energy efficiency and low-carbon on-site or offsite electrical generation is arguably the most successful strategy to achieve energy efficiency and large carbon savings. As no single parameter is responsible for low levels of energy consumption and carbon emissions, an integrated design approach that considers climate, technology, occupant behaviour, and maintenance is necessary to maximize energy efficiency and minimize GHG emissions. Other studies suggested similar strategies [66,67]. On the energy efficiency side, energy savings resulting from optimized building fabric should be considered (e.g., airtightness, increasing the U-values, optimum glazing levels, minimization of thermal bridges) as well as those deriving from building systems (e.g., low lighting intensity, efficient equipment, natural refrigerants, energy management). Finally, passive solutions should also be considered (e.g., natural daylighting, natural ventilation, windows in façades with adequate solar exposure).

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In addition, according to Jiang and Tovey [68], to achieve low carbon sustainability in large commercial buildings, five aspects should be considered: awareness raising, energy management system, energy saving technologies, deployment of renewable energy and offsetting methods as last resort. As for existing buildings, if retail buildings have a life cycle of about 50 years, then structural changes should take place in the role these buildings play in building stock renovation. The large stock of existing retail buildings that need energy retrofitting is both an opportunity and a persistent problem to decrease overall energy consumption [40].

Finally, as for best practice in envelope solutions, the use of the high-reflectivity coating in roofs could help to decrease heat gains due to the relatively high solar radiation projection of roofs, as indicated by Huang *et al.* [57]. In geographic areas with a considerable temperature delta between day and night time, insulation materials perform better in the outer part of the shell due to the heat storage capacity of envelope materials [57]. The application of simple passive cooling measures to reduce the cooling load of buildings, such as glazing, shading, insulation, and natural ventilation [69], could also yield good results in energy savings. Future trends include the possibility of incorporating in the building envelope eco-efficient thermal insulators, materials with low embodied energy, materials with high recycled content and materials with nanotech energy efficiency characteristics [70].

3.5 Limitations

Firstly, the use of existing buildings as case studies limits the generalization of results to other buildings unless they are very similar in construction, climate, and operation settings. This is a limitation that has been previously described in the literature, namely by Kelsey [50] and Dong *et al*. [71].

Secondly, using Insight 360º' exported files in another software, like Energy Plus, may not be straightforward if the user does not have the same version of the software that was used in Insight 360º' to export the file. Therefore, if running an Energy Plus file to know exactly what parameters were considered in the energy simulation is not possible, the user will have limited knowledge of the assumptions made by the software to deliver results.

Thirdly, the energy simulation settings in REVIT® are limited, as parameters are chosen from a set of pre-determined solutions. Therefore, it is not possible to detail with precision some input

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variables for energy simulation, such as HVAC systems, the exact schedule of the store according to a year of operation, or the occupancy according to the store's hourly schedule. Hence, when a more rigorous energy analysis is needed, it is advisable to use directly a whole building energy simulation program, as this is a limitation yet to be addressed by REVIT®.

4. Conclusions

Based on the analysis of a case study in Algarve, Portugal, this study set out to explore which envelope-building solutions in retail buildings lead to cost-optimal levels considering the EPBD and Portuguese correspondent regulation. For such, expedited energy simulations were run in BIM software.

Results indicate that the envelope solution that constitutes the case study is at a near cost-optimal level. Only one of the alternative tested solutions for roofs provides a positive NPV at 15 years (solution 12). Nevertheless, two other solutions with lower U-value currently not used by the retail group in their stores have positive IRR at 15 years, which makes them cost-effective considering this time frame (solutions 17 and 18 for walls).

Results indicate that under an estimated economic life cycle of the building of 50 years, as pointed out by the EPDB, several solutions can offer energy savings, namely vacuum insulation panels of 2,5 cm and sandwich panels of 8, 10 or 12 cm. This leads to the conclusion that the U-values of walls and roofs mentioned in the Portuguese decree-law 101-D/2020 and the Ordinance 138-I/2021, as the legal instruments that transpose the EPBD to Portugal, could be lower and still be cost-effective. Nevertheless, as market uncertainties, such as variations in inflation rates, energy costs and sales profitability, pose too much risk on return on investment for periods of 50 years, policymakers must determine whether the social gain of lowering code U-values is worth the economic effort. If so, the introduction of legal or financial, namely, to promote envelope retrofitting in existing buildings, may be necessary.

In summary, there is potential to improve the energy performance of retail buildings' envelopes as current practice levels of insulation of shell elements could be increased with financial benefit.

The results can be useful for retailers, design teams and building owners, as they facilitate the choice of envelope solutions to be applied in new and retrofitted retail stores, bringing clarity to the link between increased thermal performance (and thermal comfort) and energy costs. They can also inform policymakers regarding the possibility of pushing building envelope codes further within cost-effectiveness in the path towards net zero energy buildings.

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This work was supported by FCT - Fundação para a Ciência e Tecnologia [grant number PD/BD/127852/2016] under the Doctoral Program EcoCoRe - Eco-Construction and Rehabilitation. Support from CERIS and Instituto Superior Técnico is also acknowledged.

Interests Statement

Declaration of Interest: None.

Appendix 1

Table A.1- Assumptions defined for the case study's energy analysis in REVIT®

Energy Analytical Model	**Value**
Mode	Use Building Elements
Ground Plane	Storey -2
Project Phase	New Construction
Analytical Space Resolution	0.4572 m
Analytical Surface Resolution	0.3048 m
Perimeter Zone Depth	3.6000 m
Perimeter Zone Division	✓
Detailed Model	
Target Percentage Glazing	40%[1]
Target Sill Height	0.7500 m
Glazing is Shaded	
Shape Depth	0.6000 m
Target Percentage Skylights	0
Skylight Width and Depth	0.9144m
Building Data	

Building Type	Retail
Building Operating Schedule	12/7 Facility
HVAC System	Central VAV, HW Heat, Chiller 5.96
Room/Space Data	
Export Category	Rooms
Material thermal Properties	
Conceptual Types	
Schematic Types	<Building>
Detailed Elements	⌄
Building Type data for Retail *	
Occupancy schedule	12/7 Facility
People per 100m²	10.5
People sensitive heat gain (W/person)	73.3
People latent heat gain (W/person)	58.6
Lighting load density	15.1
Equipment load density	10.8
Infiltration flow	0.4
Outside air (ventilation ai) flow per person (l/s)	NULL
Outside air (ventilation ai) flow per area (m³/h/m²)	4.5
Cooling setpoint (ºC)	21
Heating setpoint (ºC)	23,3
Unoccupied cooling setpoint (ºC)	29.4
Humidification setpoint (%)	0
Dehumidification setpoint (%)	70

*These assumptions are based on ASHRAE 90.1-2010, ASHRAE 90.2-2010, ASHRAE 62.1, CBECS data, and other building surveys. According to Revit, the assumptions are used for the purpose of providing reasonable energy usage estimates and not for the purpose of code compliance.

** the detailed assumptions used for REVIT's default HVAC system (Central VAV, HW Heat, Chiller 5.96) are the following: water cooled centrifugal chiller (COP 5.96); open, atmospheric pressure cooling tower with variable speed fan and 2.8ºC approach; 871.8 pascals of water gauge static pressure VAV duct system; integrated differential dry-bulb temperature economizer; gas-fired hot water boiler with draft fan <2500 kBtuh, 84.5% combustion efficiency; variable hot water pump; hot water coil; hot water reheat boxes; variable volume chilled water pump; chilled water coil; variable volume condenser water pump; domestic hot water unit (0.575 Energy Factor)

[1] default settings when detailed building elements are not chosen

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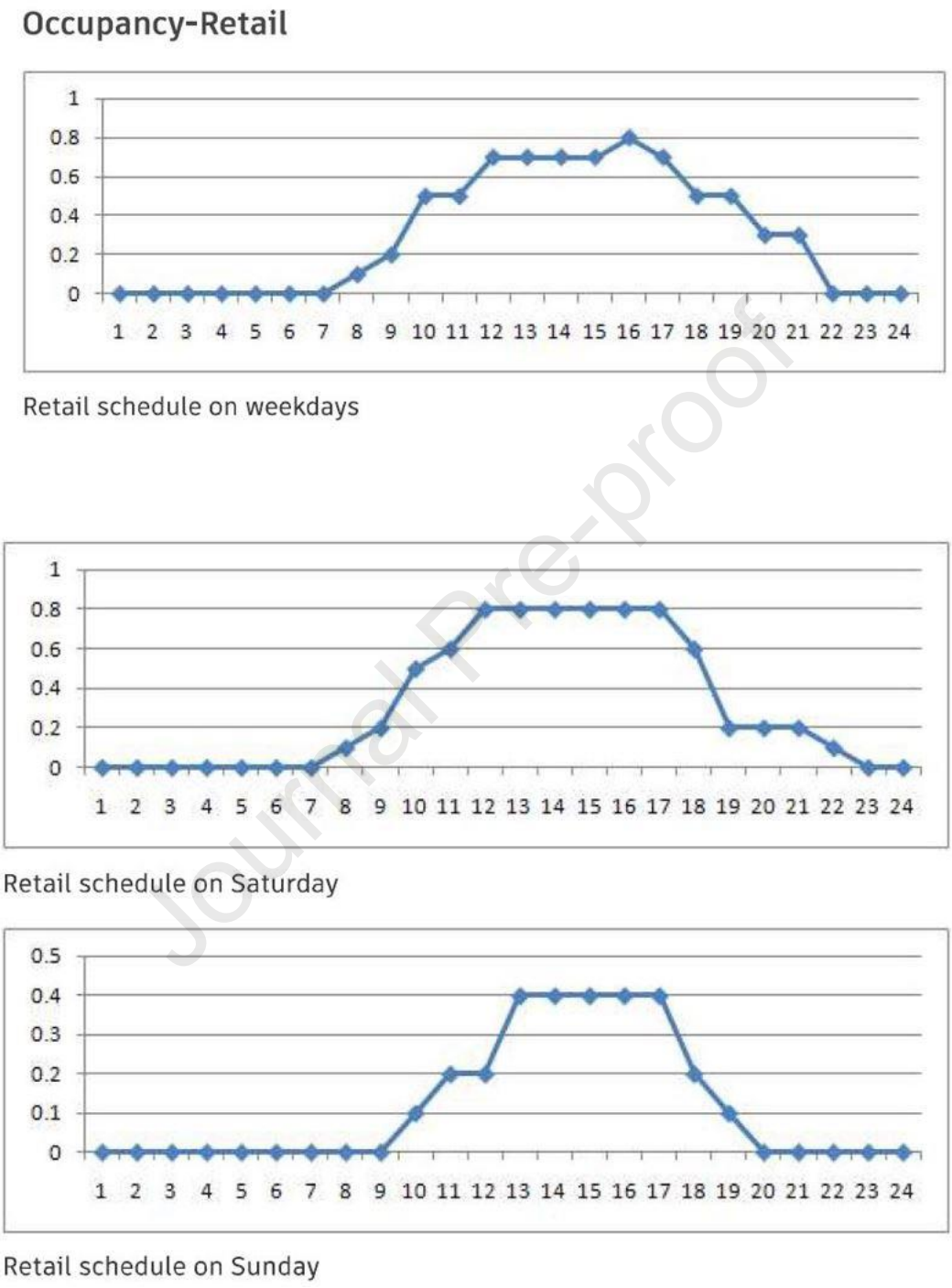


Figure A1 - Assumptions defined for the case study's energy analysis in REVIT® in terms of occupancy schedule for retail buildings

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Highlights

- Legal Portuguese U-values for retail buildings could be revised under a 50y lifecycle perspective.
- U-values for walls at 0,29-0,42 W/m^2.°K and at 0,29-0,35 W/m^2.°K for roofs can be cost-effective.
- 2,5cm VIP and 8-12cm sandwich panels are possible solutions to lower U-values of retail buildings;

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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