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# Embodied vs. Operational Energy and Carbon in Retail Building Shells: A Case Study in Portugal

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**Abstract:** (1) Background: The embodied energy of building materials is a significant contributor to climate change, in tandem with the energy use intensity (EUI). Yet, studies on the material impacts of European retail buildings, namely with relation to EUI, are missing. Hence, this study set out to: (i) evaluate the embodied energy and carbon emissions for a European retail building; (ii) quantify the material flow in terms of mass; (iii) compare the embodied aspects to the operational EUI and carbon use intensity (CUI); (iv) assess building materials with higher impacts; and (v) investigate strategies to mitigate materials' impacts. (2) Methods: A Portuguese retail building was selected as a case study. A simplified LCA method was followed (cradle-to-gate), analysing the shell building materials in terms of primary energy demand and global warming potential. (3) Results: the embodied energy represented 32% of total lifecycle energy while the embodied carbon represented 94%. EUI was 1×kWh/$m^2$/y while CUI was 21 kg $CO_2$eq/$m^2$/y. The embodied energy was 4248 kWh/$m^2$, and the embodied carbon was 1689 kg $CO_2$eq/$m^2$. Cement mortar, steel, concrete, and extruded polystyrene were the most intensive materials. (4) Conclusions: The embodied impacts of the analysed store could decrease by choosing stone wool sandwich panels for the facades instead of extruded polystyrene panels and roof systems with metal sheet coverings instead of bitumen materials.

**Keywords:** retail buildings; building shell; environmental impact; embodied energy; primary energy; GHG emissions; GWP; LCA



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## 1. Introduction

Buildings are the largest materials consumers in Europe, representing 50% of all extracted materials, 42% of the final energy consumption, 35% of greenhouse gas (GHG) emissions and 32% of waste flow [1]. GHG emissions are transversal to all aspects of the construction industry [2]. There is now robust evidence that the embodied energy of building materials is a significant contributor to climate change [3], in tandem with the consumption of energy in buildings during the operational stage [4,5]. In this context, the choice of building materials is of the utmost importance, not only because of the embodied impacts they entail, but also because they can determine lifelong profiles of energy use intensities (EUI) in buildings [3], especially regarding building envelopes. The life cycle assessment (LCA) is a preferable tool that assists in assessing the environmental impacts of building materials. It is encouraged to promote sustainable design, namely in building sustainability assessment (BSA) methods, such as LEED or BREEAM [6,7]. The European Commission has also acknowledged the importance of LCA to estimate potential environmental impacts in buildings, and as a result, CEN TC 350 was mandated for the development of standards for the sustainability assessment of construction works [1]. Subsequently, the European Commission has launched research projects to analyse the performance of residential and office buildings according to resource use, benchmarking it against the standard and best practices, to develop an LCA model for these types of buildings [1,8].

Nonetheless, retail buildings are often disregarded from such studies. However, retail buildings in particular have one of the highest EUI [9], which makes them an important sector to target towards reducing carbon emissions and supporting the transition to a competitive low-carbon economy [10]. Furthermore, retail is a particularly intensive sector in terms of direct emissions, mostly due to refrigeration and HVAC systems. Since the operational energy of buildings is being pushed down by increasingly tighter regulations, such as the Energy Performance of Buildings Directive [11], the embodied aspects of building materials are increasingly important to reduce environmental impacts in the construction industry [1]. It is therefore necessary to systematically assess the environmental impacts of retail buildings through LCA methods, as to support decision making towards building material choices that mitigate impacts, while delivering equivalent performance.

The literature review has retrieved several LCA studies that assess the environmental impact of buildings, mostly office buildings [12–15], residential buildings [16–21], or a mix of both [5]. These studies aimed mainly at identifying the impacts of building materials and understanding the relationship between embodied energy, and operational energy and quantified them with different results. Even though these studies do not relate to retail buildings, they nonetheless offer a methodology that can be transposed to this building typology, and results, namely by impact per group of material, that can be used to assess differences and similarities between several building types. Most authors agree on typical material groups where impacts are higher, as well as on the growing importance of the embodied aspects of building materials in terms of energy and carbon emissions. In that sense, Ramesh et al. [5] pointed out that operating effects were responsible for 80–90% of the impacts, against 10–20% for embodied effects. Kofoworola and Gheewala [22] suggested that the operational energy was 52% of total life-cycle impacts, despite the importance of steel and concrete regarding most of the embodied environmental impacts; Karimpour et al. [20] proposed that in milder regions, embodied energy could represent up to 25–35% of the total life cycle energy. Thormark [19] demonstrated that, for low energy buildings, 40–60% of total life cycle energy was embodied energy, and Gustavsson and Joelsson [23] argued that with increased efficiency in operational energy and effectiveness of insulation materials, embodied energy was becoming a significant factor in life cycle energy, representing 45% in conventional residential buildings and up to 60% in low energy buildings. Other authors corroborate the opinion that embodied energy is increasingly more significant [20,24–26], reaffirming the need to balance the performance of buildings in terms of both embodied and operational aspects to mitigate global environmental impacts.

Inversely, studies referring to these aspects is that retail buildings are scarce. Very few studies have addressed the embodied and operational energy in commercial buildings, and in particular, in retail buildings: Ooteghem and Xu [27] studied structural and envelope building materials in a single-story retail unit in Canada from an LCA perspective. Chau et al. [28] investigated the environmental impact of building materials for commercial buildings in Hong Kong (in which retail buildings were included). Cinneli et al. [29] examined the embodied energy contents of materials in a commercial building in Canada. Khoa et al. [30] assessed the life cycle greenhouse gas emissions for several typical commercial building fabrics in Australia, and Luo et al. [31] quantified the embodied carbon emissions of building materials in residential, office, and commercial buildings in China. These studies are too limited in number to provide approximate threshold levels that could be used to compare, for instance, the percentage of embodied aspects of building materials in terms of energy and carbon emissions vs. the percentage of energy used during the operational stage, throughout the building life cycle. They represent a small fraction of LCA knowledge concerning the impacts of retail buildings, since they vary in location, scope, and systems boundaries. In effect, the literature review confirmed that current knowledge about the impacts of embodied and operational energy in retail buildings is extremely limited, which is evidence of the gap in knowledge this study intends to address. Hence, this research intends to assess the embodied aspects of building materials in terms of energy and carbon emissions for a retail building in Portugal. In addition, it intends to compare the embodied energy and carbon emission aspects to the energy and carbon emissions consumed and produced during store operation. This quantification is in line with the studies previously mentioned for residential and office buildings and is essential to discern mitigation strategies that can be of use to reduce the environmental impact of retail buildings. The need for applied research on the subject of material impacts in retail buildings via the investigation of case studies has been identified by Omer and Noguchi, Cabeza et al. [4,24] and van Ooteghem and Xu [27]. On this matter, van Ooteghem and Xu [27] stated that the life cycle environmental impacts of retail buildings have been largely neglected and called for more investigation in this area since retail buildings have unique characteristics when compared to office and residential buildings that need special attention, namely their higher EUI in the operational stage.

Out of the few studies that addressed retail buildings, none addressed aspects related to the shell of these buildings, namely sandwich panels in facades, which is one of the most common wall solutions of recent standalone retail buildings in Europe. This is another gap in knowledge that this study will address. Van Ooteghem and Xu [27] studied the embodied impacts of steel building systems and of roofs in single-story commercial buildings in Canada. Wall systems, such as those identified in the present research, were not addressed. Khoa et al. [30] assessed four typical commercial building fabrics in Australia, leaving out sandwich panels in facades. Likewise, Luo et al. [31] and Chau et al. [28] calculated the carbon emissions of the most used materials in retail buildings in China and Hong Kong. However, these studies considered building solutions based on their geographic location, which may not be similar to those often used in European countries. Concrete blocks and bricks, for instance, were the most used construction materials for walls in the literature review. Contemporary retail buildings in west European countries tend to have an envelope made of a cladding wall system or simply of sandwich panels juxtaposed to an auxiliary structure. Thermal performance is currently of the utmost importance in Europe, due to climate change regulation. For that matter, studies on the thermal performance of retail buildings were also researched, particularly of extruded polystyrene as a material frequently used in retail building envelopes. Some of the retrieved studies explored the embodied energy of this type of material [32–34], but not the role it played in retail buildings' life cycle energy.

Hence, this study's major contributions can be summarized as follows: (i) to evaluate the embodied energy and carbon emissions for a typical contemporary European retail building, namely regarding its shell; (ii) to quantify the material flow of the shell materials in terms of mass (kg/m$^2$ of sales area); (iii) to compare the embodied impacts to the energy and carbon emissions consumed and produced during store operation, over the building life cycle (estimated in 50 years); (iv) to assess which typical building material impacts are higher; and (v) to investigate strategies that can be used to mitigate materials' impacts in retail buildings, while delivering equivalent technical performance.

As the choice of building solutions, as well as the performance of envelope materials, depends on the climatic conditions where buildings are located, a European retail building in a Mediterranean Climate was selected as a case study. To evaluate the building's environmental impact in a rapid way, a simplified LCA method with a defined system boundary is suggested. For the present study, impacts were assessed during the material production stage (cradle-to-gate), excluding the transportation and construction stage.

## 2. Materials and Methods

### *2.1. Case Study Description*

A retail store located in Loulé, Algarve, Portugal (Figure 1), was selected as a case study for the analysis of the impacts of shell building material elements in terms of embodied energy and GHG emissions. The selected store is part of a top global do-it-yourself (DIY) retail group in terms of revenue [35], with stores in Europe, America, and Asia.

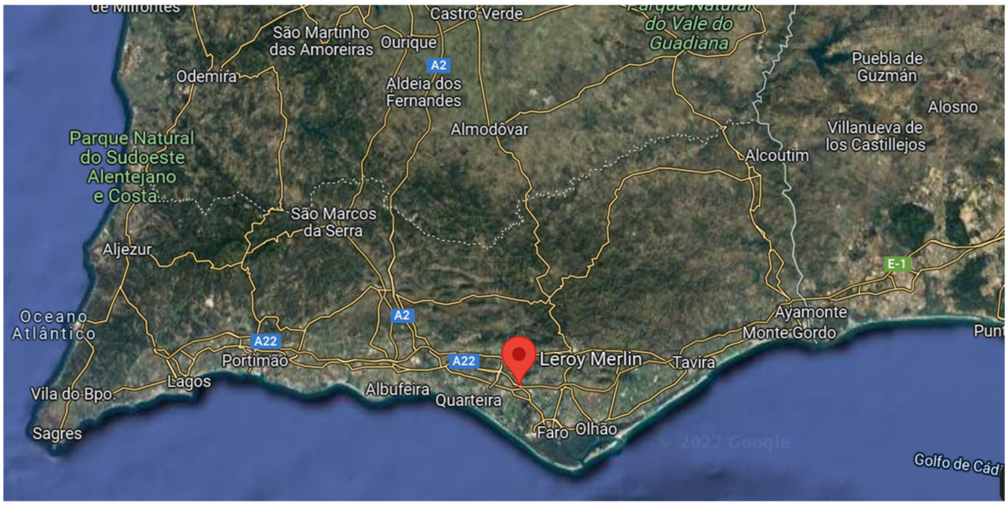


**Figure 1.** Approximate location of the retail store in Algarve, Portugal.

This store was selected as a case study because it is one of the group's most recent stores in Portugal (opened in 2017), with enough years in operation to collect data from energy bills.

The case study consists of a building located on a southeast slope, with two ventilated underground parking floors, plus the sales area floor, a mezzanine for staff facilities, and a roof with limited access, where photovoltaic (PV) panels are installed to produce green electricity (Figure 2).

**Figure 2.** Front facade and roof with photovoltaic panels of the case study store in Algarve, Portugal.

The retail building has a total gross floor area of 16,473 m$^2$ and a sales area of 9556 m$^2$ (Figure 3). The main facade of the building is opaque, and the window-to-wall ratio is about 5%, with southeast exposure (Figure 4).

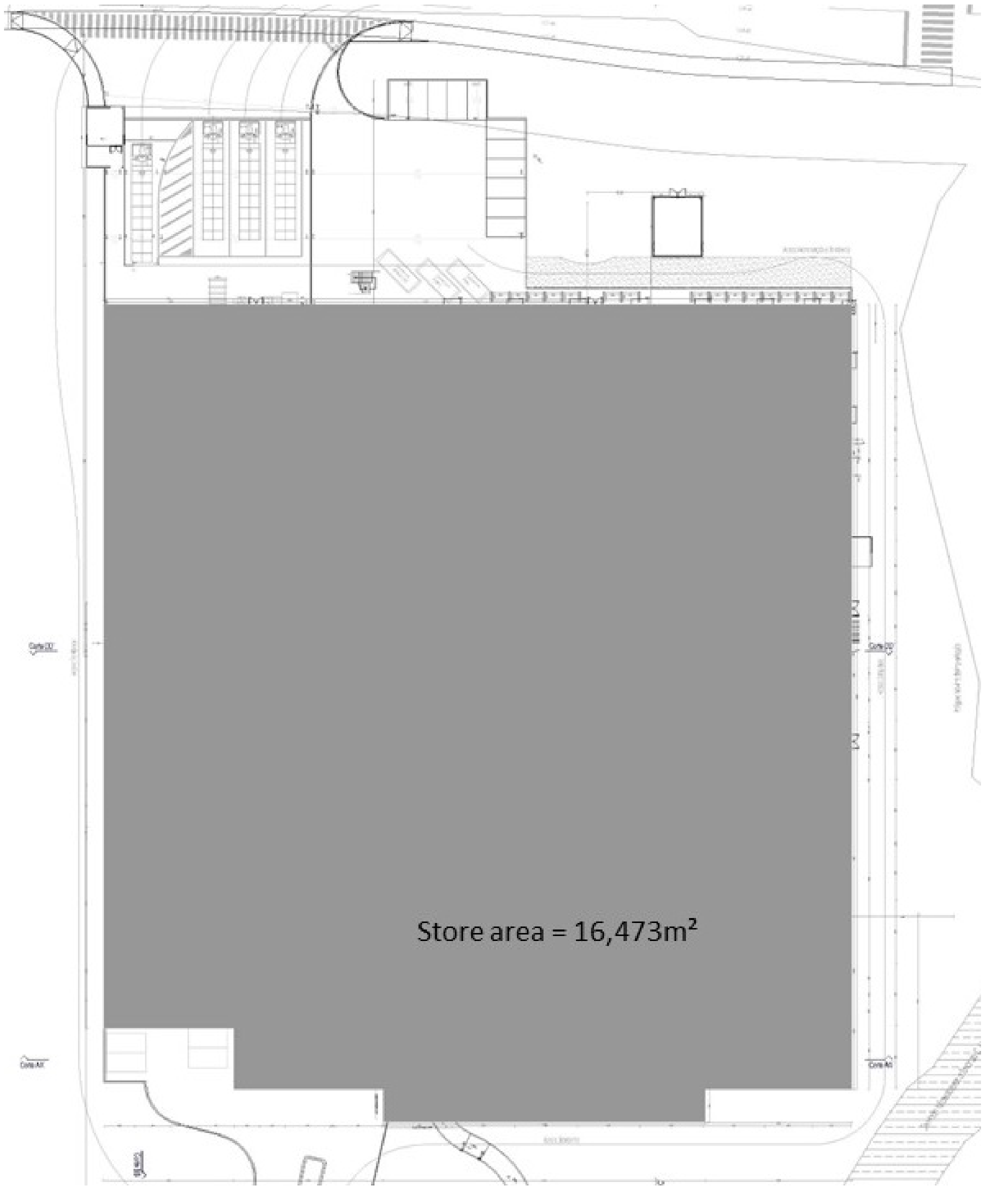


**Figure 3.** Sales level plan of the retail non-food unit in Loulé, Algarve [36].

The store is open 12 h per day, seven days per week. According to the Köppen Climate Classification, subtype for this climate is "Csa" or Mediterranean Climate. The warmest month, on average, is July, with an average temperature of 29 °C (minimum temperature of 21 °C and maximum temperature of 32 °C). The coolest month on average is January, with an average temperature of 16 °C (minimum temperature of 13 °C and maximum temperature of 22 °C). 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 peripheral urban location, store size (<9000 $m^2$ in sales area), and store layout. The choice of building solutions and building materials is also typical of retail buildings: the superstructural elements of the underground floors are made of concrete, while those of the sales floor are made of a conventional hot-rolled steel structure. The facades comprise sandwich panels, while the roof comprises ceramic blocks covered by rock wool and a flexible waterproofing bitumen membrane (Table 1).

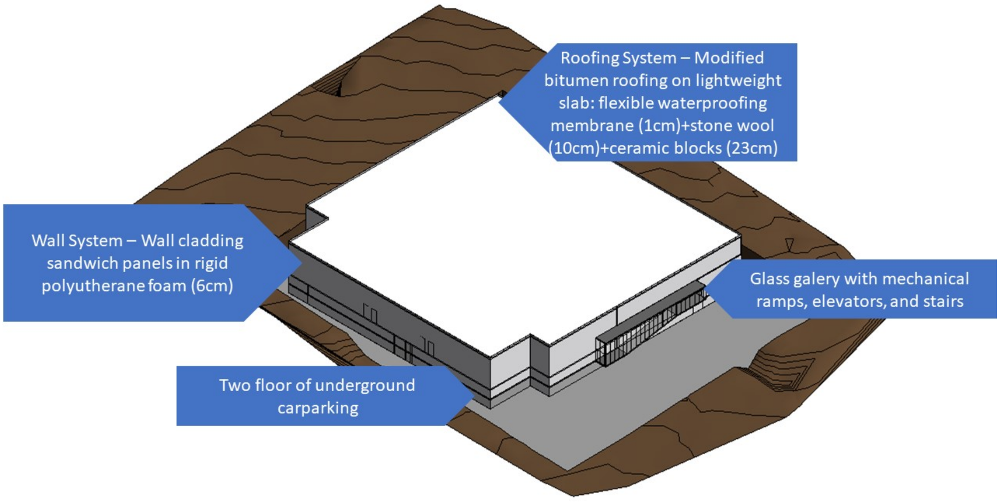


**Figure 4.** Case study's building modelling in software REVIT® with shell building material specifications.

**Table 1.** Building materials used in the envelope of the case study.

| | Energy Consumption per Building System |
|---|---|
| HVAC | 17% |
| Lighting | 41% |
| Equipment (elevators and escalators) | 42% |
| Total annual energy consumption | |

In terms of equipment, the store has LED lighting, two elevators, and two escalators. The HVAC systems comprise three heat pump packaged rooftop units 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.

| Envelope Element | Building Element Detailed Composition | Building Element Abbreviation |
|---|---|---|
| Walls | Exterior wall in white colour composed by rigid polyurethane foam (PUR) sandwich panels (6 cm thickness and a density of 35–50 kg/m$^3$) | 6 cm thick sandwich panels in rigid polyurethane foam (PUR) |
| Roofs | The roof is 34 cm thick, the external surface is white and has the following composition (from the interior to the exterior: (i) lightweight ceramic pot (2 rows of holes) and beam slab (total thickness of 23′cm and thermal resistance = 0.23 m$^2$°C/ W); (ii) rock wool (density= 35–100 kg/m$^3$, 10 cm thickness, and thermal resistance=2.50 m$^2$°C/W); and (iii) flexible waterproofing membrane impregnated with bitumen (1 cm thickness) | flexible waterproofing bitumen membrane 1 cm + rock wool 10 cm + lightweight pot and beam slab 23 cm |

*2.2. Methodology*

The data required to conduct this study were obtained from different sources: (i) the retail group's technical department provided the building's projects, bills of quantities for all building services, winning contractor's bid, and energy bills of the store; (ii) the worksheet, where the weights of building materials were inserted to calculate the total mass of building elements, was downloaded from Level(s), an European Union voluntary BSA framework [37]; (iii) the weights of building materials were estimated based on published trade literature, product technical datasheets and catalogues; and (iv) the impacts of building materials were calculated in SimaPro version 9.0.0.48 software, based on Ecoinvent version 3 database, according to the Cumulative Energy Demand (LHV) V1.00 methodology.

Hence, six main steps were considered in this study to calculate the impacts of shell building materials of a retail store (Figure 5).

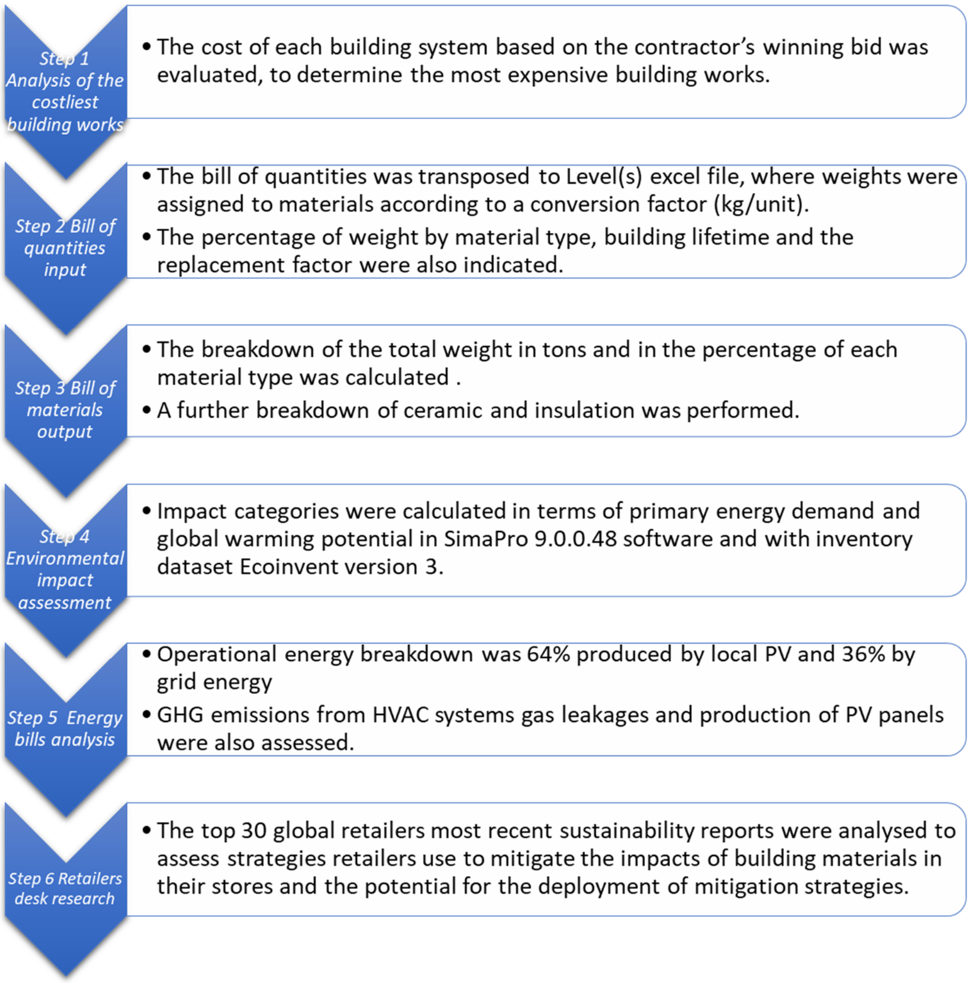


**Figure 5.** Methodology flow chart.

In step 1, analysis of the costliest building works, the cost of each building system based on the contractor's winning bid was evaluated (Figure 6 and Table S1), to determine the most expensive building works. As retailers value cost structure in their investments and prioritize decision making according to potential financial gain [38], shell elements were selected to conduct the present assessment, representing more than half of the total construction cost, and therefore were chosen to perform the present LCA. Shell elements were also selected for having a similar lifetime in years to that of the building (50), with low replacement factors.

In step 2, bill of quantities (BoQ) input, the bill of quantities for shell elements based on the contractor's winning bid was transposed to a Level(s) excel file and organized according to the main building parts proposed by the Level(s) template (Table A1 in Appendix A). Weights were assigned to building elements' materials according to a conversion factor (kg/unit). The percentage of weight split by material type was also indicated in this excel file, as well as the assumed building lifetime (considered 50 years in the present case study) and the replacement factor of each building component (Table A2 in Appendix B).

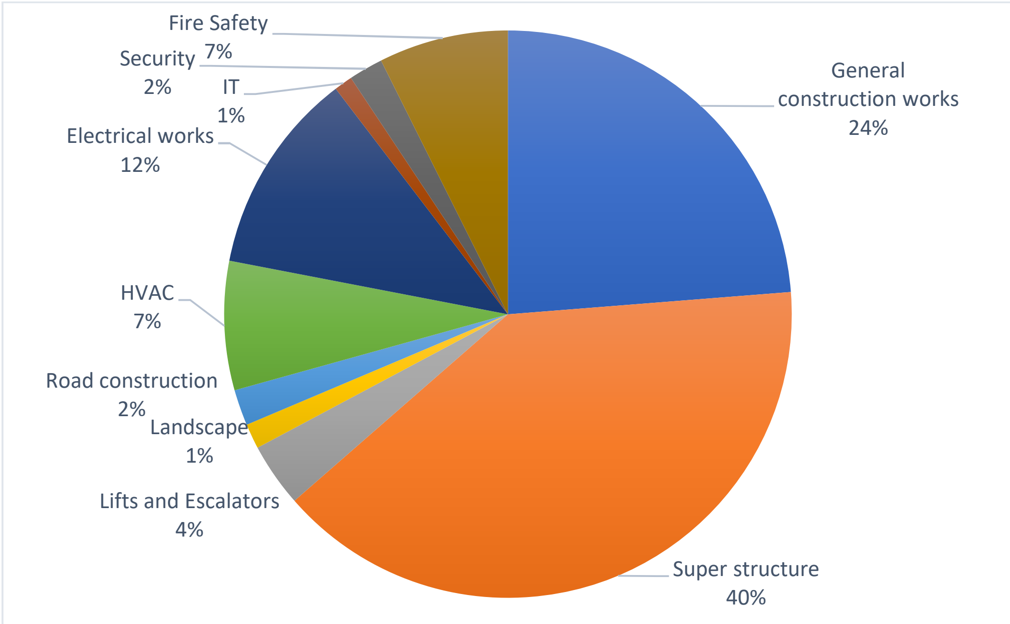


**Figure 6.** Cost disaggregation by the percentage of the cost of building system for the case study store.

In step 3, bill of materials (BoM) output, the breakdown of the total weight in tons and in the percentage of each material type was calculated (Table 3). Since Level(s) bundles insulation materials into one category and ceramic materials into the category "concrete, brick, tile, natural stone, ceramic", a further breakdown of these two categories was performed. Hence, insulation materials were split into extruded polystyrene and stone wool, and ceramic materials were split into round gravel, concrete block, cement mortar, screed, crushed limestone, ceramic tile, and concrete.

**Table 3.** Bill of materials output regarding shell building elements by material type in terms of total weight and percentage of weight.

| Material Type Breakdown | Material Total (t) | Material Total (%) |
|---|---|---|
| **Glass** | **0.37** | **0.00%** |
| **Plastic** | **2.19** | **0.01%** |
| **Bituminous mixtures** | **86.02** | **0.20%** |
| **Metals** | **2320.69** | **5.50%** |
| **Electrical and electronic equipment** | **70** | **0.17%** |
| **Concrete, brick, tile, natural stone, ceramic** | **39,415.43** | **93.44%** |
| Round gravel | 3.74 | 0.01% |
| Concrete block | 1509.3 | 3.58% |
| Cement mortar | 56.08 | 0.13% |
| Screed | 326.98 | 0.78% |
| Crushed limestone | 7154.82 | 16.96% |
| Ceramic tile | 1.38 | 0.00% |
| Reinforced concrete | 30,363.13 | 71.98% |
| **Insulation materials** | **289.61** | **0.69%** |
| Rock wool | 167.93 | 0.40% |
| Extruded polystyrene | 121.67 | 0.29% |
| Combined total * | **42,184.31** | **100.00%** |

* Material flow: 4414,43 Kg/m$^2$ (building floor area of 9556 m$^2$).

In step 4, environmental impact assessment, the impact categories of shell materials in terms of primary energy demand (PE) and global warming potential (GWP) in kg $CO_2$ eq were calculated in SimaPro 9.0.0.48 software, as a preferable life-cycle assessment tool [30]. The inventory dataset chosen to evaluate the life cycle impacts of the selected case study was Ecoinvent version 3. European averages of the Ecoinvent database inventory were selected for materials' impact calculation, and where these were not available, rest-of-the-world values were considered. System boundaries were delimited by the production and transportation of materials to the marketplace (cradle-to-gate). All other lifecycle stages were excluded from this study, namely the construction and transportation stages. One kg of material was selected as a declared unit. Primary energy demand was calculated according to the cumulative energy demand (LHV) V1.00 methodology and expressed in MJ, and later converted to kWh. GWP was calculated according to the IPCC 2013 GWP 100a V1.03 methodology and expressed in kg $CO_2$ eq. These impact categories were selected to provide comparison to familiar metrics for retailers in terms of energy use during the operation stage, namely, to compare material impacts results to EUI values and carbon use intensity (CUI) values (Table 4). Hence, to analyse further total impacts' results, they were normalized per $m^2$ of sales area of the building, which gave rise to the indicators embodied energy intensity (EEI) kWh/$m^2$ and embodied carbon intensity (ECI) in kg $CO_2$ eq /$m^2$.

**Table 4.** Impact categories of shell building elements by material type in terms of primary energy demand (in MJ and kWh) and GWP (in kg $CO_2$ eq).

| Impact Category * | Energy (MJ) | Energy (kWh) | % | IPCC GWP 100a (kg $CO_2$ eq) | % |
|---|---|---|---|---|---|
| **Concrete, brick, tile, natural stone, ceramic** | | | | | |
| Gravel, round {RoW} \| market for gravel, round \| Cut-off, S | 656 | 182 | 0% | 44 | 0% |
| Concrete block {GLO} \| market for \| Cut-off, S | 1,222,540 | 339,594 | 1% | 135,314 | 1% |
| Cement mortar {RoW} \| market for cement mortar \| Cut-off, S | 61,511,953 | 17,086,654 | 42% | 8,178,828 | 51% |
| Screed total amount | 485,943 | 134,984 | 0% | 62,547 | 0% |
| Limestone, crushed, washed {RoW} \| market for limestone, crushed, washed \| Cut-off, S | 582,959 | 161,933 | 0% | 39,466 | 0% |
| Ceramic tile {GLO} \| market for \| Cut-off, S | 16,250 | 4514 | 0% | 1130 | 0% |
| Concrete | 20,014,386 | 5,559,552 | 14% | 2,774,402 | 17% |
| **Glass** | | | 0% | | 0% |
| **Plastic** | | | 0% | | 0% |
| Acrylic varnish, without water, in 87.5% solution state {RoW} \| market for acrylic varnish, without water, in 87.5% solution state \| Cut-off, S | 66,874 | 18,576 | 0% | 4249 | 0% |
| Polycarbonate {GLO} \| market for \| Cut-off, S | 79,777 | 22,160 | 0% | 6558 | 0% |
| **Bituminous mixtures** | | | 0% | | 0% |
| Bitumen adhesive compound, hot {GLO} \| market for \| Cut-off, S | 4,519,716 | 1,255,477 | 3% | 43,842 | 0% |
| **Metals** | | | 0% | | 0% |
| Reinforcing steel {GLO} \| market for \| Cut-off, S | 57,631,652 | 16,008,792 | 39% | 4,893,783 | 30% |
| **Insulation materials** * | | | 0% | | 0% |
| Stone wool, packed {GLO} \| market for stone wool, packed \| Cut-off, S | 3,021,457 | 839,294 | 2% | 226,984 | 1% |
| Polystyrene, extruded {GLO} \| market for \| Cut-off, S | 11,559,108 | 3,210,863 | 8% | 1,176,143 | 7% |
| **Total** | 146,132,705 | 40,592,419 | | 16,140,162.98 | |

* SimaPro 9.0.0.48 software, EcoInvent database, Method: cumulative energy demand (LHV) V1.00 and IPCC 2013 GWP 100a V1.03.

In step 5, energy bills analysis, the energy bills of the store were collected from the year 2021, and data regarding the annual values of energy consumption and correspondent GHG emissions were gathered from the bills (Table 5). Normalizing annual energy consumption and GHG emissions per $m^2$ of sales area obtained EUI and CUI values for the case study store. As the store produces solar energy locally (64% of the total energy consumption), the store's EUI was calculated assuming that the energy bills represented 36% of the total operational energy. GHG emissions related to the production and installation of the PV panels were accounted for at 38 g $CO_2$eq/kWh [39]. Annual fugitive GHG emissions from HVAC systems were considered null in the present study since up to 2022, and there were no gas leakages in this store. This may be due to proper maintenance, or because the HVAC system is still relatively new. Nonetheless, it is possible that gas leakages may occur in the future. The gas load of HVAC equipment is described in Table 5. To compare the percentage of lifecycle energy and GHG emissions in terms of EEI/EUI and ECI/CUI, a static approach was considered within the defined system boundaries, in which values are set without analysing their variation over time [40].

**Table 5.** Annual energy consumption and related GHG emissions according to the store's energy bills.

| Energy Bill Month | Energy (kWh) | GHG Emissions (kg $CO_2$ eq) |
|---|---|---|
| Jan/21 | 9736 | 66,619 |
| Feb/21 | 15,121 | 50,634 |
| Mar/21 | 10,955 | 36,684 |
| Apr/21 | 11,802 | 39,518 |
| May/21 | 9101 | 33,723 |
| Jun/21 | 11,727 | 43,456 |
| Jul/21 | 11,909 | 44,130 |
| Aug/21 | 14,755 | 54,674 |
| Sep/21 | 14,832 | 51,815 |
| Oct/21 | 15,415 | 53,850 |
| Nov/21 | 14,470 | 50,551 |
| Dec/21 | 17,106 | 59,758 |
| | | 43,183 * |
| **Total** | **156,930** | **628,595 **** |
| * GHG emissions from production stage of the installed PV panels (38 g $CO_2$ eq/kWh according to the PV supplier) | | |
| ** HVAC systems did not have any leakages thus far. Their gas load is the following: | | |
| Heat pump packaged rooftop unit 1 | | 79,340 |
| Heat pump packaged rooftop unit 2 | | 79,340 |
| Heat pump packaged rooftop unit 3 | | 22,970 |
| VRF system | | 41,550 |

In step 6, retailers desk research, the top 30 global retailers most recent sustainability reports [41] were analysed to assess strategies they use to mitigate the impacts of building materials in their stores.

In the Conclusion section, the main findings of the environmental impacts of shell elements for retail buildings in terms of embodied energy and GHG emissions are described, as well as suggestions for future studies.

## 3. Results

The case study's bill of quantities based on the winning contractor's bid was analysed to assess which building system weighted the most in terms of cost (Figure 6). The costliest building systems were superstructure, general construction works, and electrical works.

Shell elements (general construction works, superstructure, and lifts and escalators) represented 67% of the total construction cost, while core elements represented 29% and external works 3%. When looking at shell elements in detail, to identify the costliest building components, concrete superstructure (31%), steel superstructure (19%) and locksmiths (15%) were the most expensive elements (Table S1).

In Table 3, the total weight of materials by material is presented. Overall, reinforced concrete was the material with the highest weight (72%), followed by crushed limestone (17%) and steel (5.5%).

In Table 4, the results of the SimaPro analysis are presented in terms of the materials' primary energy (in MJ and kWh) and GWP (in $CO_2$ eq). Cement mortar is the material with the highest embodied energy (42%) and GWP (51%), followed by steel (39% and 30%, respectively) and concrete (14% and 17%, respectively). Extruded polystyrene, which is the main material of façade sandwich panels, accounted for 8% of primary energy and 7% of GWP, whereas its contribution in weight was 0.29%. Stone wool and extruded polystyrene, as insulation materials, have important differences in their impacts, as the contribution of roofing stone wool in terms of primary energy was 2% and of GWP was 1%.

In Table 5, the store's annual energy consumption and GHG emissions are presented. The EEI of the analysed store is 4248 kWh/$m^2$, and the ECI is 1689 $CO_2$ eq/$m^2$, whereas the annual EUI is 180 kWh//$m^2$/y and annual CUI is 21 kg $CO_2$ eq/$m^2$/y.

Correspondingly, the operational energy represents 68% of the projected life cycle energy, whereas the embodied energy represents around 32%. Moreso, the GHG emissions in the operation stage represent 6% of the projected life cycle emissions, whereas those embodied in building materials represent 94%.

## 4. Discussion

By assessing the impacts of materials in retails stores, it is possible to determine the contribution of design choices in terms of environmental impact over the building life cycle, which would remain undisclosed if not for LCA accounting methods. Such information would support designers, project teams, retail owners and developers in the decision-making process of the design and refurbishment of existing retail stores. Therefore, in the Discussion section, we intend to address the results obtained for each of our research goals, which are presented in the following subsections.

### *4.1. Embodied vs. Operational Energy and Carbon Emissions*

The results of the present study indicate that according to the system boundaries defined for the analysed case study, the impacts of shell building materials in terms of primary energy demand (thereby referred to as embodied energy) represent 32% of total life cycle energy, whereas the impacts of shell building materials in terms of GWP (thereby referred to as embodied carbon) represent 94%. Inversely, 68% of life cycle energy and 6% of GHG emissions occur in the operation stage of the building. This corroborates the growing importance of embodied energy in building materials pointed out by other authors [20,23–26], as energy efficiency measures and more efficient building envelopes minimize the annual energy consumption during the operational stage. With relation to the literature review, the findings to this study corroborate the findings of Karimpour et al. [20] that argued that in milder regions, embodied energy could represent up to 35% of the total life cycle energy, of Bribián et al. [40], according to which the proportion of embodied energy in conventional buildings is of up to 38%, and of Kofoworola and Gheewala [22] that placed operational energy at 52% of total life cycle impacts, despite the importance of steel and concrete in embodied impacts. It is expected that with regulations on energy efficiency, namely the European Energy Performance of Building Directive (EPBD) [11] and the Energy Efficiency Directive [42], Member States will push towards highly energy-efficient and decarbonized buildings, as measures to mitigate climate change by 2050 [10]. Thus, the amount of embodied energy in buildings is likely to increase, especially in low energy buildings, at about 40–60% of total embodied life cycle energy, as defended by Thormark [19] and Gustavsson and Joelsson [23]. In the case of retail buildings, the ratio of operational energy versus embodied energy tends to be higher than in other building typologies, as retail EUI values in the operation stage are three to five times higher than those of office and residential buildings. Nonetheless, in retail buildings, the ratio of embodied energy is likely to augment as EUI average values have decreased in the retail sector over the past decade [43], and thus is the ratio of GHG emissions, with the increasingly more popular local production of renewable energy in retail stores.

In the analysed store, EUI was found at 180 kWh/m$^2$/y, which is 20% below the average for non-food retailers mentioned in the literature [44]. The CUI was 21 kg $CO_2$ eq/m$^2$/y, which is a top performance result based on the literature benchmarks for retail buildings [44]. The CIU of the analysed store is very low since 64% of the store's energy consumption is produced by PV panels installed onsite, which means there are no carbon emissions involved for all the energy produced on site. In addition, about half of the purchased grid energy was produced from renewable sources. Thus, with the increasing penetration of renewable energy in the market, minimizing the total energy consumption in retail buildings during the operation stage is more challenging than minimizing carbon emissions from energy consumption. From the analysed case study, with locally produced PV energy and with proper maintenance of HVAC systems, annual GHG emissions derived from the operation stage can be drastically reduced. Hence, it is apparently easier for retailers to find strategies to reduce energy consumption and carbon emissions during the operational stage than to mitigate the embodied energy and carbon emissions in buildings, mostly because of the lack of knowledge regarding the environmental impacts of building materials, a gap in knowledge which this study addressed as a research goal.

For instance, most of the energy consumed in non-food retail buildings is for HVAC systems [9], which makes the choice to use envelope building materials of retail buildings of great importance. Envelope materials with high thermal resistance enable the reduction of energy losses, as they function as powerful thermal insulators and therefore can reduce internal heat gains, in turn leading to lower energy consumption in HVAC systems [30,45]. Nonetheless, different insulation materials with similar thermal resistance can have different environmental impacts. In this sense, extruded polystyrene, the main material of the sandwich panels used in this store, accounted for 8% of embodied energy and 7% of embodied carbon, whereas rock wool used for roofing had significantly lower embodied energy (2%) and embodied carbon (1%). These findings are similar to those of Bríbian et al. [40], according to whom stone wool has a primary energy demand 4 times lower and a carbon footprint 4.7 times lower than that of rigid polyurethane foam. Hence, when using low impact materials, attention must be paid to their thermal characteristics and to their expected lifetime to effectively reduce the total building's life cycle impacts [24]. In the case of the analysed store, material impacts could be reduced by using stone wool sandwich panels for facades instead of extruded polystyrene panels, with similar thermal performance.

### *4.2. Quantification of Material Flow and Materials Intensity*

The material flow of the analysed building was 4414 kg/m$^2$. In terms of the total mass, reinforced concrete (72%), crushed limestone (17%) and steel (5.5%) were found to be the most significant materials. In terms of primary energy demand in kWh, cement mortar (42%), steel (39%), concrete (14%), and extruded polystyrene (8%) were found to be the most intensive materials. In terms of GWP in kg $CO_2$ eq, these materials were also the most intensive ones, accounting for 51%, 30%, 17% and 7% of GHG emissions, respectively. These findings are in line with those of Cabeza et al. [24] for commercial buildings that placed steel, cement, and sand as the materials with the largest contributors to embodied energy due to their mass. Likewise, Chau et al. [28] placed concrete and rebar as the largest contributors to total life cycle environmental impacts in a commercial building.

In the case of insulation materials, the findings of the present study also confirm those of Chau et al. [28], in the sense that materials with little mass may have important lifecycle impacts.

In relation to the total sales area, the EEI and ECI of shell elements were found to be 4248 kWh/m$^2$ and 1689 kg $CO_2$ eq/m$^2$, respectively. The breakdown of the most relevant building materials' impacts was the following: cement mortar 6437 kWh/m$^2$

and 856 kg $CO_2$ eq/m$^2$, steel 6031 kWh/m$^2$ and 512 $CO_2$ eq/m$^2$, concrete 2094 kWh/m$^2$ and 290 $CO_2$ eq/m$^2$, and extruded polystyrene 1210 kWh/m$^2$ and 123 kg $CO_2$ eq/m$^2$. Comparison of these values with other case studies found in the literature is difficult, as studies vary according to building type, methodology, scope, and localization, as stated by van Ooteghem and Xu [27]. In China, Luo et al. [31] obtained a material flow of 494 kg $CO_2$ eq/m$^2$, ranking steel, concrete, and mortar as the most carbon-intensive materials, which is in line with the findings of the present study. Nevertheless, the impact of steel was 195.13 $CO_2$ eq/m$^2$, the impact of concrete was 105.05 $CO_2$ eq/m$^2$, and the impact of mortar 58.05 $CO_2$ eq/m$^2$, which is significantly less than the results obtained in the present case study. Nevertheless, for the analysed case study, the amount of concrete is higher, as the store has two underground car parking floors. As for steel elements, facades and roofing, the material quantities found in this store are similar to those of similar standalone stores.

In Sri Lanka, Kumanayake et al. [46] obtained a material flow of 2318.27 kg/m$^2$ for a commercial office building, and the embodied carbon in the material production phase was 629.60 kg $CO_2$ eq/m$^2$. Reinforced steel, concrete and clay bricks were major carbon-emitting materials. In Hong Kong, Chau et al. [28] concluded that concrete, steel, plaster and render and screed were the main contributors to the total impact of commercial buildings, in which concrete accounted for up to 28% of the total impact, rebar for up to 22%, and plaster, render and screed for up to 15%.

Overall, there is a consensus in these studies that steel, cement, and concrete account for the majority of environmental impacts at the manufacturing stage [24,30,40], which is also in line with the findings of the present study.

### *4.3. Strategies to Mitigate Materials' Impacts in Retail*

Some of the solutions more frequently mentioned in the literature to mitigate life cycle impacts of building materials are [20,46]: (i) to reduce quantities of materials, (ii) to incorporate lower carbon intensity materials in concrete, (iii) to promote the use of low-carbon materials, (iv) to use recycled materials and (v) to favour materials with environmental labelling (e.g., Environmental Product Declarations (EPD)). Nonetheless, not all solutions can be performed in the retail sector. For instance, some strategies to mitigate environmental impacts must be operated during material production processes. The embodied impacts of concrete could decrease by a more eco-efficient production of clinker, the use of alternative fuels in the cement industry, the use of different types of cement waste, and the use of lime mortars instead of cement mortars [40]. The mitigation strategies that can be more sustainable for retail buildings are described in the next subsections. Some retailers already mentioned them in their sustainability reports, with varying degrees of implementation.

#### 4.3.1. Use of Low Environmental Impact Materials

Wood is acclaimed as a viable construction material for superstructures by many authors, as it is almost carbon neutral [3,31,40,47]. According to Le et al. [30], structures that combine timber with other materials have fewer impacts than those using metal, brick, or concrete. Wooden structures have been used sparsely in retail, creating a building visually lighter, adaptable, and recyclable. Some retailers' green building concepts include the use of organic building materials, namely wood for structural frames, front facades and, in many cases, the roof shell. Light steel framing has also been identified as a promising structure due to it being lightweight and for allowing for increased floor area [31]. The replacement of limestone-based clinker in Portland cement by supplementary cementitious materials (namely fly ash, granulated blast-furnace slag, and calcined clay) is suggested by Rissman et al. [47] as a way to reduce the amount of cement needed in concrete. The replacement of conventional insulation with natural materials such as cork, wood fibre and sheep's wool, or with recycled materials such as cellulose fibre, is suggested by Bribián et al. [40], which further points to the difficulty in recycling polystyrene or polyurethane at their current assemblage process, thus stressing the need to design for disassembly. Other solutions that minimize the impact of building materials mentioned in the literature include the substitution of ceramic tiles by light clay or silica-calcareous bricks [40], or the replacement of concrete by unfired bricks and stone [26].

In a general way, the use of environmentally friendly and recyclable materials is commonly highlighted by retailers in their sustainability reports, namely the use of recycled asphalt with recycled aggregate as a base material used in parking lots, the use of resources sparingly and the increased amount of recycled and sustainable materials employed in the construction of stores, or the use of prefabricated structural steel systems in new stores made of up to 80% of recycled content. The diversion of construction waste from landfill by recycling eligible roof membranes and metal fixtures was also reported by retailers, as well as the reuse of shelving fixtures and chiller cases, and of steel frames and sashes, to reduce construction waste. These actions support the findings of Bribián et al. [40] in identifying the recycling of building materials as essential to reduce the embodied energy in buildings. According to Bribián et al. [40], the use of recycled metal in structural elements can provide savings of more than 50% in terms of embodied energy.

#### 4.3.2. Optimized Design

As superstructure materials represent most of the embodied energy and carbon in buildings, largely due to their weight, the design optimization of structural elements is of the utmost importance to minimize embodied impacts. The use of bolted connections in conventional hot-rolled steel structures is also a good practice to allow for design for disassembly [27]. Nevertheless, despite the importance of steel and concrete in the total lifecycle impacts of buildings, the optimization of other shell elements such as window area, insulation level and concrete flooring, is also important [20]. Material efficiency in design also includes the reduction of material waste, the improvement of the durability of buildings, their reusability, ease of refurbishment, and towards the end of their lifecycle, their recyclability [47]. The promotion of optimized design principles is apparent in retail buildings, including modular design, reversible attachments, material standardization, and the use of prefabricated elements. These strategies are mentioned in some retailers' sustainability reports (dataset 1), although the extension of its use in retail stores remains undisclosed.

#### 4.3.3. Use of BSA Tools

BSA methods help stakeholders quantify the environmental impact of buildings, namely in terms of material choice. The growth of guidelines in BSA methods addressing waste efficiency, as well as the quantification of the embodied impacts of materials by LCA approaches, corroborates the growing importance of building materials in sustainability assessment [3]. The two most internationally used BSA methods, LEED and BREEAM [48], have integrated several of the above-mentioned strategies to reduce the impacts of buildings under their assessment processes. LEED [6] encourages the use of materials for which life cycle information is available and that have environmentally, economically, and socially preferable lifecycle impacts. These include the sourcing of raw materials (namely bio-based materials, certified wood, salvaged or refurbished materials, and of recycled content and locally sourced materials) and the careful choice of material ingredients (awarding material ingredient reporting or optimization); BREEAM [7] encourages the reduction of environmental and social impacts of buildings under a lifecycle approach, namely through the conduction of an LCA study to assist in the selection of products with a low environmental impact, ensuring that all lifecycle impacts are taken into account in the design stage, and allowing optimal solutions to be identified and adopted early on. For that purpose, BREEAM awards points to EPDs for the responsible sourcing of construction products (with lower environmental, economic, and social impacts) and the design for durability and material efficiency (encouraging the reuse of existing materials and the use of materials with recycled content). The management of waste is also considered by BREEAM, in promoting the reduction and diversion of waste to landfills during the construction and operational stage and the design for disassembly and adaptability. Nevertheless, BSA methods in Europe and throughout the world are market oriented and national policy driven, and in this sense, there is lack of an international standardized approach to measure building sustainability [49]. This context has led the European Commission to launch Level(s), as a voluntary sustainability reporting framework [48,50], with a set of indicators and metrics that consider the full life cycle of the building. Level(s) can be used directly or indirectly with other BSA methods, and therefore, the use of its bill of quantities template file is encouraged (see Appendices A and B), as it facilitates the estimation of the weight of materials used in new construction or refurbishing projects, which is fundamental for LCA studies.

#### 4.3.4. Applicability of Mitigation Strategies in Retail Buildings

The degree to which the described mitigation strategies varies within retailers may be related to several different factors, mostly related to knowledge on the environmental impact of building materials, maturity of alternative solutions in the construction industry, and cost. Many retailers are owner-occupiers, and they are in the best position to make long-term investment decisions about their buildings. They will tend to have a longer-term perspective and stand to benefit directly from their material choices. This applies both to new buildings and the refurbishment of existing ones. However, the limited mandate time of a board of administration in a retail company (usually 3 to 4 years) contributes to a greater focus and attraction on the short-term payback of the investments especially for refurbishments, thus limiting the range of alternative solutions to be considered for the buildings they use.

Developers are the primary players in commercial construction and can be speculative, which frequently results in a short-term perspective on the buildings' financial value. Speculative developers will typically be interested in material and energy efficiency only if it is a significant factor in the buying decision. This weakens the incentive for investments in materials impact mitigation strategies. Whichever is the circumstance, too much importance is placed on the initial investment required, rather than on life-cycle cost assessments and return-on-investment calculations.

The main reasons for using mitigation strategies in retail buildings are perceived to be long-term economic benefits, the availability of subsidies, image benefits, the desire to reduce environmental impacts, and because of corporate social responsibility. On the other hand, the most common barriers hindering retailers from deploying more mitigation strategies in material choices are perceived high capital costs, long payback times, ignorance and lack of knowledge regarding embodied impacts of building elements, a perception of risk and that alternative solutions are unproven, incoherent policy, and planning constraints.

Some of the suggested mitigation strategies are easy to use and do not pose a risk on retailers. If the use of wood in structural elements and light steel framing is too daring for some building owners, increasing the quantity of recycled materials in buildings is more feasible, namely in that of steel in structural elements, or that of recycled aggregates in concrete and in paving solutions. Optimizing the design of structural elements and designing for disassembly are also straightforward strategies to mitigate construction impacts. Choosing materials with equivalent performance, but with minor impacts, could also be easily achieved in retail. For instance, the embodied impacts of the materials of the analysed store could be minimized by choosing stone wool sandwich panels for the facades instead of extruded polystyrene panels and by choosing metal sheet coverings for the roof system instead of bitumen materials.

Lastly, the use of BSA tools to support project design in retail buildings will assuredly lead to better design choices, as most building sustainability aspects are covered by these methods, including different levels of LCA studies.

### 4.4. Implications

LCA studies can effectively assess the environmental performance of buildings and identify improvement opportunities; this was evident in the assessment of the case study, which identified materials that could be replaced for technically equivalent materials in terms of thermal performance (e.g., rock wool instead of extruded polystyrene or coated steel sheets instead of asphalt-based materials), at a fraction of the environmental impacts, in turn validating LCA methods as useful tools for sustainable business management and further encouraging its use.

Retail is a diverse but highly concentrated industry in terms of ownership and sales and is composed of a very large number of participants. This level of concentration allows for easier deployment of sustainable practices across the sector. In addition, the retail sector is strategically positioned in the construction industry and can influence the supply stream of materials used in this sector. Given that each studied retailer operates hundreds of stores, results show a key potential to reduce the impacts of building materials in the retail sector, in either new stores or refurbishing processes. Regarding the latter, there is a great opportunity for material impact mitigation in the upkeep of existing retail stores, as the embodied energy and carbon impacts of new structural elements could be avoided.

In addition, if core and external works' elements were included in the present study, the amount of embodied energy and embodied carbon would augment in proportion to operational energy, which further reinforces the effort that should be made in material choice at early design stages, to minimize total life cycle impacts. Accordingly, Chau et al. [28] argue that the total impact of non-structural elements is 1.4–1.6 times that of structural elements, since structural elements have no replacement factor, and core elements in retail buildings can be renovated as often as every five years, depending on market demands [51]. As the frequent refurbishment cycles of retail stores, motivated mostly by competition circumstances, lead to increased life cycle impacts in retail buildings [28], more attention should be given to strategies that save material quantities, reduce the use of materials with high energy and carbon intensities and promote the use of environmentally friendly materials [46].

### 4.5. Limitations

This study analysed the impacts of shell building materials in a retail building. The results of this study are approximate rather than precise since without EPDs, and impacts can only be estimated using existing inventories that, on occasion, are difficult to adapt to individual projects [40]. Inventory databases provide general values rather than specific, regional context-adapted values.

In further studies, it is also necessary to analyse the impact of core and external materials in the life cycle of retail buildings and to enlarge system boundaries to other life cycle stages. Nonetheless, as pointed out by Hertwich et al. [52] and Pomponi and Moncaster [3], an incomplete assessment is better than no assessment, and in the case of retail buildings, preliminary studies are necessary, as current knowledge about the impacts of materials is extremely limited [4,24].

Impacts in SimaPro software were calculated in terms of primary energy demand, whereas the EUI of the store was calculated in terms of final energy. The current default conversion coefficient is 2.1 in the European Union [53], which implies that for each unit of electricity, 2.1 units of primary energy are required. This study did not provide direct conversion of final energy into primary energy. Nevertheless, the values presented in this study provide an original understanding of the need to reduce the embodied impacts of materials at their initial lifecycle stages, since the tendency is for operational energy to decrease.

## 5. Conclusions

This study set out to assess the embodied energy and carbon emissions for a typical contemporary European retail building, while comparing it to the energy and carbon emissions consumed and produced during store operation, over the building life cycle, which represents a significant contribution to the existing body of knowledge, as no such studies were identified in the literature for European retail stores. In addition, this research also suggests strategies that can be used to mitigate materials' impacts in retail buildings in a straightforward way, enhancing the study's applicability.

The present study results place the embodied energy of a retail store in Portugal at 32% of total life cycle energy and the embodied carbon at 94% of total life cycle carbon emissions. EUI was found at 180 kWh/$m^2$/y, which is 20% below the average for non-food retailers found in previous research work. Likewise, the CUI was 21 kg $CO_2$ eq/$m^2$/y, which is a top performance result. The CIU of the analysed store is very low since most of the store's energy consumption is produced by PV panels installed onsite. In addition, about half of the purchased grid energy is produced from renewable sources. Thus, with the increasing penetration of renewable energy in the market, the CUI derived from energy consumption is likely to decrease, which reinforces the importance of building materials choice for the overall life-cycle impact of the building.

In relation to the store's sales area, the embodied energy was found to be 4248 kWh/$m^2$ and the embodied carbon 1689 kg $CO_2$ eq/$m^2$. The most intensive energy and carbon materials were cement mortar, steel, concrete, and extruded polystyrene. Embodied impacts for the present case study could be minimized by choosing stone wool sandwich panels for the facades instead of extruded polystyrene panels and by choosing metal sheet coverings for the roof system instead of bitumen materials.

Easy solutions to reduce material impacts in retail buildings include increasing the quantity of recycled materials in steel structural elements, in concrete and in paving solutions. Optimizing the design of structural elements and designing for disassembly are also straightforward strategies to mitigate construction impacts, as well as choosing materials with equivalent performance but with minor impacts.

There is a great opportunity for material impact mitigation in the upkeep of existing retail stores, especially in developed countries where the building stock is extensive, including the extension of the lifetime of buildings. The embodied energy and carbon in buildings could be drastically minimized in refurbishment processes, as the impacts of new structural elements could be avoided. In addition, with tighter regulations on the energy consumption of buildings, as set up by the EPBD, and in the emerging low-energy building era, the embodied impacts of materials are increasingly important, as the results suggest. Nevertheless, becoming carbon zero is easier to achieve in retail buildings, namely through the onsite production of renewable energy and energy offsetting methods, than becoming near zero energy, mainly due to the high EUI of the retail sector and extensive operating hours.

*Recommendations and Future Research*

In further studies, it is necessary to analyse the impact of core and external works' materials in the life cycle of retail buildings and to enlarge system boundaries to other life-cycle stages, including demolition or refurbishment options. A pluralistic approach is a key to the transition to a low-carbon built environment. In this sense, mitigation strategies that include strong policy and regulation at a governmental level, namely carbon mitigation offsets, emissions trading, carbon tax, carbon sequestration and decarbonization of the energy grid should also be under debate. Tangible benefits of integrating LCA studies in future building codes should also be considered, to accelerate the transition towards a sustainable, low-carbon building sector.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16010378/s1, Table S1: Cost disaggregation by building component for the case study store, based on the winning contractor's bid.

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## Appendix A

**Table A1.** Bill of quantities input of shell building elements for the analysed retail store, according to level(s) template file.

| Bill of Quantities Organised by the Main Building Parts and Elements | | | | | | | | Floor Area (m$^2$) | | 9556.00 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Tier 1 Building Element** | **Tier 2 Building Element** | **Tier 3 Building Element** | **Description of the Product/Material Being Purchased** | **Bill of Quantities** | **Unit** | **Conversion Factor (kg/Unit)** | **Total (kg)** | **Cost €/Unit** | **Cost €/kg** | **Total Cost (EUR)** |
| Shell | roof | Weatherproofing | roofing system: 0.75 mm metal sheet, 150 kg/m$^3$ rock wool plates, waterproofing in 3 layers of 4 kg/m$^2$ asphalt membrane | 9119 | m$^2$ | 25 | 227,975.00 | 34.45 | 1.38 | 314,149.55 |
| Shell | Roof | Weatherproofing | waterproofing membrane in polymer bitumen 3 kg/m$^2$ and fiberglass reinforcement, polymer bitumen 4 kg/m$^2$, extruded polystyrene sheets 50 mm, synthetic fibre geotextile blanket 150 g/m$^2$, pebble | 78 | m$^2$ | 56.65 | 4418.70 | 35.25 | 0.62 | 2749.50 |
| Shell | Roof | Weatherproofing | waterproofing membrane in polymer bitumen 3 kg/m$^2$ and fiberglass reinforcement, polymer bitumen 4 kg/m$^2$, 50 mm extruded polystyrene plates, 150 g/m$^2$ geotextile synthetic fibre mat; slabs, 35 mm screed and 30 mm insulation | 146 | m$^2$ | 83.65 | 12,212.90 | 52.30 | 0.63 | 7635.80 |
| Shell | Roof | Weatherproofing | steel sheet 0.75 mm | 767 | m$^2$ | 5 | 3835.00 | 16.25 | 3.25 | 12,463.75 |
| Shell | Facades | External wall systems, cladding and shading devices | 50 mm sandwich panels, with rock wool interior, and fastening structures | 3903 | m$^2$ | 19 | 74,157.00 | 33.15 | 1.74 | 129,384.45 |
| Shell | Facades | External wall systems, cladding and shading devices | 0.5 mm steel sheet, including secondary metal frame | 1288 | m$^2$ | 9 | 11,592.00 | 23.18 | 2.58 | 29,855.84 |
| Shell | Facades | External wall systems, cladding and shading devices | 3 mm perforated aluminium panels, including secondary aluminium frame | 416 | m$^2$ | 17 | 7072.00 | 101.14 | 5.95 | 42,074.24 |
| Shell | Facades | External wall systems, cladding and shading devices | 2 mm steel plate including fastening frame | 200.15 | m$^2$ | 17 | 3402.55 | 62.22 | 3.66 | 12,453.33 |
| Shell | Facades | External wall systems, cladding and shading devices | 2 mm metal grid including fastening frame | 40 | m$^2$ | 17 | 680.00 | 266.91 | 15.70 | 10,676.40 |
| Shell | Facades | External wall systems, cladding and shading devices | reinforced masonry of concrete blocks, cement mortar and sand | 5284 | m$^2$ | 270 | 1,426,680.00 | 20.51 | 0.08 | 108,374.84 |
| Shell | Facades | External wall systems, cladding and shading devices | masonry of concrete blocks 50 × 20 × 15 cm, cement and sand mortar | 306 | m$^2$ | 270 | 82,620.00 | 11.06 | 0.04 | 3384.36 |
| Shell | Facades | External wall systems, cladding and shading devices | plastering with cement mortar, hydraulic lime and sand | 674 | m$^2$ | 83.2 | 56,076.80 | 7.97 | 0.10 | 5371.78 |
| Shell | Facades | External paints, coatings and renders | Interior paintings on concrete block walls and plasterboard walls | 5241 | m$^2$ | 0.26 | 1362.66 | 3.06 | 11.77 | 16,037.46 |
| Shell | Facades | External paints, coatings and renders | Interior paintings on concrete block walls and plasterboard walls | 742 | m$^2$ | 0.26 | 192.92 | 3.42 | 13.15 | 2537.64 |
| Shell | Non_loadbearing_elements | Internal walls, partitions and doors | Steel door, metal frame, 80 cm | 14 | Unit | 10.64 | 148.96 | 1114.00 | 104.70 | 15,596.00 |
| Shell | Facades | Façade openings (including windows and external doors) | Fire door 60 min, 90 cm | 1 | Unit | 11.97 | 11.97 | 1960.00 | 163.74 | 1960.00 |

**Table A1.** *Cont.*

| Bill of Quantities Organised by the Main Building Parts and Elements | | | | | | | | Floor Area ($m^2$) | | 9556.00 |
|---|---|---|---|---|---|---|---|---|---|---|
| Tier 1 Building Element | Tier 2 Building Element | Tier 3 Building Element | Description of the Product/Material Being Purchased | Bill of Quantities | Unit | Conversion Factor (kg/Unit) | Total (kg) | Cost €/Unit | Cost €/kg | Total Cost (EUR) |
| Shell | Non_loadbearing_elements | Internal walls, partitions and doors | Fire door 60 min, 90 cm | 9 | Unit | 11.97 | 107.73 | 1960.00 | 163.74 | 17,640.00 |
| Shell | Non_loadbearing_elements | Internal walls, partitions and doors | Fire door 60 min, 90 cm | 16 | Unit | 11.97 | 191.52 | 5932.00 | 495.57 | 94,912.00 |
| Shell | Facades | Façade openings (including windows and external doors) | Automatic sliding doors, 2.00 m. Double glazing 8.8.6 (laminated colourless glass on the outside and tempered glass on the inside) | 3 | Unit | 25 | 75.00 | 6973.00 | 278.92 | 20,919.00 |
| Shell | Facades | Façade openings (including windows and external doors) | Thermo-lacquered aluminium frame with 6 mm tempered crystal glass | 12 | Unit | 33.6 | 403.20 | 336.00 | 10.00 | 4032.00 |
| Shell | Non_loadbearing_elements | Internal walls, partitions and doors | Fireproof sliding gate in iron frame, 60 min | 16 | Unit | 200 | 3200.00 | 13,166.00 | 65.83 | 210,656.00 |
| Shell | Facades | Façade openings (including windows and external doors) | Steel door, metal frame, 90 cm | 6 | Unit | 11.97 | 71.82 | 1968.00 | 164.41 | 11,808.00 |
| Shell | Facades | Façade openings (including windows and external doors) | Steel door, metal frame, 140 cm | 7 | Unit | 18.62 | 130.34 | 6134.00 | 329.43 | 42,938.00 |
| Shell | Facades | Façade openings (including windows and external doors) | Steel door, metal frame, 140 cm | 3 | Unit | 14 | 42.00 | 1167.00 | 83.36 | 3501.00 |
| Shell | Roof | Weatherproofing | Smoke exhaustion skylight 2000 × 2000 mm in transparent honeycomb polycarbonate | 49 | Unit | 7.08 | 346.92 | 1487.00 | 210.03 | 72,863.00 |
| Shell | Roof | Weatherproofing | Skylight 2000 × 2000 mm | 89 | Unit | 4.58 | 407.62 | 668.00 | 145.85 | 59,452.00 |
| Shell | Roof | Weatherproofing | Day light and smoke-exhaustion skylight 1400 × 1400 mm, 16 mm transparent honeycomb polycarbonate. | 2 | Unit | 5.92 | 11.84 | 1166.00 | 196.96 | 2332.00 |
| Shell | Roof | Weatherproofing | Natural tubular lighting system SOLATUBE®, 35 cm diameter | 17 | Unit | 1.75 | 29.75 | 703.00 | 401.71 | 11,951.00 |
| Shell | Facades | External wall systems, cladding and shading devices | Double-skinned sectional door filled with rigid polyurethane foam | 1 | unit | 200 | 200.00 | 4742.00 | 23.71 | 4742.00 |
| Shell | Facades | External wall systems, cladding and shading devices | Micro-perforated metal rolling grille | 4 | unit | 22 | 88.00 | 9725.00 | 442.05 | 38,900.00 |
| Shell | Facades | External wall systems, cladding and shading devices | Stapled glass facade composed of double-glazing: 12 mm tempered glass + 16 mm air chamber + 10+10.4 tempered, transparent laminated glass. Stainless steel fasteners. | 1 | unit | 10.5 | 10.50 | 117,390.00 | 11,180.00 | 117,390.00 |
| Shell | Parking_facilities | Above ground and underground (within the curtilage of the building and servicing the building occupiers) | Foam insulation 50 mm | 73596 | $m^2$ | 1.65 | 121,433.40 | 5.17 | 3.13 | 380,491.32 |
| Shell | Parking_facilities | Above ground and underground (within the curtilage of the building and servicing the building occupiers) | soundproofing mineral wool 45 mm | 565 | $m^2$ | 4.5 | 2542.50 | 3.79 | 0.84 | 2141.35 |
| Shell | Facades | External paints, coatings and renders | Bituminous emulsion; Waterproofing membrane in polymer bitumen 4 kg/$m^2$ and polyester reinforcement protected with polyethylene on both sides; High density polyethylene granular sheet with embedded geotextile | 2613 | $m^2$ | 4.4 | 11,497.20 | 15.00 | 3.41 | 39,195.00 |
| Shell | Foundations_substructure | Basements | C12/15 concrete | 2266 | $m^2$ | 144.3 | 326,983.80 | 6.39 | 0.04 | 14,479.74 |
| Shell | Foundations_substructure | Basements | Rockfill in limestone quarry gravel, Ø40/70 mm | 8684 | $m^2$ | 640 | 5,557,760.00 | 11.61 | 0.02 | 100,821.24 |
| Shell | Foundations_substructure | Retaining walls | formwork with modular metal panels for reinforced concrete walls | 5226 | $m^2$ | 13 | 67,938.00 | 13.67 | 1.05 | 71,439.42 |
| Shell | Foundations_substructure | Basements | C30/37 reinforced concrete wall, A500 NR steel, 86.6 kg/$m^3$ | 676.32 | $m^3$ | 2586.6 | 1,749,369.31 | 135.29 | 0.05 | 91,499.33 |
| Shell | Foundations_substructure | Retaining walls | Gabion wall: 2.70 mm diameter galvanized steel wire mesh box, 80 × 100 $mm^2$ hexagonal mesh, and limestone, on tires | 1050.695 | $m^3$ | 1600 | 1,681,112.00 | 50.86 | 0.03 | 53,438.35 |
| Shell | Foundations_substructure | Piles | metal panel formwork for foundations | 2005.92 | $m^2$ | 13 | 26,076.96 | 11.39 | 0.88 | 22,847.43 |
| Shell | Foundations_substructure | Piles | Foundation in reinforced concrete C30/37, steel A500 NR, 42.6 kg/$m^3$ | 1430.316 | $m^3$ | 2542.6 | 3,636,721.46 | 104.53 | 0.04 | 149,510.93 |
| Shell | Foundations_substructure | Retaining walls | Reinforced concrete foundation and concrete walls C30/37, A500 NR steel, 67.9 kg/$m^3$ | 182.83 | $m^3$ | 2567.9 | 469,489.16 | 122.22 | 0.05 | 22,345.48 |
| Shell | Non_loadbearing_elements | Ground floor slab | Slab in reinforced concrete C30/37 and steel A500 NR, 50 kg/$m^3$ | 173.04 | $m^3$ | 2550 | 441,252.00 | 109.70 | 0.04 | 18,982.49 |
| Shell | Loadbearing_structural_frame | Frame (beams, columns and slabs) | Steel S275JR (Fe430) in metallic structure, HEA | 450959 | kg | 1 | 450,959.00 | 2.18 | 2.18 | 983090.62 |
| Shell | Loadbearing_structural_frame | Frame (beams, columns and slabs) | C30/37 reinforced concrete column, A500 NR steel, 235.6 kg/$m^3$; sheet metal formwork | 317 | $m^3$ | 2736 | 867,312.00 | 345.00 | 0.13 | 109,365.00 |
| Shell | Loadbearing_structural_frame | Frame (beams, columns and slabs) | Reinforced concrete beam, C30/37, A500 NR steel, 122.8 kg/$m^3$; wooden formwork | 1400 | $m^3$ | 2623 | 3,672,200.00 | 176.00 | 0.07 | 246,400.00 |
| Shell | Non_loadbearing_elements | Ground floor slab | Slab foundation in reinforced concrete C30/37, steel A500 NR, 48 kg/$m^2$; wooden formwork; quartz hardener powder 7 kg/$m^2$ | 8284.31 | $m^2$ | 1305 | 10,811,024.55 | 89.40 | 0.07 | 740,617.31 |

**Table A1.** *Cont.*

| Bill of Quantities Organised by the Main Building Parts and Elements | | | | | | | | Floor Area ($m^2$) | | 9556.00 |
|---|---|---|---|---|---|---|---|---|---|---|
| Tier 1 Building Element | Tier 2 Building Element | Tier 3 Building Element | Description of the Product/Material Being Purchased | Bill of Quantities | Unit | Conversion Factor (kg/Unit) | Total (kg) | Cost €/Unit | Cost €/kg | Total Cost (EUR) |
| Shell | Non_loadbearing_elements | Ground floor slab | Slab of reinforced concrete C30/37, steel A500 NR, 48 kg/$m^2$; wooden formwork; quartz hardener powder 7 kg/$m^2$ | 63.2 | $m^2$ | 555 | 35,076.00 | 44.55 | 0.08 | 2815.56 |
| Shell | Non_loadbearing_elements | Ground floor slab | Slab of reinforced concrete C30/37, steel A500 NR, 48 kg/$m^2$; quartz hardener powder 7 kg/$m^2$ | 317 | $m^2$ | 805 | 255,185.00 | 57.30 | 0.07 | 18,164.10 |
| Shell | Loadbearing_structural_frame | Upper floors | Fungiform slab of reinforced concrete C30/37, volume 0.269 $m^3/m^2$, steel A500 NR, 13.7 kg/$m^2$; lightweight concrete block with expanded clay FB65/40; electrowelded mesh AR42 of A500 EL steel and quartz powder hardener 7 kg/$m^2$ | 3295 | $m^2$ | 1631 | 5,374,145.00 | 59.00 | 0.04 | 194,405.00 |
| Shell | Loadbearing_structural_frame | External walls | C30/37 reinforced concrete wall, A500 NR steel, 183.4 kg/$m^3$ | 61 | $m^3$ | 670.75 | 40,915.75 | 337.00 | 0.50 | 20,557.00 |
| Shell | Non_loadbearing_elements | Ground floor slab | C30/37 concrete flooring, steel fibres, polyethylene mesh, quartz hardener powder 7 kg/$m^2$ | 8624 | $m^2$ | 501.4 | 4,324,073.60 | 21.60 | 0.04 | 186,278.40 |
| Shell | Loadbearing_structural_frame | Upper floors | Slab with galvanized steel plate and reinforced concrete C30/37, total volume of concrete 0.082 $m^3/m^2$, steel A500 NR, 1 kg/$m^2$ | 716 | $m^2$ | 300.84 | 215,401.44 | 30.78 | 0.10 | 22,038.48 |
| Shell | Non_loadbearing_elements | Stairs and ramps | Concrete staircase C30/37, A500 NR steel, 22 kg/$m^2$, olive leaf plate sill | 114 | $m^2$ | 504.4 | 57,501.60 | 79.88 | 0.16 | 9106.32 |
| Shell | Non_loadbearing_elements | Stairs and ramps | Escalators, with a load capacity of 9000 kg/120 people | 4 | Unit | 15000 | 60,000.00 | 66823.00 | 4.45 | 267,292.00 |
| Shell | Non_loadbearing_elements | Stairs and ramps | Lift, with a load capacity of 2000 kg/27 people | 2 | unit | 5000 | 10,000.00 | 34778.00 | 6.96 | 69,556.00 |
| Shell | Non_loadbearing_elements | Internal walls, partitions and doors | Ceramic tile, mortar of cement, hydraulic lime and sand | 153 | $m^2$ | 9 | 1377.00 | 29.51 | 3.28 | 4515.03 |

## Appendix B

**Table A2.** Bill of materials input of shell building elements according to material type for the analysed retail store, in terms of percentage of weight for each building element, assumed lifetime and replacement factor, according to Level(s) template file.

| Bill of Materials by Material Type (% Weight). | | | | | | | | | | Normalised Weight of Materials Needed over Lifetime | Normalised Cost of Materials Needed over Lifetime |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Concrete, Brick, Tile, Ceramic, etc. | Glass | Plastic | Bituminous Mixtures | Metals | Insulation Materials | Electrical and Electronic Equipment | Total % (Should Be 100%) | Assumed Lifetime of Product/Material (Years) | Normalised Requirement Factor over Building Lifetime | | |
| | | | 32.0% | 20.0% | 48.0% | | 100.0% | 50 | 1.5 | 341,962.50 | 471,224.32 |
| 84.7% | | | 12.4% | | 2.9% | | 100.0% | 50 | 1.5 | 6628.05 | 4124.25 |
| 89.7% | | | 8.4% | | 2.0% | | 100.0% | 50 | 1.5 | 18,319.35 | 11,453.70 |
| | | | | 100.0% | | | 100.0% | 50 | 2 | 7670.00 | 24,927.50 |
| | | | | 25.0% | 75.0% | | 100.0% | 50 | 2 | 148,314.00 | 258,768.90 |
| | | | | 100.0% | | | 100.0% | 50 | 2 | 23,184.00 | 59,711.68 |
| | | | | 100.0% | | | 100.0% | 50 | 1 | 7072.00 | 42,074.24 |
| | | | | 100.0% | | | 100.0% | 50 | 1.5 | 5103.82 | 18,679.99 |
| | | | | 100.0% | | | 100.0% | 50 | 2 | 1360.00 | 21,352.80 |
| 100.0% | | | | | | | 100.0% | 50 | 1 | 1,426,680.00 | 108,374.84 |
| 100.0% | | | | | | | 100.0% | 50 | 1 | 82,620.00 | 3384.36 |
| 100.0% | | | | | | | 100.0% | 50 | 1 | 56,076.80 | 5371.78 |
| | | 100.0% | | | | | 100.0% | 50 | 3 | 4087.98 | 48,112.38 |
| | | 100.0% | | | | | 100.0% | 50 | 3 | 578.76 | 7612.92 |
| | | | | 75.0% | 25.0% | | 100.0% | 50 | 2 | 297.92 | 31,192.00 |
| | | | | 75.0% | 25.0% | | 100.0% | 50 | 2 | 23.94 | 3920.00 |
| | | | | 75.0% | 25.0% | | 100.0% | 50 | 2 | 215.46 | 35,280.00 |
| | | | | 75.0% | 25.0% | | 100.0% | 50 | 2 | 383.04 | 189,824.00 |
| | 75.0% | | | 25.0% | | | 100.0% | 50 | 2 | 150.00 | 41,838.00 |
| | 75.0% | | | 25.0% | | | 100.0% | 50 | 2 | 806.40 | 8064.00 |
| | | | | 75.0% | 25.0% | | 100.0% | 50 | 2 | 6400.00 | 421,312.00 |
| | | | | 75.0% | 25.0% | | 100.0% | 50 | 2 | 143.64 | 23,616.00 |
| | | | | 75.0% | 25.0% | | 100.0% | 50 | 2 | 260.68 | 85,876.00 |
| | | | | 100.0% | | | 100.0% | 50 | 2 | 84.00 | 7002.00 |
| | | 75.0% | | 25.0% | | | 100.0% | 50 | 2 | 693.84 | 145,726.00 |
| | | 85.0% | | 15.0% | | | 100.0% | 50 | 2 | 815.24 | 118,904.00 |
| | | 75.0% | | 25.0% | | | 100.0% | 50 | 2 | 23.68 | 4664.00 |
| | | 75.0% | | 25.0% | | | 100.0% | 50 | 1.5 | 44.62 | 17,926.50 |
| | | | | 75.0% | 25.0% | | 100.0% | 50 | 3 | 600.00 | 14,226.00 |
| | | | | 100.0% | | | 100.0% | 50 | 2 | 176.00 | 77,800.00 |
| | 75.0% | | | 25.0% | | | 100.0% | 50 | 1 | 10.50 | 117,390.00 |
| | | | | | 100.0% | | 100.0% | 50 | 1 | 121,433.40 | 380,491.32 |
| | | | | | 100.0% | | 100.0% | 50 | 1 | 2542.50 | 2141.35 |
| | | | 100.0% | | | | 100.0% | 50 | 1 | 11,497.20 | 39,195.00 |
| 100.0% | | | | | | | 100.0% | 50 | 1 | 326,983.80 | 14,479.74 |
| 100.0% | | | | | | | 100.0% | 50 | 1 | 5,557,760.00 | 100,821.24 |
| | | | | 100.0% | | | 100.0% | 50 | 1 | 67,938.00 | 71,439.42 |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 1,749,369.31 | 91,499.33 |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 1,681,112.00 | 53,438.34 |
| | | | | 100.0% | | | 100.0% | 50 | 1 | 26,076.96 | 22,847.42 |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 3,636,721.46 | 149,510.93 |

**Table A2.** *Cont.*

| Bill of Materials by Material Type (% Weight). | | | | | | | | | | Normalised Weight of Materials Needed over Lifetime | Normalised Cost of Materials Needed over Lifetime |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Concrete, Brick, Tile, Ceramic, etc. | Glass | Plastic | Bituminous Mixtures | Metals | Insulation Materials | Electrical and Electronic Equipment | Total % (Should Be 100%) | Assumed Lifetime of Product/Material (Years) | Normalised Requirement Factor over Building Lifetime | | |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 469,489.15 | 22,345.48 |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 441,252.00 | 18,982.48 |
| | | | | 100.0% | | | 100.0% | 50 | 1 | 450,959.00 | 983,090.62 |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 867,312.00 | 109,365.00 |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 3,672,200.00 | 246,400.00 |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 10,811,024.55 | 740,617.31 |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 35,076.00 | 2815.56 |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 255,185.00 | 18,164.10 |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 5,374,145.00 | 194,405.00 |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 40,915.75 | 20,557.00 |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 4,324,073.60 | 186,278.40 |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 215,401.44 | 22,038.48 |
| 95.0% | | | | 5.0% | | | 100.0% | 50 | 1 | 57,501.60 | 9106.32 |
| | | | | | | 100.0% | 100.0% | 50 | 1.5 | 90,000.00 | 400,938.00 |
| | | | | | | 100.0% | 100.0% | 50 | 1.5 | 15,000.00 | 104,334.00 |
| 100.0% | | | | | | | 100.0% | 50 | 1 | 1377.00 | 4515.03 |

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