

## Article

# A Practical Framework for Cradle-to-Site Embodied Carbon Assessment: Application to a Multifamily Residential Building in Faro, Portugal

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## Abstract

The growing importance of embodied carbon (EC) in building decarbonisation requires transparent, context-specific Life Cycle Assessment (LCA) approaches. This study develops a practical framework for quantifying cradle-to-site EC (A1–A4), combining detailed post-construction material quantification with a structured data selection methodology. Carbon factors (CFs) are primarily sourced from geographically representative Environmental Product Declarations (EPDs) and evaluated through a reliability framework that incorporates material similarity, geographical proximity, and data completeness. An Analytic Hierarchy Process (AHP) is further applied to select representative values for key materials such as ready-mix concrete. The application of this framework highlights the critical influence of data representativeness on EC results and demonstrates a transparent and reproducible approach for reducing uncertainty in early-stage assessments. The case study yields a total EC of 228 kg CO<sub>2</sub>e/m<sup>2</sup>, with structural materials identified as the main carbon hotspots: ready-mix concrete accounts for approximately 40% of total impacts, reinforcing steel for around 11%, while masonry systems, infill, and levelling layers contribute a significant additional share. Together, these materials represent slightly more than 75% of total embodied emissions. Beyond the numerical results, the study shows that a limited number of material categories dominate the carbon footprint, enabling targeted decarbonisation strategies. The proposed framework is designed to be transferable to similar building contexts and supports more robust, data-driven decision-making in the Portuguese construction sector and beyond. It is particularly relevant in regions where locally representative environmental data are not necessarily sufficient, as it provides a structured approach for developing embodied carbon assessments under such condition.

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## 1. Introduction

Concern over climate change and the environmental impact of the construction sector has intensified interest in emissions associated with building materials. As operational energy systems progressively decarbonise, embodied carbon (EC), arising from material

extraction, processing and transport, becomes increasingly significant. These emissions occur at the early stages of a project and therefore contribute directly to short-term climate targets, particularly in new residential developments.

Across Europe, life cycle-based approaches to environmental assessment are gaining increasing regulatory relevance. The Energy Performance of Buildings Directive highlights the need to progressively consider the whole-life-cycle emissions of buildings, recognizing that buildings act as long-term repositories of materials and that design choices and material selection significantly influence environmental performance throughout their life cycle. This perspective applies not only to new construction but also to renovation projects, reflecting the growing importance of reducing life-cycle emissions across the building sector [1]. Despite this shift, practical implementation remains constrained by gaps in data availability, uneven publication of Environmental Product Declarations (EPDs), and limited integration between environmental assessment tools and conventional design practice. This becomes particularly relevant in Portugal, where locally representative environmental data for many commonly used construction materials remain scarce, making the selection of representative datasets a significant challenge.

The product stage is likely to account for the greatest share of EC emissions for many construction materials, making material selection a key determinant of environmental performance within Life Cycle Assessment (LCA) [2,3]. Decisions made in early design stages have a disproportionate influence on overall impacts and should therefore consider full life cycle implications. Environmental burdens arise throughout all stages of a material's life cycle: extraction processes alter ecosystems and require intensive primary energy consumption; manufacturing demands substantial energy and water inputs while generating emissions and waste streams; and construction activities contribute significantly to global waste generation due to inefficient material management. Operational performance is also conditioned by initial material choices, which affect durability, maintenance requirements, and indoor environmental quality. End-of-life scenarios frequently involve landfill disposal, particularly for treated materials that cannot be easily recycled [4].

Several strategies have been proposed to mitigate EC through informed material selection. Bio based materials and reclaimed or recycled products can substantially reduce emissions compared to conventional alternatives. Steel, for example, demonstrates recovery rates approaching full recyclability. Additional measures include local sourcing, structural optimisation to reduce self-weight, prioritising renovation over new construction, and integrating circular design strategies that enable dismantling and reuse. Embedding durability, recyclability and low embodied energy as key selection criteria is therefore essential to advancing more resilient construction models [4–6].

Despite increasing awareness, the construction industry faces significant challenges in quantifying EC. Robust assessment depends on reliable data, consistent metrics, and advanced measurement tools. However, persistent limitations in data availability, quality, and geographical representativeness constrain the practical application of LCA. Evidence from cradle-to-gate studies of multifamily buildings indicates that only a limited share of carbon values is derived directly from Building Information Modelling, with most data depending on two-dimensional drawings or fragmented sources. Additionally, calculations commonly rely on industry-average EPDs rather than product-specific data [7].

Obtaining detailed information on material quantities (MQs) and specifications remains labour-intensive, particularly where subcontractors do not provide structured digital models or where composite elements contain multiple materials. The absence of mandatory EPDs for many manufacturers further complicates accurate quantification. As a result, assessments often depend on approximations that may not fully represent actual project conditions. Interior works and mechanical, electrical, and plumbing systems are

frequently excluded due to complexity and limited data availability, despite their potential contribution to overall impacts [7–9].

A significant geographical gap also persists. Carbon data for similar products may vary substantially between countries due to differences in energy mix, production technology, and transport distances. Bacheva and Raposo Grau (2025) [10] observe that research remains concentrated in a limited number of countries, creating regional bias and limiting contextual applicability. The use of generic databases with unclear system boundaries may lead to overestimation or inconsistent results, whereas more detailed and geographically representative datasets improve accuracy but increase analytical complexity [11].

Besides primary structural systems, envelope and finishing assemblies such as external thermal insulation systems, interior finishes, and waterproofing layers also add to embodied impacts. Although lighter than structural components, these multilayered systems can generate significant emissions because of the extensive surface areas they cover. Their assessment heavily relies on the availability and relevance of environmental data, which are often limited or sourced from different geographical contexts. More complex assemblies, including glazing, joinery, and mechanical systems, pose additional challenges in quantification due to their composite nature and the difficulty of assigning accurate carbon factors (CFs).

Despite these challenges, there remains a lack of practical and transferable frameworks that bridge the gap between methodological rigour and real-world application. Existing studies often rely on simplified assumptions or highly controlled datasets, limiting their applicability in design and construction practice. There is therefore a need for approaches that integrate detailed material quantification with systematic and transparent methods for evaluating data reliability, allowing practitioners to balance accuracy, data availability, and uncertainty in a consistent manner.

Within this context, this study proposes a practical framework for project-specific embodied carbon assessment focused on the cradle-to-site stage (A1–A4). The framework combines detailed post-construction material quantification with a structured evaluation of environmental data reliability, incorporating criteria such as material similarity, geographical representativeness, and data completeness. The main aim of this study is to develop and demonstrate a transferable methodology for embodied carbon assessment based on geographically representative and validated environmental data sources, primarily derived from EPDs and complemented by peer-reviewed literature when necessary. Specifically, the study aims to: (1) quantify the embodied carbon of a multifamily residential building in Faro, Portugal, for stages A1–A4; (2) establish a structured approach for selecting and evaluating carbon factors; and (3) develop a framework that can be adapted to other construction projects and potentially extended to broader life cycle stages and additional environmental indicators.

## 2. Methodology

### 2.1. LCA Framework

This study develops a structured LCA framework to quantify EC in buildings, focusing on the A1–A4 stages, in accordance with ISO 14040/44, EN 15978, and EN 15804 standards [12–18]. The methodology is designed to be practical and adaptable to different construction contexts, particularly in regions with limited availability of geographically representative environmental data. It follows a sequence of steps, including the definition of the functional unit and system boundaries, detailed material quantification through a material quantity takeoff (MQT), transport modelling for stage A4, selection and evaluation of CFs using a structured reliability assessment, and final EC calculation integrating all previous components.

The case study building is used exclusively as a practical application to demonstrate the implementation of the proposed framework and to validate its applicability under real project conditions, rather than constituting the primary focus of the research. This approach ensures that the main contribution of the study lies in the methodology itself, providing a consistent and context-sensitive framework for EC assessment in similar construction projects.

## 2.2. Case Study

The case study building is a multifamily residential building located in Faro, in the Algarve region of southern Portugal, with a total gross floor area of 6351 m<sup>2</sup>, including six storeys above ground and two underground parking levels. The structure is predominantly reinforced concrete, used in foundations, columns, beams, slabs, stairs and walls, combined with masonry systems for internal partitions and external façades.

The analysis focuses exclusively on a defined set of construction elements to quantify their contribution to embodied GHG emissions: earthworks, structural concrete, reinforcing steel, structural steel, masonry systems, insulation systems, exterior finishes, interior finishes and waterproofing systems. These categories were selected because they were supported by detailed MQT data and project specifications, allowing a more reliable estimation of material quantities and associated carbon impacts.

Other building components that may also contribute significantly to embodied carbon emissions, including mechanical, electrical and plumbing (MEP) systems, windows, carpentry, coatings, built-in components and other remaining building elements, were excluded due to insufficient project information and limitations in the available project documentation. Consequently, the reported results should be interpreted as representing only the construction systems for which sufficiently detailed quantity and environmental data were available. Due to the absence of reliable project-specific inventories, the contribution of the excluded components could not be robustly quantified and was therefore considered beyond the scope of the present study.

## 2.3. Selection of Global Warming Potential (GWP) Indicator

EC was quantified using the GWP indicator, expressed in kg CO<sub>2</sub>e. The GWP metric allows emissions of different GHG to be aggregated into a common unit by multiplying the quantity of each gas by its respective GWP relative to carbon dioxide [19]. Consequently, all carbon factors used in this study are expressed as kg CO<sub>2</sub>e per unit of material and were used to calculate the EC associated with the analysed construction systems.

Careful consideration was given to the selection of the GWP indicator. For materials without significant biogenic carbon content, which represent most of the inventory, the influence of biogenic carbon is negligible, resulting in little or no difference between GWP-total and GWP-fossil. Therefore, the GWP-total values reported in the selected EPDs were adopted. As one of the most reported climate change indicators in EPDs, GWP-total is widely used in both practice and peer-reviewed literature.

For timber-based and other bio-based products, GWP-fossil values were used instead. GWP-total values for such materials can be strongly influenced by biogenic carbon uptake and storage, potentially resulting in negative A1–A3 values. Although these results are valid under EN 15804:2012+A2:2019, previous studies have shown that they primarily reflect temporary carbon storage rather than a permanent reduction in atmospheric greenhouse gas concentrations [20]. Since the present assessment is limited to modules A1–A4 and does not include end-of-life stages (C1–C4), where the release of stored biogenic carbon would normally be accounted for, the use of GWP-fossil was considered more appropriate. This avoids attributing a temporary carbon storage benefit without

simultaneously accounting for its potential future release and therefore provides a more conservative representation of climate impacts within the adopted system boundary.

#### *2.4. Functional Unit and System Boundaries*

The functional unit adopted in this study is 1 m<sup>2</sup> of gross floor area of the residential building, assessed for stages A1–A4. This unit was selected to ensure comparability with other studies and to express results using a widely recognised indicator of building performance.

Processes outside this scope were excluded, including the construction stage (A5), the use stage (B1–B7), end of life stages (C1–C4), and module D. Ancillary activities such as site machinery, temporary works and minor auxiliary materials were also omitted, as their contribution to overall GWP is expected to be negligible compared with the main construction elements analysed.

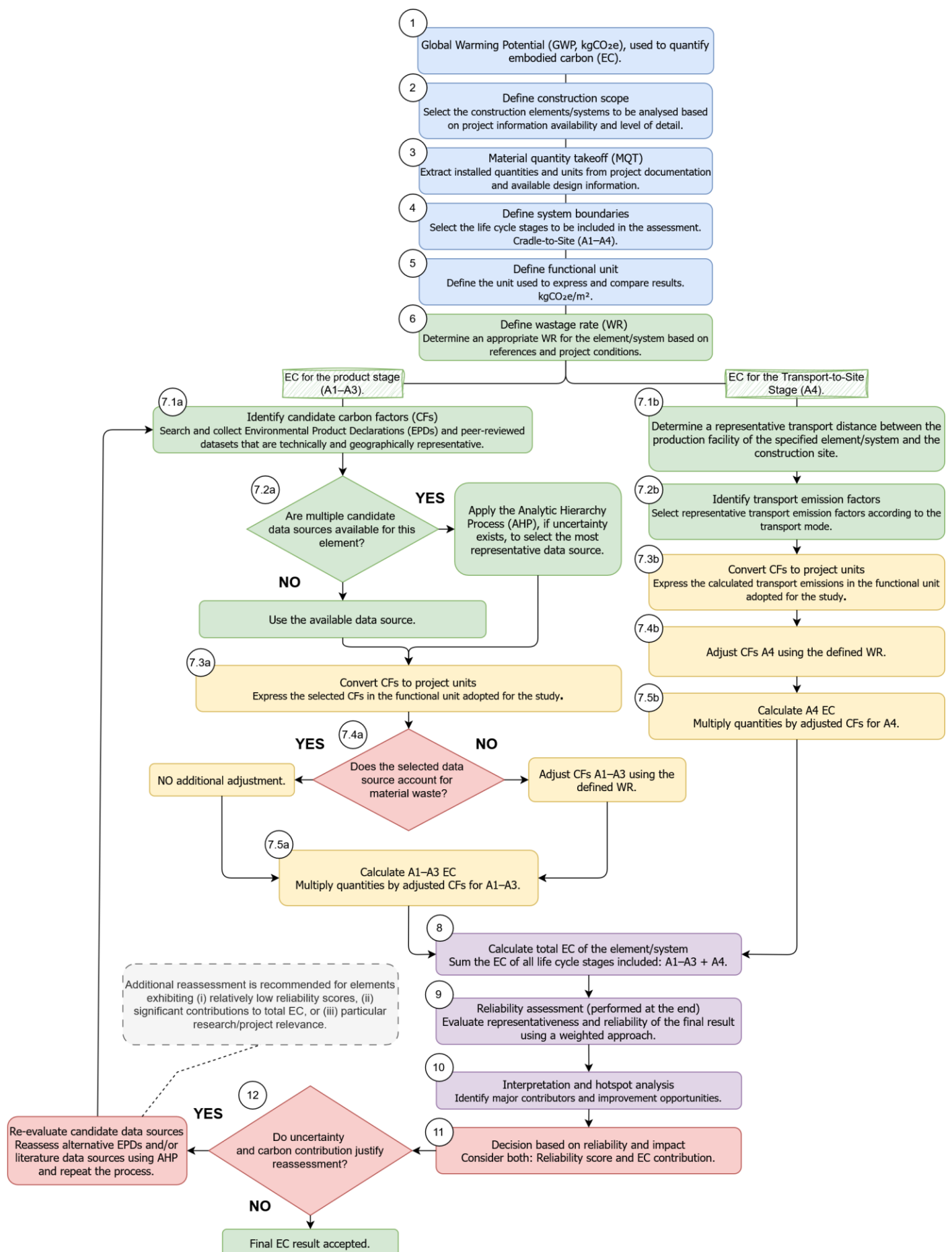
#### *2.5. Methodological Workflow for Embodied Carbon Calculation*

Figure 1 presents the proposed methodological framework developed for the cradle-to-site embodied carbon assessment of building construction systems. The framework integrates material quantity take-off, carbon factor selection, transport modelling, wastage rate (WR) application and embodied carbon calculation within a structured and transparent workflow. In addition, a reliability assessment stage is incorporated to evaluate the representativeness of the selected data sources and support the interpretation of results. The framework also includes a decision-making process for situations where significant uncertainty or high carbon contributions justify the reassessment of selected carbon factor sources.

#### *2.6. Data Sources and Reliability Assessment*

MQs were determined through a MQT derived from a BIM model and complemented with project specifications, providing a reliable estimate of the materials incorporated into the building. CFs were obtained primarily from verified EPDs, with a limited number sourced from peer-reviewed academic studies. Generic databases were deliberately avoided, and preference was given to sources that were geographically representative of the project context and sufficiently specific to the materials assessed. Priority was given to EPDs developed in accordance with EN 15804:2012+A2:2019 to maximise methodological consistency. However, where equivalent sources complying with this version were not available, EPDs developed under previous versions of EN 15804 were also considered. These were retained when they represented the most geographically relevant and material-specific CF sources available for the corresponding construction products.

To improve the reliability and transparency of the GWP calculations, a quality rating system was applied to evaluate the two key inputs of the analysis: MQ and CFs. The system is based on three criteria: material similarity, geographical proximity and data completeness. Material similarity assesses the degree of correspondence between the material described in the dataset and the material used in the project. Geographical proximity evaluates how closely the geographical context of the dataset reflects the location of the case study. Data completeness measures the extent to which the dataset includes all materials composing the analysed element. The scoring framework applied for this assessment is presented in Table 1.



**Figure 1.** Proposed methodological framework for embodied carbon calculation, data source selection and reliability assessment.

For each material, the reliability score was calculated as the arithmetic mean of the three evaluation criteria. Equal weighting was assigned to all criteria to avoid introducing additional complexity and subjectivity into the assessment, while recognising that material similarity, geographical proximity, and data completeness are all fundamental contributors to data reliability.

The overall reliability score of the construction system was then calculated as a weighted average of the individual material reliability scores, where the weighting factor corresponds to the contribution of each material to the total CF of the system. This approach assigns greater influence on materials with a higher contribution to the embodied carbon of the analysed construction system.

$$R_i = \frac{S_{m,i} + S_{g,i} + S_{c,i}}{3} \quad (1)$$

where

$R_i$  = reliability score for material  $i$ ,

$S_{m,i}$  = material similarity score for material  $i$ ,

$S_{g,i}$  = geographical proximity score for material  $i$ ,

$S_{c,i}$  = data completeness score for material  $i$ .

For a construction system composed of multiple materials:

$$R_{\text{system}} = \sum_{i=1}^n \left( R_i \times \frac{CF_i}{CF_{\text{system}}} \right) \quad (2)$$

**Table 1.** Scoring Criteria for data quality and reliability assessment.

| Criteria                    | Score 5                                                                                    | Score 4                                                                                                  | Score 3                                                                                                        | Score 2–1                                                                                                                        |
|-----------------------------|--------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| Material similarity (C1)    | Identical material by a product-specific Environmental Product Declaration (EPD) or source | Very similar material represented by a narrow product family EPD/source with minor technical differences | Functionally equivalent material represented by a product family EPD/source covering multiple related products | Generic or proxy material represented by a broad or generic database or source with limited similarity to the assessed material. |
| Geographical proximity (C2) | Same country                                                                               | Iberian Peninsula                                                                                        | Neighbouring European countries                                                                                | Distant countries                                                                                                                |
| Data completeness (C3)      | Primary and secondary materials fully represented                                          | Minor components missing                                                                                 | Several components missing                                                                                     | Major components missing                                                                                                         |

The reliability assessment was conducted using the predefined criteria presented in Table 1 and was based on a detailed evaluation of the quality and representativeness of the available data sources. In cases where any of the evaluated criteria were not straightforward, carbon factor sources, technical documentation, and project specifications were further reviewed to support the evaluation. When uncertainty remained between two possible scores, a conservative approach was adopted by assigning the lower score to avoid overestimating data reliability.

## 2.7. Material Wastage Assumptions

Material wastage was considered to reflect the difference between installed quantities and the materials that must be ordered in practice. Since the quantities used in this study were derived from a BIM model representing installed amounts, allowance factors were applied to account for surplus materials produced and delivered to site. When the declared unit in the data source already includes installation losses, no additional wastage was applied in A1–A3 to avoid double counting. In contrast, wastage was always considered in stage A4, as transport emissions depend on the total quantity of materials delivered rather than the quantities finally installed. For composite systems, wastage was distributed proportionally according to the contribution of each component to the total GWP of the element. Importantly, this allowance was not added to the installed quantities obtained from the BIM model but applied directly as a proportional increase to the calculated GWP, reflecting the additional environmental burden associated with the production and transport of surplus materials that do not appear in the installed quantities.

## 2.8. Emission Factors and Transport Modelling for Stage A4

Transport emissions for stage A4 were calculated using emission factors expressed either in g CO<sub>2</sub>e per tonne kilometre (t-km) or g CO<sub>2</sub>e per kilometre, depending on the dataset used, as shown in Table 2. Delivery distances were estimated based on approximate routes between production facilities and the construction site using Google Maps [21]. Given the relatively compact geography of the Algarve region, a representative regional delivery (RD) distance of 50 km was adopted based on Google Maps estimates for a range of typical supplier-to-site routes. Distances exceeding this threshold were classified as long-haul deliveries (LH).

For earthworks, aggregate delivery and concrete transport, both outbound and return trips were considered. These operations typically involve mixer trucks or tipper trucks that return empty after unloading at the construction site. For other construction materials, only the outbound trip was considered, assuming that transport logistics are optimised and vehicles continue with subsequent deliveries rather than returning empty to the original production facility.

**Table 2.** Emission factors adopted for transport modelling in LCA stage A4.

| Use Case                        | Vehicle Description                         | Emission Factor                |
|---------------------------------|---------------------------------------------|--------------------------------|
| Regional delivery (VECTO 4-RD)  | Rigid truck, >16 tonnes                     | 197.6 g CO <sub>2</sub> e/t-km |
| Long haul delivery (VECTO 5-LH) | Tractor–semitrailer combination, >16 tonnes | 55.5 g CO <sub>2</sub> e/t-km  |
| Construction (VECTO 16)         | Concrete mixer and tipper trucks            | 1080.8 g CO <sub>2</sub> e/km  |
| Maritime delivery (MD)          | Container ship                              | 29.7 g CO <sub>2</sub> /t-nm * |

Note. Values for VECTO groups 4-RD, 5-LH and 16 are based on the ICCT working paper on CO<sub>2</sub> emissions from trucks in the European Union [22], while values for MD are taken from the JRC technical report on Quantifying emissions in the European maritime sector [23]. \* t-nm refers to tonne-nautical mile.

## 2.9. EC Calculation Method for Stages A1–A4

The EC for stages A1–A4 is calculated as follows. Where the CF source already accounts for wastage in modules A1–A3,  $WR_{A1-A3}$  shall be set to zero in Equation (3) to prevent double counting.

$$CF_{A1-A3} = CF_{A1-A3} \times (1 + WR_{A1-A3}) \quad (3)$$

$$CF_{A4} = CF_{A4} \times (1 + WR_{A4}) \quad (4)$$

The EC for stages A1–A3 and A4 is obtained by multiplying the MQ by their corresponding CFs:

$$EC_{A1-A3} = MQ \times CF_{A1-A3} \quad (5)$$

$$EC_{A4} = MQ \times CF_{A4} \quad (6)$$

Therefore, the EC for the cradle-to-site scope is:

$$EC_{A1-A4} = EC_{A1-A3} + EC_{A4} \quad (7)$$

## 2.10. Worked Example of the Embodied Carbon Calculation Methodology

This example illustrates the application of the proposed methodology to an infill and levelling system composed of EPS insulation boards, a polyethylene membrane and a lightweight levelling screed. The objective is to demonstrate the calculation procedure from MQT to the determination of EC for stages A1–A4. This construction system was selected because it comprises multiple materials with distinct CFs and represents a relevant contributor to the overall EC of the building, making it suitable for illustrating the complete assessment workflow.

The example follows the methodological workflow presented in Figure 1 and demonstrates the implementation of each assessment step.

### 2.10.1. Steps 1–5: Definition of the Assessment Scope

The environmental indicator assessed is the EC, expressed through the GWP indicator. The analysed construction system corresponds to the infill and levelling system used in the interior areas of the building, with a total installed area of 3674.2 m<sup>2</sup>. The assessment considers stages A1–A4, and results are expressed using a functional unit of kg CO<sub>2</sub>e/m<sup>2</sup>.

### 2.10.2. Step 6: Selection of WR

WR values were assigned to each material based on construction industry estimating references and quantity surveying guides, as presented in Table 3.

**Table 3.** Emission factors adopted for transport modelling in LCA stage A4 for the worked example.

| Element                                                            | Wastage Rate (WR) |
|--------------------------------------------------------------------|-------------------|
| Lightweight concrete with EPS                                      | 5.0%              |
| Cross-linked polyethylene foam membrane (0.272 kg/m <sup>2</sup> ) | 1.0%              |
| Self-levelling screed                                              | 5.0%              |

### 2.10.3. Steps 7.1a–7.1b: Identification of Candidate CF Sources for A1–A3

The specific CFs adopted for the materials comprising the analysed system are presented in Table 4. These factors correspond to the stage A1–A3 and are expressed according to the declared units reported by the selected data sources.

**Table 4.** Specific CFs for the worked example.

| Element                         | Specific Carbon Factors (CF)<br>(A1–A3) (kg CO <sub>2</sub> e/Unit) | Declared<br>Unit | Data Source<br>Type | Reference                                                    |
|---------------------------------|---------------------------------------------------------------------|------------------|---------------------|--------------------------------------------------------------|
| Regranulated additivated<br>EPS | 17.20                                                               | m <sup>3</sup>   | Article             | Gomes et al. (2020) [24]                                     |
| Cement                          | 750.00                                                              | t                | EPD                 | Associação Técnica Da<br>Indústria De Cimento<br>(ATIC) [25] |

|                                                                    |      |                |     |                                 |
|--------------------------------------------------------------------|------|----------------|-----|---------------------------------|
| Sand                                                               | 4.48 | t              | EPD | Federación de Áridos (FdA) [26] |
| Cross-linked polyethylene foam membrane (0.272 kg/m <sup>2</sup> ) | 7.51 | m <sup>2</sup> | EPD | Danosa S.A. [27]                |
| Self-levelling screed                                              | 0.20 | kg             | EPD | Saint-Gobain Portugal S.A. [28] |

The identified CF sources were considered sufficiently representative of the analysed material. Therefore, the assessment proceeded to the next step without requiring the application of the Analytic Hierarchy Process (AHP) methodology.

#### 2.10.4. Steps 7.3a–7.4a: Conversion of CF to Project Units and WR

The material composition of the analysed system was quantified based on technical datasheets and product specifications. Table 5 presents the material consumption associated with each construction layer, together with the constituent materials considered in the embodied carbon calculations.

**Table 5.** Material consumption for the worked example.

| Element                                                                 | Material Consumption (kg/m <sup>2</sup> ) |
|-------------------------------------------------------------------------|-------------------------------------------|
| <b>Lightweight concrete with EPS</b>                                    |                                           |
| Regranulated additivated EPS                                            | 0.90                                      |
| Cement                                                                  | 30.00                                     |
| Sand                                                                    | 10.00                                     |
| <b>Cross-linked polyethylene foam membrane (0.272 kg/m<sup>2</sup>)</b> | 0.27                                      |
| <b>Self-levelling screed</b>                                            | 60.00                                     |

Note. Bold entries represent the main construction systems analysed, while non-bold entries correspond to the constituent materials used to quantify material consumption.

Table 6 shows the WR values adopted for stage A1–A3 for each construction system and indicates whether the selected data source already accounts for material wastage. Where wastage was not included in the original data source, the WR values defined in Table 3 were applied to adjust the A1–A3 CFs.

**Table 6.** WR for the worked example.

| Element                                                            | WR (A1–A3) | Data Source Accounts for WR |
|--------------------------------------------------------------------|------------|-----------------------------|
| Lightweight concrete with EPS                                      | 5.0%       | No                          |
| Cross-linked polyethylene foam membrane (0.272 kg/m <sup>2</sup> ) | 0.0%       | Yes                         |
| Self-levelling screed                                              | 5.0 %      | Yes                         |

#### 2.10.5. Steps 7.1b–7.2b: Representative Transport Distance and Emissions Factor A4

One-way delivery distances were estimated for each material based on the location of the selected suppliers and the construction site. Corresponding transport emission factors were then assigned according to the selected transport datasets and vehicle categories. The adopted distances and emission factors for LH and RD transport are presented in Table 7.

**Table 7.** Delivery distance and transport emission factors for the worked example.

| Element                                                                 | One-Way Delivery Distance |         | Emission Factor              |                               |
|-------------------------------------------------------------------------|---------------------------|---------|------------------------------|-------------------------------|
|                                                                         | LH (km)                   | RD (km) | LH                           | RD                            |
| <b>Lightweight concrete with EPS</b>                                    |                           |         |                              |                               |
| Regranulated additivated EPS                                            | 316.0                     | 50.0    | 55.5 gCO <sub>2</sub> e/t-km | 197.6 gCO <sub>2</sub> e/t-km |
| Cement                                                                  | 0.0                       | 26.0    | 0.0                          | 1080.8 g CO <sub>2</sub> e/km |
| Sand                                                                    | 0.0                       | 26.0    | 0.0                          | 1080.8 g CO <sub>2</sub> e/km |
| <b>Cross-linked polyethylene foam membrane (0.272 kg/m<sup>2</sup>)</b> | 355.0                     | 50.0    | 55.5 gCO <sub>2</sub> e/t-km | 197.6 gCO <sub>2</sub> e/t-km |
| <b>Self-levelling screed</b>                                            | 440.0                     | 50.0    | 55.5 gCO <sub>2</sub> e/t-km | 197.6 gCO <sub>2</sub> e/t-km |

Note. Bold entries represent the main construction systems analysed, while non-bold entries correspond to the constituent materials used.

#### 2.10.6. Steps 7.5a, 7.5b and 8: Adjusted CFs Including the Corresponding WR for Each Phase and Total EC

The EC associated with each element of the construction system was calculated by combining MQs with the corresponding A1–A3 and A4 CFs. The resulting EC contributions for each system and the total A1–A4 EC are summarized in Table 8.

**Table 8.** Total MQ, CF (A1–A4) and EC for the worked example.

| Element                                                            | MQ (m <sup>2</sup> ) | CF (kg CO <sub>2</sub> e/m <sup>2</sup> ) |      | EC (kg CO <sub>2</sub> e) |           |
|--------------------------------------------------------------------|----------------------|-------------------------------------------|------|---------------------------|-----------|
|                                                                    |                      | A1–A3                                     | A4   | A1–A4                     | A1–A4     |
| Lightweight concrete with EPS                                      | 3674.20              | 25.5                                      | 0.2  | 25.7                      | 94,466.6  |
| Cross-linked polyethylene foam membrane (0.272 kg/m <sup>2</sup> ) | 3674.20              | 7.5                                       | 0.01 | 7.5                       | 27,623.1  |
| Self-levelling screed                                              | 3674.20              | 12.85                                     | 2.2  | 15.0                      | 55,160.4  |
| Total EC                                                           | -                    | 45.84                                     | 2.4  | 48.2                      | 177,250.1 |

#### 2.10.7. Step 9. Reliability Assessment

The reliability of the selected data sources was evaluated using the criteria described in Section 2.6. The resulting scores for each construction system are presented in Table 9.

**Table 9.** Reliability assessment for the worked example.

| Element                                                            | Material Similarity | Geographic Proximity | Data Completeness | Score |
|--------------------------------------------------------------------|---------------------|----------------------|-------------------|-------|
| Lightweight concrete with EPS                                      | 5.0                 | 5.0                  | 5.0               | 5.0   |
| Cross-linked polyethylene foam membrane (0.272 kg/m <sup>2</sup> ) | 5.0                 | 5.0                  | 5.0               | 5.0   |
| Self-levelling screed                                              | 5.0                 | 5.0                  | 5.0               | 5.0   |
| Data reliability score                                             | 5.0                 | 5.0                  | 5.0               | 5.0   |

### 3. Results

#### 3.1. Selection of a Representative GWP Factor for the Reinforced Concrete

Concrete was selected as a priority material for detailed carbon factor evaluation due to its dominant contribution to the building mass and volume and, consequently, to the overall embodied carbon of the structure. Most structural elements in the building are composed of C30/37 concrete and are specified with an exposure class XC3, while lower-strength concretes such as C16/20 and C25/30 are used only in limited applications. Therefore, the selection of an appropriate carbon factor (CF) for concrete is particularly im-

portant, as variations in the adopted CF can significantly influence the final embodied carbon results.

In Portugal, structural concrete production is governed by NP EN 206 [29], which defines requirements related to compressive strength class, exposure class, chloride content, consistency class and maximum aggregate size. According to NP EN 206 and the Portuguese durability specification LNEC E 464,, the minimum cement content required for XC3 concrete depends on the cement type adopted. Concretes produced with CEM I or CEM II/A require a minimum cement content of 280 kg/m<sup>3</sup>, whereas concretes produced with CEM II/B, CEM III, CEM IV or CEM V require a minimum cement content of 300 kg/m<sup>3</sup> to achieve the same durability requirements [30]. Consequently, concrete mixes with the same strength class (e.g., C30/37) may contain substantially different quantities of cement depending on the selected cement type.

From an environmental perspective, the composition of the concrete mix plays a critical role in determining its GWP. Cement production represents the dominant source of emissions within concrete, and GWP values are therefore strongly influenced by both the type of cement used and its clinker content. In general, mixes incorporating CEM I exhibit higher emissions than those using CEM II, while CEM III mixes tend to present lower GWP values due to their reduced clinker content. Cement content within the mix is therefore one of the most influential parameters when assessing the EC of concrete. Consequently, variations in cement type and dosage can lead to significant differences in the reported carbon factors for otherwise comparable concrete mixes [31,32].

Numerous sources report GWP values for concrete mixes comparable to those used in this study. However, differences in cement type, cement content, clinker factor, mix composition, regional production conditions and methodological assumptions can result in considerable variation among reported emission factors. Consequently, the selection of a representative CF required a systematic evaluation rather than the adoption of a single dataset.

To address this challenge, a multi-criteria decision-making method based on the AHP was applied, as mentioned in Step 7.2a of Figure 1. The AHP method structures the decision problem into a hierarchy of criteria and evaluates alternative CF sources through pairwise comparisons using a predefined importance scale presented in Table 10 [33].

Several candidate sources were initially identified. To ensure methodological consistency and comparability among the alternatives evaluated within the AHP framework, only sources developed in accordance with EN 15804:2012+A2:2019 were considered. Furthermore, the selected sources had to represent concrete mixes comparable to the project specifications and be developed under the same Product Category Rules. Following this screening process, four EPDs were retained as candidate CF sources.

**Table 10.** The fundamental scale of absolute numbers.

| Intensity of Importance     | Definition                                                                                                   |
|-----------------------------|--------------------------------------------------------------------------------------------------------------|
| 1                           | Equal importance                                                                                             |
| 3                           | The moderate importance of one over another                                                                  |
| 5                           | Strong importance                                                                                            |
| 7                           | Very strong importance                                                                                       |
| 9                           | Extreme importance or absolute preference                                                                    |
| 2, 4, 6, 8                  | Intermediate values between the main intensities                                                             |
| Reciprocals (1/2, 1/3, ...) | If activity <i>i</i> is assigned a value compared to <i>j</i> , then <i>j</i> vs. <i>i</i> is its reciprocal |

Note. Adapted from Darko et al. (2019) [34].

Four criteria were defined to evaluate the suitability of each emission factor source:

C1—Geographical proximity: geographical closeness of the data source to the project location

C2—Product Specificity: degree of specificity of the CF source in representing the material, product, or construction system used in the project.

C3—Cement type: differences in emissions associated with CEM I, CEM II/A, CEM II/B and CEM III cement systems.

C4—Cement content: quantity of cement used in the mix.

The relative importance of the selected criteria was determined through pairwise comparisons, which were summarised in the comparison matrix presented in Table 11. The matrix was subsequently normalised to derive the criteria priorities ( $w_i$ ), as presented in Table 12.

**Table 11.** Pairwise comparison matrix of criteria (A).

|     | C1  | C2  | C3  | C4   |
|-----|-----|-----|-----|------|
| C1  | 1   | 3   | 5   | 6    |
| C2  | 1/3 | 1   | 3   | 4    |
| C3  | 1/5 | 1/3 | 1   | 2    |
| C4  | 1/6 | 1/4 | 1/2 | 1    |
| Sum | 1.7 | 4.6 | 9.5 | 13.0 |

**Table 12.** Normalised pairwise comparison matrix of criteria.

|     | C1   | C2   | C3   | C4   | $w_i$ |
|-----|------|------|------|------|-------|
| C1  | 0.59 | 0.65 | 0.53 | 0.46 | 0.56  |
| C2  | 0.20 | 0.22 | 0.32 | 0.31 | 0.26  |
| C3  | 0.12 | 0.07 | 0.11 | 0.15 | 0.11  |
| C4  | 0.10 | 0.05 | 0.05 | 0.08 | 0.07  |
| Sum | 1.00 | 1.00 | 1.00 | 1.00 | 1.00  |

Note.  $w_i$  represents the criteria priority.

The results show that geographical proximity represents the most influential parameter in determining the environmental impact of concrete in this case study, followed by product specificity, cement type and cement content.

The Consistency Index (CI) given by Equation (8) and the Consistency Ratio (CR) given by Equation (10) were calculated to ensure the logical coherence of this selection process. A CR value above 0.10 indicates inconsistency in the pairwise comparisons and signals the need to revise the judgments [35].

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (8)$$

where  $\lambda_{\max}$  is the maximum eigenvalue of the pairwise comparison matrix and  $n$  is the number of criteria or alternatives being evaluated. The value of  $\lambda_{\max}$  is obtained by averaging the ratios between the product of the comparison matrix and the priority vector, and the priority vector itself:

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^n \frac{(A \times w)_i}{w_i} \quad (9)$$

In Equation (9)  $A$  represents the pairwise comparison matrix and  $w$  is the normalised priority vector.

$$CR = \frac{CI}{RI} \quad (10)$$

With  $RI$  is the Random Index, which, denotes the Random Index, which, according to several authors, can be calculated using Equation (11) [36].

$$RI = \frac{1.98 \times (n - 2)}{n} \quad (11)$$

The resulting consistency indicators for the criteria pairwise comparison matrix are presented in Table 13.

**Table 13.** Consistency analysis for the criteria pairwise comparison matrix.

| $\lambda_{\max}$ | n    | CI   | RI   | CR   |
|------------------|------|------|------|------|
| 4.08             | 4.00 | 0.03 | 0.99 | 0.03 |

The characteristics of the candidate CF sources considered in the analysis are summarised in Table 14.

**Table 14.** Characteristics of the candidate CF sources evaluated for C30/37 concrete.

| Alternative | Source                          | GWP (kg CO <sub>2</sub> e/m <sup>3</sup> ) | Geographical Scope | Product Specificity       | Cement Type                                      | Cement Content |
|-------------|---------------------------------|--------------------------------------------|--------------------|---------------------------|--------------------------------------------------|----------------|
| A           | Secil Betão, S.A. EPD [37]      | 227                                        | Portugal           | Product-Specific EPD      | N/E                                              | ≈223–558 (390) |
| B           | Secil Betão Verdi Zero EPD [38] | 202                                        | Portugal           | Broad Product Group EPD   | CEM II/B-M (V-L)                                 | ≈238–357 (297) |
| C           | Interbeton EPD [39]             | 221                                        | Greece             | Narrow Product Family EPD | N/E                                              | ≈333–357 (345) |
| D           | PREFA Invest, a.s. EPD [40]     | 305                                        | Slovakia           | Product Family EPD        | CEM II/B-S 42.5N (≈12%) + CEM II/A-S 42.5R (≈4%) | ≈359.7         |

For each criterion, the alternative carbon factor sources were evaluated through pairwise comparisons. Tables 15–18 present the pairwise comparison matrices for criteria C1, C2, C3 and C4, respectively. The corresponding normalised matrices and priority vectors are presented in Tables 19–22, while the consistency analyses used to verify the coherence of the judgements are reported in Tables 23–26, respectively. In all cases, the calculated CR are below the recommended threshold of 0.10, indicating an acceptable level of consistency in the pairwise comparisons.

**Table 15.** Pairwise comparison matrix (A) with respect to C1.

| Alternative | A    | B    | C     | D     |
|-------------|------|------|-------|-------|
| A           | 1    | 1    | 7     | 5     |
| B           | 1    | 1    | 7     | 5     |
| C           | 1/7  | 1/7  | 1     | 1/3   |
| D           | 1/5  | 1/5  | 3     | 1     |
| Sum         | 2.34 | 2.34 | 18.00 | 11.33 |

**Table 16.** Pairwise comparison matrix (A) with respect to C2.

| Alternative | A    | B     | C    | D    |
|-------------|------|-------|------|------|
| A           | 1    | 7     | 3    | 4    |
| B           | 1/7  | 1     | 1/5  | 1/3  |
| C           | 1/3  | 5     | 1    | 2    |
| D           | 1/4  | 3     | 1/2  | 1    |
| Sum         | 1.73 | 16.00 | 4.70 | 7.33 |

**Table 17.** Pairwise comparison matrix (A) with respect to C3.

| Alternative | A     | B    | C     | D    |
|-------------|-------|------|-------|------|
| A           | 1     | 1/5  | 1     | 1/6  |
| B           | 5     | 1    | 5     | 1/2  |
| C           | 1     | 1/5  | 1     | 1/6  |
| D           | 6     | 2    | 6     | 1    |
| Sum         | 13.00 | 3.40 | 13.00 | 1.83 |

**Table 18.** Pairwise comparison matrix (A) with respect to C4.

| Alternative | A     | B    | C    | D    |
|-------------|-------|------|------|------|
| A           | 1     | 1/7  | 1/6  | 1/5  |
| B           | 7     | 1    | 2    | 3    |
| C           | 6     | 1/2  | 1    | 2    |
| D           | 5     | 1/3  | 1/2  | 1    |
| Sum         | 19.00 | 1.98 | 3.67 | 6.20 |

**Table 19.** Normalised pairwise comparison matrix with respect to C1.

| Alternative | A    | B    | C    | D    | wi   |
|-------------|------|------|------|------|------|
| A           | 0.43 | 0.43 | 0.39 | 0.44 | 0.42 |
| B           | 0.43 | 0.43 | 0.39 | 0.44 | 0.42 |
| C           | 0.06 | 0.06 | 0.06 | 0.03 | 0.05 |
| D           | 0.09 | 0.09 | 0.17 | 0.09 | 0.11 |
| Sum         | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

**Table 20.** Normalised pairwise comparison matrix with respect to C2.

| Alternative | A    | B    | C    | D    | A    |
|-------------|------|------|------|------|------|
| A           | 0.58 | 0.44 | 0.64 | 0.55 | 0.55 |
| B           | 0.08 | 0.06 | 0.04 | 0.05 | 0.06 |
| C           | 0.19 | 0.31 | 0.21 | 0.27 | 0.25 |
| D           | 0.14 | 0.19 | 0.11 | 0.14 | 0.14 |
| Sum         | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

**Table 21.** Normalised pairwise comparison matrix with respect to C3.

| Alternative | A    | B    | C    | D    | A    |
|-------------|------|------|------|------|------|
| A           | 0.08 | 0.06 | 0.08 | 0.09 | 0.08 |
| B           | 0.38 | 0.29 | 0.38 | 0.27 | 0.33 |
| C           | 0.08 | 0.06 | 0.08 | 0.09 | 0.08 |
| D           | 0.46 | 0.59 | 0.46 | 0.55 | 0.51 |
| Sum         | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

**Table 22.** Normalised pairwise comparison matrix with respect to C4.

| Alternative | A    | B    | C    | D    | A    |
|-------------|------|------|------|------|------|
| A           | 0.05 | 0.07 | 0.05 | 0.03 | 0.05 |
| B           | 0.37 | 0.51 | 0.55 | 0.48 | 0.48 |
| C           | 0.32 | 0.25 | 0.27 | 0.32 | 0.29 |
| D           | 0.26 | 0.17 | 0.14 | 0.16 | 0.18 |
| Sum         | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

**Table 23.** Consistency analysis for the pairwise matrix with respect to C1.

| $\lambda_{\max}$ | n    | CI   | RI   | CR   |
|------------------|------|------|------|------|
| 4.07             | 4.00 | 0.02 | 0.99 | 0.03 |

**Table 24.** Consistency analysis for the pairwise matrix with respect to C2.

| $\lambda_{\max}$ | n    | CI   | RI   | CR   |
|------------------|------|------|------|------|
| 4.07             | 4.00 | 0.02 | 0.99 | 0.02 |

**Table 25.** Consistency analysis for the pairwise matrix with respect to C3.

| $\lambda_{\max}$ | n    | CI   | RI   | CR   |
|------------------|------|------|------|------|
| 4.07             | 4.03 | 0.01 | 0.99 | 0.01 |

**Table 26.** Consistency analysis for the pairwise matrix with respect to C4.

| $\lambda_{\max}$ | n    | CI   | RI   | CR   |
|------------------|------|------|------|------|
| 4.08             | 4.00 | 0.03 | 0.99 | 0.03 |

To obtain the global priority vector in the AHP, the local priority vector of each criterion is multiplied by its corresponding criterion weight. The resulting weighted vectors are then aggregated to produce a single global priority vector.

This global priority vector, presented in Table 27, represents the overall ranking of the alternatives by simultaneously considering the relative importance of all evaluation criteria. Alternatives with higher global priority values are considered more representative of the project conditions and are therefore preferred for the selection of the final CF source.

**Table 27.** Global priority vector.

| Alternative | Weight |
|-------------|--------|
| A           | 0.39   |
| B           | 0.32   |
| C           | 0.12   |
| D           | 0.17   |

The results identify Alternative A as the most representative CF source, achieving the highest global priority weight (0.39) and corresponding to a GWP value of 227 kg CO<sub>2</sub>e/m<sup>3</sup> for C30/37 concrete.

For the C16/20 and C25/30 strength classes, product-specific EPDs with a geographical scope corresponding to Portugal were available and considered sufficiently representative of the intended application. In accordance with the decision-making procedure presented in Figure 1, their geographical relevance and material specificity were deemed adequate to justify direct adoption without a further AHP evaluation. Consequently, the GWP values reported in these EPDs were used directly as CFs for the respective concrete classes, as shown in Table 28.

**Table 28.** EC emission factors by concrete strength class.

| Concrete Class | Emission Factor (kg CO <sub>2</sub> e/m <sup>3</sup> ) | Source                 |
|----------------|--------------------------------------------------------|------------------------|
| C16/20         | 170                                                    | Secil Betão, S.A. [41] |
| C25/30         | 186                                                    | Secil Betão, S.A. [42] |
| C30/37         | 227                                                    | Secil Betão, S.A. [37] |

### 3.2. Specific EC

The specific EC refers to the EC reported in the sources from which the values were obtained, in some of them it was necessary to do the conversion, so the units from the specific EC are converted to match the characteristics of the material employed in the study. Table 29 presents the specific EC values as reported in the original sources.

**Table 29.** Specific EC values for building elements excluding concrete.

| Element                                                                                                                      | Declared Unit  | Specific EC (A1–A3) (kg CO <sub>2</sub> e/Unit) | Data Source Type | Reference                                              |
|------------------------------------------------------------------------------------------------------------------------------|----------------|-------------------------------------------------|------------------|--------------------------------------------------------|
| Crushed stone and sand                                                                                                       | t              | 4.48                                            | EPD              | Federación de Áridos (FdA) [26]                        |
| Rebar                                                                                                                        | t              | 336.00                                          | EPD              | SN Seixal Siderúrgica Nacional S.A. [43]               |
| Welded wire mesh                                                                                                             | t              | 359.00                                          | EPD              | Metalúrgica Galaica [44]                               |
| Structural steel hollow sections                                                                                             | t              | 2500.0                                          | EPD              | Ferpinta S.A. [45]                                     |
| Lightweight concrete block (30 × 10 × 20 cm <sup>3</sup> and 50 × 20 × 20 cm)                                                | t              | 184.00                                          | EPD              | Leca Portugal S.A. [46]                                |
| Lightweight concrete block (40 × 15 × 19 cm <sup>3</sup> and 40 × 20 × 19 cm <sup>3</sup> )                                  | m <sup>2</sup> | 37.80                                           | EPD              | Artefactos de betão S.A. [47]                          |
| Concrete block (50 × 20 × 20 cm <sup>3</sup> , 50 × 10 × 20 cm <sup>3</sup> and 50 × 25 × 20 cm <sup>3</sup> )               | t              | 76.80                                           | EPD              | ANDECE [48]                                            |
| Hollow clay brick (29 × 14.6 × 18.9 cm <sup>3</sup> , 29 × 6.9 × 18.9 cm <sup>3</sup> and 29 × 10.6 × 18.9 cm <sup>3</sup> ) | t              | 209.00                                          | EPD              | HISPALYT [49]                                          |
| Pre-dosed mortar                                                                                                             | kg             | 0.15                                            | EPD              | Saint-Gobain Portugal S.A. [50]                        |
| ETICS with EPS panels                                                                                                        | m <sup>2</sup> | 12.46                                           | EPD              | Saint-Gobain Weber Cemarsa S.A. [51]                   |
| Pre-mixed polymer mortar                                                                                                     | kg             | 0.29                                            | EPD              | Saint-Gobain Portugal S.A. [52]                        |
| Fibreglass mesh                                                                                                              | m <sup>2</sup> | 0.46                                            | EPD              | Saint-Gobain ADFORS CZ s.r.o. [53]                     |
| Primer coat                                                                                                                  | kg             | 0.08                                            | EPD              | Nordia S.A. [54]                                       |
| Decorative organic coating                                                                                                   | kg             | 1.31                                            | EPD              | Saint-Gobain Construction Products CZ a.s. [55]        |
| Facing bricks (24 × 11.5 × 7 cm <sup>3</sup> )                                                                               | kg             | 226.00                                          | EPD              | HISPALYT [56]                                          |
| XPS panel, 50 mm thick                                                                                                       | m <sup>2</sup> | 2.42                                            | EPD              | Soprema Iberia S.L.U. [57]                             |
| Regenerated additivated EPS                                                                                                  | m <sup>3</sup> | 17.2                                            | Article          | Gomes et al. (2020) [24]                               |
| Cement                                                                                                                       | t              | 750.00                                          | EPD              | Associação Técnica Da Indústria De Cimento (ATIC) [25] |
| Cross-linked polyethylene foam membrane (0.272 kg/m <sup>2</sup> )                                                           | m <sup>2</sup> | 7.51                                            | EPD              | Danosa S.A. [27]                                       |
| Self-levelling screed                                                                                                        | kg             | 0.20                                            | EPD              | Saint-Gobain Portugal, S.A. [28]                       |
| Porcelain tiles                                                                                                              | m <sup>2</sup> | 11.80                                           | EPD              | CINCA S.A. [58]                                        |
| Polished marble tiles                                                                                                        | t              | 60.70                                           | EPD              | Levantina y Asociados de Minerales S.A. [59]           |
| Multilayer oak floating floor                                                                                                | m <sup>2</sup> | 9.70                                            | EPD              | Tarkett France [60]                                    |
| MDF panelling with melamine finish                                                                                           | m <sup>2</sup> | 2.12                                            | EPD              | Financiera Maderera S.A. [61]                          |
| Interior plastering and skimming                                                                                             | m <sup>2</sup> | 3.72                                            | EPD              | Grupo Puma España S.L. [62]                            |
| Cross-linked polyethylene foam membrane (0.154 kg/m <sup>2</sup> )                                                           | m <sup>2</sup> | 4.72                                            | EPD              | Danosa S.A. [27]                                       |
| Coloured grouting mortar                                                                                                     | m              | 0.02                                            | EPD              | Chemical Building Project [63]                         |

|                                                                                                                     |                |        |     |                                               |
|---------------------------------------------------------------------------------------------------------------------|----------------|--------|-----|-----------------------------------------------|
| Tile adhesive                                                                                                       | kg             | 0.29   | EPD | Saint-Gobain Portugal S.A. [64]               |
| Satin finish varnish                                                                                                | m <sup>2</sup> | 1.09   | EPD | Industrias Juno S.A. [65]                     |
| Standard plasterboard, 12.5 mm                                                                                      | m <sup>2</sup> | 0.87   | EPD | Saint-Gobain Placo Ibérica [66]               |
| Moisture-resistant plasterboard, 15 mm                                                                              | m <sup>2</sup> | 1.91   | EPD | Saint-Gobain Placo Ibérica [67]               |
| Fire-resistant plasterboard, 15 mm                                                                                  | m <sup>2</sup> | 1.50   | EPD | Saint-Gobain Placo Ibérica [68]               |
| Tapered edge plasterboard, 12.5 mm                                                                                  | m <sup>2</sup> | 1.50   | EPD | Saint-Gobain Placo Ibérica [69]               |
| Tapered edge moisture-resistant plasterboard, 12.5 mm                                                               | m <sup>2</sup> | 1.92   | EPD | Saint-Gobain Placo Ibérica [70]               |
| Galvanised steel profiles                                                                                           | kg             | 2.98   | EPD | Saint-Gobain Placo Ibérica [71]               |
| Joint filler                                                                                                        | m <sup>2</sup> | 0.06   | EPD | Saint-Gobain Placo Ibérica [72]               |
| Mineral wool, 48 mm thick                                                                                           | m <sup>2</sup> | 0.92   | EPD | Saint-Gobain Isover Ibérica S.L. [73]         |
| Mineral wool, 60 mm thick                                                                                           | m <sup>2</sup> | 1.36   | EPD | Termolan S.A. [74]                            |
| Two-layer bituminous waterproofing system with a 3 kg/m <sup>2</sup> base sheet and a 4 kg/m <sup>2</sup> top sheet | m <sup>2</sup> | 5.13   | EPD | Danosa S.A. [75]                              |
| Polyester-reinforced bituminous membrane                                                                            | m <sup>2</sup> | 1.75   | EPD | European Waterproofing Association AISBL [76] |
| Lightweight concrete screed layer (1–5 mm grain size)                                                               | m <sup>3</sup> | 202.84 | EPD | Leca International [77]                       |
| Lightweight concrete screed layer (4–12.5 mm grain size)                                                            | m <sup>3</sup> | 127.96 | EPD | Leca International [78]                       |
| Bituminous emulsion primer                                                                                          | t              | 389.00 | EPD | Probisa productos bituminosos S.L.U. [79]     |
| Rigid mineral wool panel, 120 mm thick                                                                              | m <sup>2</sup> | 17.60  | EPD | Saint-Gobain Isover Ibérica SL. [80]          |
| Rigid mineral wool panel, 50 mm thick                                                                               | m <sup>2</sup> | 7.90   | EPD | Saint-Gobain Isover Ibérica SL. [81]          |
| Geotextile fabric                                                                                                   | kg             | 0.75   | EPD | Danosa S.A. [68]                              |
| Expanded clay aggregate                                                                                             | m <sup>3</sup> | 74.98  | EPD | Leca International [82]                       |
| Flexible cementitious waterproof mortar                                                                             | kg             | 2.44   | EPD | Danosa S.A. [83]                              |

### 3.3. EC Calculation for Earthworks, Substructure, Reinforced Concrete and Structural Steel Elements

Earthworks in this case study refer specifically to the transportation of surplus soil generated during the excavation of the building substructures. Once the excavation works are completed and the excess material has been removed, a 10 cm layer of natural gravel is placed to provide stable bedding for the ground floor slab.

Within the scope of this study, the analysis is limited to the transportation stage of the excavated material, as this is the only activity included within Phase A4 of the LCA framework. All other construction-related processes associated with earthworks are therefore considered outside the system boundaries of the study.

For the concrete strength classes used in the different structural elements, the EC values applied in the calculations correspond to those described in Section 3.1.

Structural reinforcement consists mainly of ribbed steel bars produced via the secondary production route, using recycled scrap melted in an Electric Arc Furnace. In addition, welded wire mesh manufactured from steel wire rods is used in the ground floor slab.

The use of structural steel sections in the case study is very limited, as they are incorporated only in a small number of elements. In this project, circular hollow sections (CHS) are used as columns, primarily serving an architectural or aesthetic function.

The resulting EC calculations for earthworks, substructure, reinforced concrete and structural steel elements are presented in Tables 30 and 31.

**Table 30.** EC for earthworks.

| Element                                                     | Unit           | MQ     | WR    |      | CF (kgCO <sub>2</sub> /Unit) |      |       | EC (kgCO <sub>2</sub> ) |          |          | Data Reliability |     |     |     |       | EC Share |
|-------------------------------------------------------------|----------------|--------|-------|------|------------------------------|------|-------|-------------------------|----------|----------|------------------|-----|-----|-----|-------|----------|
|                                                             |                |        | A1–A3 | A4   | A1–A3                        | A4   | A1–A4 | A1–A3                   | A4       | A1–A4    | System Share     | C1  | C2  | C3  | Score |          |
| Transport of excess soil (includes a 20% bulking allowance) | m <sup>3</sup> | 7073.0 | 0.0%  | 0.0% | 0.00                         | 4.33 | 4.33  | 0.0                     | 30,623.3 | 30,623.3 | 100.0%           | 5.0 | 5.0 | 5.0 | 5.0   | 2.1%     |
| Total                                                       |                |        |       |      |                              |      |       | 0.0                     | 30,623.3 | 30,623.3 |                  |     |     |     | 5.0   | 2.1%     |

**Table 31.** EC for substructure, reinforced concrete and structural steel elements.

| Element                                                     | Unit           | MQ    | WR    |      | CF (kgCO <sub>2</sub> /Unit) |       |        | EC (kgCO <sub>2</sub> ) |        |          | Data Reliability |     |     |     |       | EC Share |
|-------------------------------------------------------------|----------------|-------|-------|------|------------------------------|-------|--------|-------------------------|--------|----------|------------------|-----|-----|-----|-------|----------|
|                                                             |                |       | A1–A3 | A4   | A1–A3                        | A4    | A1–A4  | A1–A3                   | A4     | A1–A4    | System Share     | C1  | C2  | C3  | Score |          |
| Blinding layer, ready mix concrete C16/20, 100 mm thickness | m <sup>3</sup> | 59.0  | 2.0%  | 2.0% | 173.40                       | 6.35  | 179.75 | 10,230.6                | 374.5  | 10,605.1 | 100.0%           | 5.0 | 5.0 | 5.0 | 5.0   | 0.7%     |
| Crushed stone as sub-base for the ground floor slab         | ton            | 171.2 | 10%   | 10%  | 4.93                         | 4.26  | 9.19   | 843.7                   | 729.3  | 1573.0   | 100.0%           | 3.0 | 4.0 | 5.0 | 4.0   | 0.1%     |
| Ground floor slab, 150 mm thickness                         | m <sup>3</sup> | -     | -     | -    | -                            | -     | -      | 4889.0                  | 165.2  | 5054.2   | 100.0%           | -   | -   | -   | 5.0   | 0.3%     |
| Ready mix concrete C25/30                                   | m <sup>3</sup> | 25.5  | 2.0%  | 2.0% | 189.72                       | 6.35  | 196.07 | 4837.9                  | 161.9  | 4999.7   | 98.9%            | 5.0 | 5.0 | 5.0 | 5.0   | -        |
| Welded wire mesh                                            | ton            | 0.1   | 10%   | 10%  | 369.60                       | 23.75 | 393.35 | 51.1                    | 3.3    | 54.4     | 1.1%             | 5.0 | 5.0 | 5.0 | 5.0   | -        |
| Foundation beams and footings                               | m <sup>3</sup> | -     | -     | -    | -                            | -     | -      | 78,953.9                | 2429.1 | 81,383.0 | 100.0%           | -   | -   | -   | 5.0   | 5.6%     |
| Ready mix concrete C30/37                                   | m <sup>3</sup> | 310.0 | 2.0%  | 2.0% | 231.54                       | 6.35  | 237.89 | 71,777.4                | 1968.0 | 73,745.4 | 90.6%            | 5.0 | 5.0 | 5.0 | 5.0   | -        |
| Rebar                                                       | ton            | 19.4  | 10%   | 10%  | 369.60                       | 23.75 | 393.35 | 7176.5                  | 461.1  | 7637.7   | 9.4%             | 5.0 | 5.0 | 5.0 | 5.0   | -        |
| Structural walls                                            | m <sup>3</sup> | -     | -     | -    | -                            | -     | -      | 54,061.1                | 1895.8 | 55,956.9 | 100.0%           | -   | -   | -   | 5.0   | 3.9%     |
| Ready mix concrete C30/37                                   | m <sup>3</sup> | 185.0 | 2.0%  | 2.0% | 231.54                       | 6.35  | 237.89 | 42,834.9                | 1174.4 | 44,009.3 | 78.6%            | 5.0 | 5.0 | 5.0 | 5.0   | -        |
| Rebar                                                       | ton            | 30.4  | 10%   | 10%  | 369.60                       | 23.75 | 393.35 | 11,226.2                | 721.4  | 11,947.6 | 21.4%            | 5.0 | 5.0 | 5.0 | 5.0   | -        |
| Partition walls                                             | m <sup>3</sup> | -     | -     | -    | -                            | -     | -      | 64,602.1                | 2445.2 | 67,047.3 | 100.0%           | -   | -   | -   | 5.0   | 4.6%     |

|                                                 |                      |        |       |       |         |       |         |           |          |           |        |     |     |     |     |       |
|-------------------------------------------------|----------------------|--------|-------|-------|---------|-------|---------|-----------|----------|-----------|--------|-----|-----|-----|-----|-------|
| <i>Ready mix concrete C30/37</i>                | <i>m<sup>3</sup></i> | 200.0  | 2.0%  | 2.0%  | 231.54  | 6.35  | 237.89  | 46,308.0  | 1269.7   | 47,577.7  | 71.0%  | 5.0 | 5.0 | 5.0 | 5.0 | -     |
| <i>Rebar</i>                                    | <i>ton</i>           | 49.5   | 10%   | 10%   | 369.60  | 23.75 | 393.35  | 18,294.1  | 1175.5   | 19,469.6  | 29.0%  | 5.0 | 5.0 | 5.0 | 5.0 | -     |
| <i>Columns</i>                                  | <i>m<sup>3</sup></i> | -      | -     | -     | -       | -     | -       | 66,303.1  | 2639.8   | 68,942.9  | 100.0% | -   | -   | -   | 5.0 | 4.8%  |
| <i>Ready mix concrete C30/37</i>                | <i>m<sup>3</sup></i> | 190.0  | 2.0%  | 2.0%  | 231.54  | 6.35  | 237.89  | 43,992.6  | 1206.2   | 45,198.8  | 65.6%  | 5.0 | 5.0 | 5.0 | 5.0 | -     |
| <i>Rebar</i>                                    | <i>ton</i>           | 60.4   | 10%   | 10%   | 369.60  | 23.75 | 393.35  | 22,310.5  | 1433.6   | 23,744.2  | 34.4%  | 5.0 | 5.0 | 5.0 | 5.0 | -     |
| <i>Solid slabs</i>                              | <i>m<sup>3</sup></i> | -      | -     | -     | -       | -     | -       | 416,303.4 | 14,595.5 | 430,898.9 | 100.0% | -   | -   | -   | 5.0 | 29.8% |
| <i>Ready mix concrete C30/37</i>                | <i>m<sup>3</sup></i> | 1425.0 | 2.0%  | 2.0%  | 231.54  | 6.35  | 237.89  | 329,944.5 | 9046.3   | 338,990.8 | 78.7%  | 5.0 | 5.0 | 5.0 | 5.0 | -     |
| <i>Rebar</i>                                    | <i>ton</i>           | 233.7  | 10%   | 10%   | 369.60  | 23.75 | 393.35  | 86,358.9  | 5549.2   | 91,908.1  | 21.3%  | 5.0 | 5.0 | 5.0 | 5.0 | -     |
| <i>Parapets</i>                                 | <i>m<sup>3</sup></i> | -      | -     | -     | -       | -     | -       | 14,373.4  | 497.1    | 14,870.5  | 100.0% | -   | -   | -   | 5.0 | 1.0%  |
| <i>Ready mix concrete C30/37</i>                | <i>m<sup>3</sup></i> | 50.0   | 2.0%  | 2.0%  | 231.54  | 6.35  | 237.89  | 11,577.0  | 317.4    | 11,894.4  | 80.0%  | 5.0 | 5.0 | 5.0 | 5.0 | -     |
| <i>Rebar</i>                                    | <i>ton</i>           | 7.6    | 10%   | 10%   | 369.60  | 23.75 | 393.35  | 2796.4    | 179.7    | 2976.1    | 20.0%  | 5.0 | 5.0 | 5.0 | 5.0 | -     |
| <i>Stairs</i>                                   | <i>m<sup>3</sup></i> | -      | -     | -     | -       | -     | -       | 10,766.1  | 359.1    | 11,125.2  | 100.0% | -   | -   | -   | 5.0 | 0.8%  |
| <i>Ready mix concrete C30/37</i>                | <i>m<sup>3</sup></i> | 39.0   | 2.0%  | 2.0%  | 231.54  | 6.35  | 237.89  | 9030.1    | 247.6    | 9277.6    | 83.4%  | 5.0 | 5.0 | 5.0 | 5.0 | -     |
| <i>Rebar</i>                                    | <i>ton</i>           | 4.7    | 10%   | 10%   | 369.60  | 23.75 | 393.35  | 1736.0    | 111.6    | 1847.6    | 16.6%  | 5.0 | 5.0 | 5.0 | 5.0 | -     |
| <i>Structural steel hollow sections columns</i> | <i>ton</i>           | 0.9    | 10.0% | 10.0% | 2750.00 | 39.62 | 2789.62 | 2359.5    | 34.0     | 2393.5    | 100.0% | 5.0 | 5.0 | 5.0 | 5.0 | 0.2%  |
| <i>Total</i>                                    | <i>-</i>             | -      | -     | -     | -       | -     | -       | 723,685.9 | 26,164.7 | 749,850.6 | -      | -   | -   | -   | 5.0 | 51.8% |

Note. Italicised entries represent the constituent materials forming each construction system.

### 3.4. EC Calculation for Masonry Elements

Masonry works in the case study building can be categorised into three systems. The predominant system (approximately 79% of the total masonry surface) consists of lightweight concrete blocks manufactured with expanded clay aggregates. These blocks are mainly used in external façades, separations between apartments and common circulation areas, and long non-load-bearing walls.

The second system (about 13%) consists of hollow ceramic bricks manufactured from quarried clay that is subsequently moulded and fired. These units are mainly used in internal partition walls, particularly between bedrooms, between different functional areas, and in chimney ducts at roof level.

The third system (around 8%) corresponds to prefabricated hollow concrete blocks composed primarily of cement and aggregates. These blocks are used internally in lift shafts, stairwells, service ducts and technical rooms.

All masonry units are bonded using an industrial lightweight pre-dosed mortar composed of binders, aggregates and additives, with consumption determined according to the supplier's specifications and the type of masonry unit applied.

The resulting EC calculations for the masonry systems considered in the case study are presented in Table 32.

Table 32. EC for masonry elements.

| Element                                                                                    | Unit           | MQ     | WR    |      | CF (kgCO <sub>2</sub> /Unit) |      |       | EC (kgCO <sub>2</sub> ) |        |          | Data Reliability |     |     |     | EC Share |       |
|--------------------------------------------------------------------------------------------|----------------|--------|-------|------|------------------------------|------|-------|-------------------------|--------|----------|------------------|-----|-----|-----|----------|-------|
|                                                                                            |                |        | A1–A3 | A4   | A1–A3                        | A4   | A1–A4 | A1–A3                   | A4     | A1–A4    | System Share     | C1  | C2  | C3  |          | Score |
| Exterior masonry                                                                           |                |        |       |      |                              |      |       |                         |        |          |                  |     |     |     |          |       |
| Lightweight concrete 30 × 10 × 20 cm <sup>3</sup> block for exterior masonry wall (LCB1-E) | m <sup>2</sup> | -      | -     | -    | 28.35                        | 3.30 | 31.65 | 8963.3                  | 1044.0 | 10,007.3 | 100.0%           | -   | -   | -   | 4.7      | 0.7%  |
| Lightweight concrete block                                                                 | m <sup>2</sup> | 316.2  | 5.0%  | 5.0% | 26.71                        | 2.91 | 29.62 | 8445.1                  | 918.8  | 9363.8   | 93.6%            | 4.0 | 5.0 | 5.0 | 4.7      | -     |
| Pre-dosed mortar                                                                           | m <sup>2</sup> | 316.2  | 0.0%  | 5.0% | 1.64                         | 0.40 | 2.04  | 518.2                   | 125.3  | 643.5    | 6.4%             | 5.0 | 5.0 | 5.0 | 5.0      | -     |
| Lightweight concrete 50 × 20 × 20 cm <sup>3</sup> block for exterior masonry wall (LCB2-E) | m <sup>2</sup> | -      | -     | -    | 57.25                        | 7.15 | 64.39 | 70,345.8                | 8780.6 | 79,126.4 | 100.0%           | -   | -   | -   | 4.7      | 5.5%  |
| Lightweight concrete block                                                                 | m <sup>2</sup> | 1228.8 | 5.0%  | 5.0% | 54.12                        | 6.39 | 60.51 | 66,500.8                | 7851.2 | 74,352.0 | 94.0%            | 4.0 | 5.0 | 5.0 | 4.7      | -     |
| Pre-dosed mortar                                                                           | m <sup>2</sup> | 1228.8 | 0.0%  | 5.0% | 3.13                         | 0.76 | 3.89  | 3845.0                  | 929.4  | 4774.4   | 6.0%             | 5.0 | 5.0 | 5.0 | 5.0      | -     |
| Hollow clay 29 × 14,6 × 18.9 cm <sup>3</sup> brick for exterior masonry wall (HCB1-E)      | m <sup>2</sup> | -      | -     | -    | 22.85                        | 3.74 | 26.59 | 1815.6                  | 297.1  | 2112.7   | 100.0%           | -   | -   | -   | 4.8      | 0.1%  |

|                                                                               |                      |       |      |      |       |      |       |                 |                 |                 |        |     |     |     |            |             |
|-------------------------------------------------------------------------------|----------------------|-------|------|------|-------|------|-------|-----------------|-----------------|-----------------|--------|-----|-----|-----|------------|-------------|
| <i>Hollow clay brick</i>                                                      | <i>m<sup>2</sup></i> | 79.4  | 5.0% | 5.0% | 18.38 | 2.66 | 21.04 | 1460.5          | 211.3           | 1671.8          | 79.1%  | 5.0 | 4.0 | 5.0 | 4.7        | -           |
| <i>Pre-dosed mortar</i>                                                       | <i>m<sup>2</sup></i> | 79.4  | 0.0% | 5.0% | 4.47  | 1.08 | 5.55  | 355.1           | 85.8            | 440.9           | 20.9%  | 5.0 | 5.0 | 5.0 | 5.0        | -           |
| <b>Total</b>                                                                  |                      | -     | -    | -    | -     | -    | -     | <b>81,124.7</b> | <b>10,121.7</b> | <b>91,246.4</b> | -      | -   | -   | -   | <b>4.7</b> | <b>6.3%</b> |
| <b>Interior masonry</b>                                                       |                      | -     | -    | -    | 15.18 | 1.36 | 16.53 | 2864.3          | 256.2           | 3120.6          | 100.0% | -   | -   | -   | 4.8        | 0.2%        |
| Concrete 50 × 20 × 20 cm <sup>3</sup> block for interior masonry wall (CB1-I) | <i>m<sup>2</sup></i> | 188.7 | 5.0% | 5.0% | 12.05 | 0.60 | 12.65 | 2273.8          | 113.5           | 2387.3          | 76.5%  | 5.0 | 4.0 | 5.0 | 4.7        | -           |
| <i>Concrete block</i>                                                         | <i>m<sup>2</sup></i> | 188.7 | 0.0% | 5.0% | 3.13  | 0.76 | 3.89  | 590.6           | 142.7           | 733.3           | 23.5%  | 5.0 | 5.0 | 5.0 | 5.0        | -           |
| <i>Pre-dosed mortar</i>                                                       | <i>m<sup>2</sup></i> | -     | -    | -    | 9.54  | 0.79 | 10.34 | 822.3           | 68.1            | 890.4           | 100.0% | -   | -   | -   | 4.8        | 0.1%        |
| Concrete 50 × 10 × 20 cm <sup>3</sup> block for interior masonry wall (CB2-I) | <i>m<sup>2</sup></i> | 86.2  | 5.0% | 5.0% | 7.91  | 0.39 | 8.30  | 681.1           | 34.0            | 715.1           | 80.3%  | 5.0 | 4.0 | 5.0 | 4.7        | -           |
| <i>Concrete block</i>                                                         | <i>m<sup>2</sup></i> | 86.2  | 0.0% | 5.0% | 1.64  | 0.40 | 2.04  | 141.2           | 34.1            | 175.3           | 19.7%  | 5.0 | 5.0 | 5.0 | 5.0        | -           |
| <i>Pre-dosed mortar</i>                                                       | <i>m<sup>2</sup></i> | -     | -    | -    | 18.11 | 1.56 | 19.67 | 873.8           | 75.3            | 949.1           | 100.0% | -   | -   | -   | 4.8        | 0.1%        |
| Concrete 50 × 25 × 20 cm <sup>3</sup> block for interior masonry wall (CB3-I) | <i>m<sup>2</sup></i> | 48.3  | 5.0% | 5.0% | 14.68 | 0.73 | 15.42 | 708.4           | 35.4            | 743.8           | 78.4%  | 5.0 | 4.0 | 5.0 | 4.7        | -           |
| <i>Concrete block</i>                                                         | <i>m<sup>2</sup></i> | 48.3  | 0.0% | 5.0% | 3.43  | 0.83 | 4.26  | 165.4           | 40.0            | 205.3           | 21.6%  | 5.0 | 5.0 | 5.0 | 5.0        | -           |
| <i>Pre-dosed mortar</i>                                                       | <i>m<sup>2</sup></i> | -     | -    | -    | 24.46 | 4.33 | 28.78 | 9261.8          | 1639.4          | 10,901.2        | 100.0% | -   | -   | -   | 4.7        | 0.8%        |
| Lightweight concrete 40 × 15 × 19 cm <sup>3</sup>                             | <i>m<sup>2</sup></i> | 378.7 | 5.0% | 5.0% | 22.07 | 3.75 | 25.82 | 8358.9          | 1421.1          | 9780.1          | 89.7%  | 4.0 | 5.0 | 5.0 | 4.7        | -           |

|                                                                                            |                |        |      |      |       |      |       |          |        |          |        |     |     |     |     |      |
|--------------------------------------------------------------------------------------------|----------------|--------|------|------|-------|------|-------|----------|--------|----------|--------|-----|-----|-----|-----|------|
| block for interior masonry wall (LCB3-I)                                                   |                |        |      |      |       |      |       |          |        |          |        |     |     |     |     |      |
| Lightweight concrete block                                                                 | m <sup>2</sup> | 378.7  | 0.0% | 5.0% | 2.38  | 0.58 | 2.96  | 902.9    | 218.2  | 1121.1   | 10.3%  | 5.0 | 5.0 | 5.0 | 5.0 | -    |
| Pre-dosed mortar                                                                           | m <sup>2</sup> | -      | -    | -    | 32.56 | 6.01 | 38.57 | 44,638.5 | 8239.8 | 52,878.3 | 100.0% | -   | -   | -   | 4.7 | 3.7% |
| Lightweight concrete 40 × 20 × 19 cm <sup>3</sup> block for interior masonry wall (LCB4-I) |                |        |      |      |       |      |       |          |        |          |        |     |     |     |     |      |
| Lightweight concrete block                                                                 | m <sup>2</sup> | 1371.1 | 5.0% | 5.0% | 29.43 | 5.25 | 34.68 | 40,348.5 | 7202.8 | 47,551.3 | 89.9%  | 4.0 | 5.0 | 5.0 | 4.7 | -    |
| Pre-dosed mortar                                                                           | m <sup>2</sup> | -      | -    | -    | 12.57 | 2.04 | 14.61 | 692.6    | 112.4  | 805.0    | 100.0% | -   | -   | -   | 4.8 | 0.1% |
| Hollow clay 29 × 6.9 × 18.9 cm <sup>3</sup> brick for interior masonry wall (HCB2-I)       |                |        |      |      |       |      |       |          |        |          |        |     |     |     |     |      |
| Hollow clay brick                                                                          | m <sup>2</sup> | 55.1   | 5.0% | 5.0% | 10.48 | 1.53 | 12.02 | 577.7    | 84.6   | 662.2    | 82.3%  | 5.0 | 4.0 | 5.0 | 4.7 | -    |
| Pre-dosed mortar                                                                           | m <sup>2</sup> | -      | -    | -    | 17.31 | 2.79 | 20.10 | 5864.3   | 944.3  | 6808.6   | 100.0% | -   | -   | -   | 4.8 | 0.5% |
| Hollow clay 29 × 10.6 × 18.9 cm <sup>3</sup> brick for interior masonry wall (HCB3-I)      |                |        |      |      |       |      |       |          |        |          |        |     |     |     |     |      |
| Hollow clay brick                                                                          | m <sup>2</sup> | 338.8  | 5.0% | 5.0% | 14.03 | 1.99 | 16.03 | 4753.7   | 675.9  | 5429.6   | 79.7%  | 5.0 | 4.0 | 5.0 | 4.7 | -    |

|                                                                                                      |                      |       |      |      |       |      |       |                 |                 |                 |        |     |     |     |            |             |
|------------------------------------------------------------------------------------------------------|----------------------|-------|------|------|-------|------|-------|-----------------|-----------------|-----------------|--------|-----|-----|-----|------------|-------------|
| <i>Hollow clay brick</i>                                                                             | <i>m<sup>2</sup></i> | 338.8 | 0.0% | 5.0% | 3.28  | 0.79 | 4.07  | 1110.6          | 268.4           | 1379.0          | 20.3%  | 5.0 | 5.0 | 5.0 | 5.0        | -           |
| <i>Pre-dosed mortar</i>                                                                              | <i>m<sup>2</sup></i> | -     | -    | -    | 22.85 | 3.74 | 26.59 | 1718.7          | 281.3           | 1999.9          | 100.0% | -   | -   | -   | 4.8        | 0.1%        |
| Hollow clay<br>29 × 14.6 ×<br>18.9 cm <sup>3</sup> brick<br>for interior<br>masonry wall<br>(HCB1-I) | m <sup>2</sup>       | 75.2  | 5.0% | 5.0% | 18.38 | 2.66 | 21.04 | 1382.5          | 200.0           | 1582.5          | 79.1%  | 5.0 | 4.0 | 5.0 | 4.7        | -           |
| <i>Hollow clay brick</i>                                                                             | <i>m<sup>2</sup></i> | 75.2  | 0.0% | 5.0% | 4.47  | 1.08 | 5.55  | 336.1           | 81.2            | 417.4           | 20.9%  | 5.0 | 5.0 | 5.0 | 5.0        | -           |
| <i>Pre-dosed mortar</i>                                                                              | <i>m<sup>2</sup></i> | -     | -    | -    | -     | -    | -     | <b>66,736.3</b> | <b>11,616.8</b> | <b>78,353.1</b> |        |     |     |     | <b>4.7</b> | <b>5.4%</b> |
| <b>Total</b>                                                                                         |                      | -     | -    | -    | -     | -    | -     | <b>66,736.3</b> | <b>11,616.8</b> | <b>78,353.1</b> |        |     |     |     | <b>4.7</b> | <b>5.4%</b> |

Note. Bold entries represent the main construction categories, standard entries represent the construction systems, and italicised entries represent the constituent materials forming each construction system.

### 3.5. EC Calculation for External Cladding Systems

The external envelope of the building is predominantly insulated using an External Thermal Insulation Composite System (ETICS). This system is applied to most external surfaces, including façades, ceilings, balcony walls and parapets, covering more than 3000 m<sup>2</sup>.

Other solutions are used in smaller portions of the façade. The inner face of the balcony walls is finished with reinforced mortar, while a specific section of the façade is clad with clinker bricks combined with an XPS insulation system.

The resulting EC calculations for the external cladding systems are presented in Table 33.

**Table 33.** EC c for external cladding systems.

| Element                                                                         | Unit           | MQ     | WR    |       | CF (kgCO <sub>2</sub> /Unit) |      |       |          | EC (kgCO <sub>2</sub> ) |          |              | Data Reliability |     |     |       | EC Share |
|---------------------------------------------------------------------------------|----------------|--------|-------|-------|------------------------------|------|-------|----------|-------------------------|----------|--------------|------------------|-----|-----|-------|----------|
|                                                                                 |                |        | A1–A3 | A4    | A1–A3                        | A4   | A1–A4 | A1–A3    | A4                      | A1–A4    | System Share | C1               | C2  | C3  | Score |          |
| ETICS with EPS panels for external wall and ceiling                             | m <sup>2</sup> | 2823.9 | 0.0%  | 5.0%  | 12.46                        | 0.70 | 13.16 | 35,186.2 | 1985.7                  | 37,171.8 | 100.0%       | 4.0              | 4.0 | 4.0 | 4.0   | 2.6%     |
| ETICS with EPS panels for balcony wall cladding and external thermal insulation | m <sup>2</sup> | 278.4  | 0.0%  | 5.0%  | 12.46                        | 0.70 | 13.16 | 3469.0   | 195.8                   | 3664.8   | 100.0%       | 4.0              | 4.0 | 4.0 | 4.0   | 0.3%     |
| ETICS with EPS panels for inner faces of parapet walls at roof level            | m <sup>2</sup> | 195.4  | 0.0%  | 5.0%  | 12.46                        | 0.70 | 13.16 | 2434.7   | 137.4                   | 2572.1   | 100.0%       | 4.0              | 4.0 | 4.0 | 4.0   | 0.2%     |
| Interior balcony wall coating                                                   | m <sup>2</sup> | -      | -     | -     | 4.49                         | 0.42 | 4.91  | 1041.9   | 96.6                    | 1138.4   | 100.0%       | -                | -   | -   | 4.6   | 0.1%     |
| Pre-mixed polymer mortar                                                        | m <sup>2</sup> | 231.8  | 0.0%  | 5.0%  | 2.63                         | 0.32 | 2.95  | 609.2    | 75.1                    | 684.4    | 60.1%        | 5.0              | 5.0 | 5.0 | 5.0   | -        |
| Fibreglass mesh                                                                 | m <sup>2</sup> | 231.8  | 2.0%  | 2.0%  | 0.47                         | 0.00 | 0.47  | 108.1    | 1.1                     | 109.1    | 9.6%         | 5.0              | 3.0 | 5.0 | 4.3   | -        |
| Primer coat                                                                     | m <sup>2</sup> | 231.8  | 5.0%  | 5.0%  | 0.09                         | 0.00 | 0.09  | 20.4     | 0.7                     | 21.1     | 1.9%         | 4.0              | 3.0 | 5.0 | 4.0   | -        |
| Decorative organic coating                                                      | m <sup>2</sup> | 231.8  | 0.0%  | 10.0% | 1.31                         | 0.08 | 1.40  | 304.1    | 19.7                    | 323.8    | 28.4%        | 4.0              | 3.0 | 5.0 | 4.0   | -        |
| Exposed face brick wall with thermal insulation                                 | m <sup>2</sup> | -      | -     | -     | 32.78                        | 5.66 | 38.45 | 12,687.3 | 2191.0                  | 14,878.3 | 100.0%       | -                | -   | -   | 4.4   | 1.0%     |
| Facing bricks (24 × 11.5 × 7 cm)                                                | m <sup>2</sup> | 387.0  | 3.0%  | 3.0%  | 26.98                        | 4.84 | 31.82 | 10,442.8 | 1871.5                  | 12,314.3 | 82.8%        | 4.0              | 4.0 | 5.0 | 4.3   | -        |

|                                            |                      |       |      |      |      |      |      |          |        |          |       |     |     |     |     |      |
|--------------------------------------------|----------------------|-------|------|------|------|------|------|----------|--------|----------|-------|-----|-----|-----|-----|------|
| <i>Pre-dosed mortar</i>                    | <i>m<sup>2</sup></i> | 387.0 | 3.0% | 3.0% | 3.38 | 0.78 | 4.15 | 1306.6   | 300.8  | 1607.4   | 10.8% | 5.0 | 5.0 | 5.0 | 5.0 | -    |
| <i>Thermal insulation, 50 mm thick XPS</i> | <i>m<sup>2</sup></i> | 387.0 | 0.0% | 2.0% | 2.42 | 0.05 | 2.47 | 937.9    | 18.7   | 956.6    | 6.4%  | 4.0 | 3.0 | 5.0 | 4.0 | -    |
| Total                                      |                      | -     | -    | -    | -    | -    | -    | 54,819.0 | 4606.4 | 59,425.4 |       |     |     |     | 4.1 | 4.1% |

Note. Italicised entries represent the constituent materials forming each construction system.

### 3.6. EC Calculation for Infill and Floor Levelling Systems, Wall and Floor Finishes

For floor infill and levelling, a layered system is used. The infill layer consists of a lightweight concrete screed incorporating regranulated EPS, designed to reduce structural load while providing thermal and acoustic benefits. Above this layer, a self-levelling screed is applied to create a smooth and uniform substrate for the installation of floor finishes.

Below these layers, an acoustic insulation membrane made of closed-cell cross-linked polyethylene is installed to reduce sound transmission and improve the acoustic performance of the floor system.

Internal finishes consist of different floor and wall systems defined according to the function of each area. Floors in common areas are finished with porcelain stoneware tiles; while living rooms, dining areas and bedrooms have multi-layer wooden flooring. Sanitary facilities, kitchens and laundries are finished with glazed porcelain tiles, installed over a resilient polyethylene membrane. Staircases and landings are covered with porcelain tiles, and natural stone flooring is used in the main entrance hall and stairs.

Walls are generally finished with cement-based plaster to create a smooth surface suitable for painting. In sanitary facilities, kitchens and laundries, walls are clad with glazed ceramic tiles. In circulation areas around the lifts, veneered MDF panels with a satin finish are used as wall cladding.

The resulting EC calculations for infill and floor levelling systems, as well as wall and floor finishes, are presented in Table 34.

**Table 34.** EC for infill and floor levelling systems, wall and floor finishes.

| Element                                                                                                                                             | Unit           | MQ     | WR    |      | CF (kgCO <sub>2</sub> /Unit) |      |       |           | EC (kgCO <sub>2</sub> ) |           |              | Data Reliability |     |     |       | EC Share |
|-----------------------------------------------------------------------------------------------------------------------------------------------------|----------------|--------|-------|------|------------------------------|------|-------|-----------|-------------------------|-----------|--------------|------------------|-----|-----|-------|----------|
|                                                                                                                                                     |                |        | A1–A3 | A4   | A1–A3                        | A4   | A1–A4 | A1–A3     | A4                      | A1–A4     | System Share | C1               | C2  | C3  | Score |          |
| Infill and floor level-ling                                                                                                                         |                |        |       |      |                              |      |       |           |                         |           |              |                  |     |     |       |          |
| Lightweight concrete with EPS (400 kg/m <sup>3</sup> ), levelling screed layer, cross-linked polyethylene foam mem-brane (0.272 kg/m <sup>2</sup> ) | m <sup>2</sup> | -      | -     | -    | 45.84                        | 2.40 | 48.24 | 168,425.5 | 8824.6                  | 177,250.1 | 100.0%       | -                | -   | -   | 5.0   | 12.3%    |
| Lightweight concrete with EPS                                                                                                                       | m <sup>2</sup> | 3674.2 | 5.0%  | 5.0% | 25.48                        | 0.23 | 25.71 | 93,611.4  | 855.2                   | 94,466.6  | 53.3%        | 5.0              | 5.0 | 5.0 | 5.0   | -        |
| Cross-linked polyethylene                                                                                                                           | m <sup>2</sup> | 3674.2 | 0.0%  | 1.0% | 7.51                         | 0.01 | 7.52  | 27,593.2  | 29.9                    | 27,623.1  | 15.6%        | 5.0              | 5.0 | 5.0 | 5.0   | -        |

|                                                                                                                                                                |                |        |      |       |       |      |       |           |        |           |        |     |     |     |     |       |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|--------|------|-------|-------|------|-------|-----------|--------|-----------|--------|-----|-----|-----|-----|-------|
| foam mem-<br>brane (0.272<br>kg/m <sup>2</sup> )                                                                                                               |                |        |      |       |       |      |       |           |        |           |        |     |     |     |     |       |
| Self-levelling<br>screed                                                                                                                                       | m <sup>2</sup> | 3674.2 | 5.0% | 5.0%  | 12.85 | 2.16 | 15.01 | 47,220.8  | 7939.6 | 55,160.4  | 31.1%  | 5.0 | 5.0 | 5.0 | 5.0 | -     |
| Cement-<br>sand (1:3 ra-<br>tio) screed<br>layer for stair<br>floors                                                                                           | m <sup>2</sup> | 289.5  | 5.0% | 5.0%  | 10.88 | 0.36 | 11.24 | 3149.2    | 103.5  | 3252.7    | 100.0% | 5.0 | 5.0 | 5.0 | 5.0 | 0.2%  |
| Total                                                                                                                                                          |                | -      | -    | -     | -     | -    | -     | 171,574.7 | 8928.1 | 180,502.8 |        |     |     |     | 5.0 | 12.5% |
| <b>Floor fin-<br/>ishes</b>                                                                                                                                    |                |        |      |       |       |      |       |           |        |           |        |     |     |     |     |       |
| Technical<br>porcelain<br>mosaic tile<br>flooring and<br>skirting, ap-<br>plied in the<br>condomin-<br>ium hall and<br>associated<br>sanitary fa-<br>cilities. | m <sup>2</sup> | 489.8  | -    | -     | 16.28 | 0.85 | 17.13 | 7974.7    | 414.8  | 8389.5    | 100.0% | -   | -   | -   | 4.7 | 0.6%  |
| Porcelain tiles<br>(30 × 30 × 0.8<br>cm)                                                                                                                       | m <sup>2</sup> | 489.8  | 3.0% | 3.0%  | 14.39 | 0.63 | 15.02 | 7050.5    | 306.6  | 7357.0    | 87.7%  | 4.0 | 5.0 | 5.0 | 4.7 | -     |
| Coloured<br>grouting mor-<br>tar                                                                                                                               | m <sup>2</sup> | 489.8  | 0.0% | 3.0%  | 0.12  | 0.01 | 0.13  | 60.2      | 4.4    | 64.6      | 0.8%   | 5.0 | 4.0 | 5.0 | 4.7 | -     |
| Tile adhesive                                                                                                                                                  | m <sup>2</sup> | 489.8  | 0.0% | 3.0%  | 1.76  | 0.21 | 1.98  | 864.0     | 103.8  | 967.8     | 11.5%  | 5.0 | 5.0 | 5.0 | 5.0 | -     |
| Multilayer<br>floating oak<br>wood floor-<br>ing, applied<br>in living,<br>dining, and<br>bedroom ar-<br>eas                                                   | m <sup>2</sup> | 2555.8 | -    | -     | 17.69 | 0.78 | 18.47 | 45,212.1  | 1981.5 | 47,193.6  | 100.0% | -   | -   | -   | 4.7 | 3.3%  |
| Multilayer<br>oak floating<br>floor                                                                                                                            | m <sup>2</sup> | 2555.8 | 0.0% | 3.0%  | 9.70  | 0.76 | 10.46 | 24,791.3  | 1954.8 | 26,746.1  | 56.7%  | 5.0 | 4.0 | 5.0 | 4.7 | -     |
| Cross-linked<br>polyethylene<br>foam mem-<br>brane (0.154<br>kg/m <sup>2</sup> )                                                                               | m <sup>2</sup> | 2555.8 | 0.0% | 1.0%  | 4.72  | 0.00 | 4.72  | 12,063.4  | 11.8   | 12,075.1  | 25.6%  | 5.0 | 5.0 | 5.0 | 5.0 | -     |
| Satin finish<br>varnish                                                                                                                                        | m <sup>2</sup> | 2555.8 | 0.0% | 10.0% | 3.27  | 0.01 | 3.28  | 8357.5    | 14.9   | 8372.3    | 17.7%  | 4.0 | 4.0 | 5.0 | 4.3 | -     |
| Glazed<br>porcelain<br>stoneware<br>tile flooring<br>and skirting,<br>applied in<br>sanitary fa-<br>cilities                                                   | m <sup>2</sup> | 243.7  | -    | -     | 18.86 | 0.73 | 19.59 | 4595.6    | 178.8  | 4774.4    | 100.0% | -   | -   | -   | 5.0 | 0.3%  |

|                                                                                                                           |                |       |      |      |       |      |       |        |       |        |        |     |     |     |     |      |
|---------------------------------------------------------------------------------------------------------------------------|----------------|-------|------|------|-------|------|-------|--------|-------|--------|--------|-----|-----|-----|-----|------|
| Porcelain tiles<br>(30 × 30 × 0.7 cm)                                                                                     | m <sup>2</sup> | 243.7 | 3.0% | 3.0% | 12.25 | 0.51 | 12.76 | 2985.5 | 124.1 | 3109.6 | 65.1%  | 5.0 | 5.0 | 5.0 | 5.0 | -    |
| Coloured<br>grouting mortar                                                                                               | m <sup>2</sup> | 243.7 | 0.0% | 3.0% | 0.12  | 0.01 | 0.13  | 29.9   | 1.9   | 31.9   | 0.7%   | 5.0 | 4.0 | 5.0 | 4.7 | -    |
| Tile adhesive                                                                                                             | m <sup>2</sup> | 243.7 | 0.0% | 3.0% | 1.76  | 0.21 | 1.98  | 429.9  | 51.7  | 481.5  | 10.1%  | 5.0 | 5.0 | 5.0 | 5.0 | -    |
| Cross-linked<br>polyethylene<br>foam membrane (0.154 kg/m <sup>2</sup> )                                                  | m <sup>2</sup> | 243.7 | 0.0% | 1.0% | 4.72  | 0.00 | 4.72  | 1150.3 | 1.1   | 1151.4 | 24.1%  | 5.0 | 5.0 | 5.0 | 5.0 | -    |
| Glazed<br>porcelain<br>stoneware<br>tile flooring<br>and skirting,<br>Applied in<br>kitchens and<br>laundry areas         | m <sup>2</sup> | 316.6 | -    | -    | 18.86 | 0.73 | 19.59 | 5970.3 | 232.3 | 6202.6 | 100.0% | -   | -   | -   | 5.0 | 0.4% |
| Porcelain tiles<br>(30 × 30 × 0.7 cm)                                                                                     | m <sup>2</sup> | 316.6 | 3.0% | 3.0% | 12.25 | 0.51 | 12.76 | 3878.6 | 161.2 | 4039.8 | 65.1%  | 5.0 | 5.0 | 5.0 | 5.0 | -    |
| Coloured<br>grouting mortar                                                                                               | m <sup>2</sup> | 316.6 | 0.0% | 3.0% | 0.12  | 0.01 | 0.13  | 38.9   | 2.5   | 41.4   | 0.7%   | 5.0 | 4.0 | 5.0 | 4.7 | -    |
| Tile adhesive                                                                                                             | m <sup>2</sup> | 316.6 | 0.0% | 3.0% | 1.76  | 0.21 | 1.98  | 558.5  | 67.1  | 625.6  | 10.1%  | 5.0 | 5.0 | 5.0 | 5.0 | -    |
| Cross-linked<br>polyethylene<br>foam membrane (0.154 kg/m <sup>2</sup> )                                                  | m <sup>2</sup> | 316.6 | 0.0% | 1.0% | 4.72  | 0.00 | 4.72  | 1494.4 | 1.5   | 1495.8 | 24.1%  | 5.0 | 5.0 | 5.0 | 5.0 | -    |
| Technical<br>porcelain<br>mosaic tile<br>flooring and<br>skirting, applied on stair<br>landings,<br>treads, and<br>risers | m <sup>2</sup> | 274.1 | -    | -    | 16.28 | 0.85 | 17.13 | 4461.9 | 232.1 | 4694.0 | 100.0% | -   | -   | -   | 4.7 | 0.3% |
| Porcelain tiles<br>(30 × 30 × 0.8 cm)                                                                                     | m <sup>2</sup> | 274.1 | 3.0% | 3.0% | 14.39 | 0.63 | 15.02 | 3944.8 | 171.5 | 4116.4 | 87.7%  | 4.0 | 5.0 | 5.0 | 4.7 | -    |
| Coloured<br>grouting mortar                                                                                               | m <sup>2</sup> | 274.1 | 0.0% | 3.0% | 0.12  | 0.01 | 0.13  | 33.7   | 2.5   | 36.1   | 0.8%   | 5.0 | 4.0 | 5.0 | 4.7 | -    |
| Tile adhesive                                                                                                             | m <sup>2</sup> | 274.1 | 0.0% | 3.0% | 1.76  | 0.21 | 1.98  | 483.4  | 58.1  | 541.5  | 11.5%  | 5.0 | 5.0 | 5.0 | 5.0 | -    |
| Polished<br>marble tiles<br>and skirting,<br>applied in<br>the main entrance hall<br>and staircases                       | m <sup>2</sup> | 15.4  | -    | -    | 5.44  | 1.43 | 6.87  | 83.8   | 22.1  | 105.9  | 100.0% | -   | -   | -   | 4.8 | 0.0% |

|                                                                                                                      |                |        |      |      |      |      |      |          |        |          |        |     |     |     |     |      |
|----------------------------------------------------------------------------------------------------------------------|----------------|--------|------|------|------|------|------|----------|--------|----------|--------|-----|-----|-----|-----|------|
| Polished marble tiles                                                                                                | m <sup>2</sup> | 15.4   | 3.0% | 3.0% | 3.33 | 1.16 | 4.50 | 51.4     | 17.9   | 69.3     | 65.5%  | 5.0 | 4.0 | 5.0 | 4.7 | -    |
| Coloured grouting mortar                                                                                             | m <sup>2</sup> | 15.4   | 0.0% | 3.0% | 0.05 | 0.02 | 0.07 | 0.7      | 0.3    | 1.1      | 1.0%   | 5.0 | 4.0 | 5.0 | 4.7 | -    |
| Tile adhesive                                                                                                        | m <sup>2</sup> | 15.4   | 0.0% | 3.0% | 2.06 | 0.25 | 2.31 | 31.7     | 3.8    | 35.5     | 33.5%  | 5.0 | 5.0 | 5.0 | 5.0 | -    |
| Total                                                                                                                |                | -      | -    | -    | -    | -    | -    | 68,298.4 | 3061.6 | 71,360.0 |        |     |     |     | 4.8 | 4.9% |
| <b>Wall finishes</b>                                                                                                 |                |        |      |      |      |      |      |          |        |          |        |     |     |     |     |      |
| Base coat plastering and fine cement skim coat on interior walls                                                     | m <sup>2</sup> | 2496.4 | 0.0% | 5.0% | 3.72 | 0.09 | 3.81 | 9286.4   | 215.5  | 9501.9   | 100.0% | 5.0 | 4.0 | 5.0 | 4.7 | 0.7% |
| MDF paneling with oak-effect melamine finish, on the walls surrounding the lift areas in the floor circulation zones | m <sup>2</sup> | 60.2   | -    | -    | 5.95 | 0.64 | 6.59 | 357.9    | 38.7   | 396.6    | 100.0% | -   | -   | -   | 4.3 | 0.0% |
| Plastering and skimming                                                                                              | m <sup>2</sup> | 60.2   | 0.0% | 5.0% | 3.72 | 0.09 | 3.81 | 223.9    | 5.2    | 229.1    | 57.8%  | 5.0 | 4.0 | 4.0 | 4.3 | -    |
| MDF paneling with melamine finish                                                                                    | m <sup>2</sup> | 60.2   | 5.0% | 5.0% | 2.23 | 0.56 | 2.78 | 134.0    | 33.5   | 167.5    | 42.2%  | 4.0 | 5.0 | 4.0 | 4.3 | -    |
| Glazed porcelain stoneware tiles, applied to the walls of sanitary facilities                                        | m <sup>2</sup> | 1279.3 | -    | -    | 9.22 | 0.50 | 9.72 | 11,791.4 | 641.9  | 12,433.2 | 100.0% | -   | -   | -   | 5.0 | 0.9% |
| Porcelain stoneware tiles (15 × 15 × 0.58 cm)                                                                        | m <sup>2</sup> | 1279.3 | 3.0% | 3.0% | 7.51 | 0.31 | 7.82 | 9602.6   | 399.1  | 10,001.7 | 80.4%  | 5.0 | 5.0 | 5.0 | 5.0 | -    |
| Coloured grouting mortar                                                                                             | m <sup>2</sup> | 1279.3 | 0.0% | 3.0% | 0.24 | 0.01 | 0.25 | 308.2    | 16.8   | 325.0    | 2.6%   | 5.0 | 4.0 | 5.0 | 4.7 | -    |
| Tile adhesive                                                                                                        | m <sup>2</sup> | 1279.3 | 0.0% | 3.0% | 1.47 | 0.18 | 1.65 | 1880.5   | 226.0  | 2106.5   | 16.9%  | 6.0 | 5.0 | 5.0 | 5.3 | -    |
| Glazed porcelain stoneware tiles, applied to the walls of kitchens                                                   | m <sup>2</sup> | 115.0  | -    | -    | 9.22 | 0.50 | 9.72 | 1060.0   | 57.7   | 1117.7   | 100.0% | -   | -   | -   | 5.0 | 0.1% |
| Porcelain stoneware tiles (15 × 15 × 0.58 cm)                                                                        | m <sup>2</sup> | 115.0  | 3.0% | 3.0% | 7.51 | 0.31 | 7.82 | 863.2    | 35.9   | 899.1    | 80.4%  | 5.0 | 5.0 | 5.0 | 5.0 | -    |

|                                 |                      |       |      |      |      |      |      |                 |              |                 |       |     |     |     |            |             |
|---------------------------------|----------------------|-------|------|------|------|------|------|-----------------|--------------|-----------------|-------|-----|-----|-----|------------|-------------|
| <i>Coloured grouting mortar</i> | <i>m<sup>2</sup></i> | 115.0 | 0.0% | 3.0% | 0.24 | 0.01 | 0.25 | 27.7            | 1.5          | 29.2            | 2.6%  | 5.0 | 4.0 | 5.0 | 4.7        | -           |
| <i>Tile adhesive</i>            | <i>m<sup>2</sup></i> | 115.0 | 0.0% | 3.0% | 1.47 | 0.18 | 1.65 | 169.1           | 20.3         | 189.4           | 16.9% | 6.0 | 5.0 | 5.0 | 5.3        | -           |
| <b>Total</b>                    |                      | -     | -    | -    | -    | -    | -    | <b>22,495.6</b> | <b>953.7</b> | <b>23,449.4</b> |       |     |     |     | <b>4.9</b> | <b>1.6%</b> |

Note. Bold entries represent the main construction categories, standard entries represent the construction systems, and italicised entries represent the constituent materials forming each construction system.

### 3.7. EC Calculation for Plasterboard Linings, Partitions and Ceilings

Interior wall linings consist mainly of plasterboard systems installed on metal stud frameworks, with mineral wool insulation placed within the cavities. These systems are used both as linings for the inner face of external walls and as non-structural partition walls dividing interior spaces. Standard boards are applied in dry areas, while moisture-resistant boards are used in humid zones such as kitchens and sanitary facilities.

Service ducts and vertical shafts are enclosed with double-layer fire-resistant plasterboard mounted on galvanised metal frames and filled with mineral wool insulation.

Suspended ceilings are formed with plasterboard panels fixed to a metal suspension system attached to the structural slab, with mineral wool insulation placed above the panels. In the staircase area, ceilings are finished with a cement-based render instead of plasterboard.

The resulting EC calculations for plasterboard linings, partitions and ceiling systems are presented in Table 35.

**Table 35.** EC for plasterboard linings, partitions and ceilings.

| Element                                                                                        | Unit           | MQ    | WR    |      | CF (kgCO <sub>2</sub> /Unit) |      |       | EC (kgCO <sub>2</sub> ) |        |        | System Share | Data Reliability |     |     |       | EC Share |
|------------------------------------------------------------------------------------------------|----------------|-------|-------|------|------------------------------|------|-------|-------------------------|--------|--------|--------------|------------------|-----|-----|-------|----------|
|                                                                                                |                |       | A1-A3 | A4   | A1-A3                        | A4   | A1-A4 | A1-A3                   | A4     | A1-A4  |              | C1               | C2  | C3  | Score |          |
| Plasterboard lining and partition elements                                                     |                |       |       |      |                              |      |       |                         |        |        |              |                  |     |     |       |          |
| Wall linings for external and separating walls between dwellings and common areas in dry zones | m <sup>2</sup> | 818.0 | -     | -    | 8.13                         | 1.36 | 9.49  | 6647.2                  | 1113.6 | 7760.8 | 100.0%       | -                | -   | -   | 4.7   | 0.5%     |
| Standard plasterboard, 12.5 mm, double layer                                                   | m <sup>2</sup> | 818.0 | 0.0%  | 5.0% | 1.82                         | 1.20 | 3.02  | 1489.3                  | 983.6  | 2472.9 | 31.9%        | 5.0              | 5.0 | 4.0 | 4.7   | -        |
| Galvanised steel profile, track 48 mm                                                          | m <sup>2</sup> | 818.0 | 0.0%  | 5.0% | 1.46                         | 0.02 | 1.48  | 1194.4                  | 19.8   | 1214.3 | 15.6%        | 5.0              | 5.0 | 4.0 | 4.7   | -        |
| Galvanised steel profile, stud 48 mm                                                           | m <sup>2</sup> | 818.0 | 0.0%  | 5.0% | 3.82                         | 0.06 | 3.88  | 3122.6                  | 51.8   | 3174.4 | 40.9%        | 5.0              | 5.0 | 4.0 | 4.7   | -        |
| Joint filler                                                                                   | m <sup>2</sup> | 818.0 | 0.0%  | 5.0% | 0.06                         | 0.02 | 0.08  | 50.5                    | 13.3   | 63.8   | 0.8%         | 5.0              | 5.0 | 4.0 | 4.7   | -        |
| Mineral wool, 48 mm thick                                                                      | m <sup>2</sup> | 818.0 | 0.0%  | 5.0% | 0.97                         | 0.06 | 1.02  | 790.4                   | 45.1   | 835.4  | 10.8%        | 5.0              | 5.0 | 4.0 | 4.7   | -        |

|                                                                                                |                |        |      |      |       |      |       |          |        |          |        |     |     |     |     |      |
|------------------------------------------------------------------------------------------------|----------------|--------|------|------|-------|------|-------|----------|--------|----------|--------|-----|-----|-----|-----|------|
| Wall linings for external and separating walls between dwellings and common areas in wet zones | m <sup>2</sup> | 1430.8 | -    | -    | 8.31  | 0.94 | 9.25  | 11,891.7 | 1342.5 | 13,234.1 | 100.0% | -   | -   | -   | 4.7 | 0.9% |
| Moisture-resistant plaster-board, 15 mm                                                        | m <sup>2</sup> | 1430.8 | 0.0% | 5.0% | 2.01  | 0.78 | 2.78  | 2869.5   | 1115.1 | 3984.6   | 30.1%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| Galvanised steel profile, track 48 mm                                                          | m <sup>2</sup> | 1430.8 | 0.0% | 5.0% | 1.46  | 0.02 | 1.48  | 2089.3   | 34.6   | 2123.9   | 16.0%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| Galvanised steel profile, stud 48 mm                                                           | m <sup>2</sup> | 1430.8 | 0.0% | 5.0% | 3.82  | 0.06 | 3.88  | 5462.0   | 90.6   | 5552.6   | 42.0%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| Joint filler                                                                                   | m <sup>2</sup> | 1430.8 | 0.0% | 5.0% | 0.06  | 0.02 | 0.08  | 88.3     | 23.3   | 111.6    | 0.8%   | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| Mineral wool, 48 mm thick                                                                      | m <sup>2</sup> | 1430.8 | 0.0% | 5.0% | 0.97  | 0.06 | 1.02  | 1382.5   | 78.8   | 1461.3   | 11.0%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| Internal partitions in dry zones                                                               | m <sup>2</sup> | 875.2  | -    | -    | 11.51 | 2.60 | 14.12 | 10,074.4 | 2279.6 | 12,354.0 | 100.0% | -   | -   | -   | 4.7 | 0.9% |
| Standard plasterboard, 12.5 mm, double layer per side                                          | m <sup>2</sup> | 875.2  | 0.0% | 5.0% | 3.65  | 2.40 | 6.06  | 3197.9   | 2104.7 | 5302.6   | 42.9%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| Galvanised steel profile, track 48 mm                                                          | m <sup>2</sup> | 875.2  | 0.0% | 5.0% | 1.31  | 0.02 | 1.34  | 1150.1   | 19.1   | 1169.2   | 9.5%   | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| Galvanised steel profile, stud 48 mm                                                           | m <sup>2</sup> | 875.2  | 0.0% | 5.0% | 5.45  | 0.09 | 5.54  | 4772.7   | 79.1   | 4851.9   | 39.3%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| Joint filler                                                                                   | m <sup>2</sup> | 875.2  | 0.0% | 5.0% | 0.12  | 0.03 | 0.16  | 108.0    | 28.5   | 136.5    | 1.1%   | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| Mineral wool, 48 mm thick                                                                      | m <sup>2</sup> | 875.2  | 0.0% | 5.0% | 0.97  | 0.06 | 1.02  | 845.6    | 48.2   | 893.8    | 7.2%   | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| Internal partitions in wet zones                                                               | m <sup>2</sup> | 875.3  | -    | -    | 11.69 | 2.18 | 13.87 | 10,231.5 | 1909.5 | 12,141.1 | 100.0% | -   | -   | -   | 4.7 | 0.8% |
| Standard plasterboard, 12.5 mm, double layer on one side                                       | m <sup>2</sup> | 875.3  | 0.0% | 5.0% | 1.83  | 1.20 | 3.03  | 1599.1   | 1052.4 | 2651.5   | 21.8%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| Moisture-resistant plaster-board, 15 mm, on the other side                                     | m <sup>2</sup> | 875.3  | 0.0% | 5.0% | 2.01  | 0.78 | 2.78  | 1755.3   | 682.1  | 2437.5   | 20.1%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| Galvanised steel profile, track 48 mm                                                          | m <sup>2</sup> | 875.3  | 0.0% | 5.0% | 1.31  | 0.02 | 1.34  | 1150.2   | 19.1   | 1169.3   | 9.6%   | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| Galvanised steel profile, stud 48 mm                                                           | m <sup>2</sup> | 875.3  | 0.0% | 5.0% | 5.45  | 0.09 | 5.54  | 4773.1   | 79.2   | 4852.3   | 40.0%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| Joint filler                                                                                   | m <sup>2</sup> | 875.3  | 0.0% | 5.0% | 0.12  | 0.03 | 0.16  | 108.0    | 28.5   | 136.6    | 1.1%   | 5.0 | 5.0 | 4.0 | 4.7 | -    |

|                                                                              |                      |        |      |      |       |      |       |          |        |          |        |     |     |     |     |      |
|------------------------------------------------------------------------------|----------------------|--------|------|------|-------|------|-------|----------|--------|----------|--------|-----|-----|-----|-----|------|
| <i>Mineral wool, 48 mm thick</i>                                             | <i>m<sup>2</sup></i> | 875.3  | 0.0% | 5.0% | 0.97  | 0.06 | 1.02  | 845.7    | 48.2   | 893.9    | 7.4%   | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| <b>Service-duct enclosures</b>                                               | <b>m<sup>2</sup></b> | 353.6  | -    | -    | 9.37  | 2.00 | 11.37 | 3313.3   | 705.6  | 4018.9   | 100.0% | -   | -   | -   | 4.7 | 0.3% |
| <i>Fire-resistant plasterboard, 15 mm, on each side</i>                      | <i>m<sup>2</sup></i> | 353.6  | 0.0% | 5.0% | 3.15  | 1.86 | 5.01  | 1113.7   | 656.1  | 1769.8   | 44.0%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| <i>Galvanised steel profile, track 48 mm</i>                                 | <i>m<sup>2</sup></i> | 353.6  | 0.0% | 5.0% | 1.31  | 0.02 | 1.34  | 464.6    | 7.7    | 472.3    | 11.8%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| <i>Galvanised steel profile, stud 48 mm</i>                                  | <i>m<sup>2</sup></i> | 353.6  | 0.0% | 5.0% | 3.82  | 0.06 | 3.88  | 1349.7   | 22.4   | 1372.1   | 34.1%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| <i>Joint filler</i>                                                          | <i>m<sup>2</sup></i> | 353.6  | 0.0% | 5.0% | 0.12  | 0.06 | 0.18  | 43.6     | 19.5   | 63.1     | 1.6%   | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| <i>Mineral wool, 48 mm thick</i>                                             | <i>m<sup>2</sup></i> | 353.6  | 0.0% | 5.0% | 0.97  | 0.00 | 0.97  | 341.6    | 0.0    | 341.6    | 8.5%   | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| <b>Total</b>                                                                 |                      | -      | -    | -    | -     | -    | -     | 42,158.1 | 7350.8 | 49,508.9 |        |     |     |     | 4.7 | 3.4% |
| <b>Ceiling elements</b>                                                      |                      |        |      |      |       |      |       |          |        |          |        |     |     |     |     |      |
| <b>Suspended ceilings in dry zones</b>                                       | <b>m<sup>2</sup></b> | 3058.8 | -    | -    | 10.92 | 0.85 | 11.77 | 33,400.2 | 2610.9 | 36,011.1 | 100.0% | -   | -   | -   | 4.5 | 2.5% |
| <i>Tapered edge plasterboard, 12.5 mm</i>                                    | <i>m<sup>2</sup></i> | 3058.8 | 0.0% | 5.0% | 1.58  | 0.60 | 2.18  | 4817.6   | 1839.0 | 6656.6   | 18.5%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| <i>Galvanised steel ceiling channel</i>                                      | <i>m<sup>2</sup></i> | 3058.8 | 0.0% | 5.0% | 4.11  | 0.07 | 4.18  | 12,579.0 | 208.6  | 12,787.6 | 35.5%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| <i>Joint filler</i>                                                          | <i>m<sup>2</sup></i> | 3058.8 | 0.0% | 5.0% | 0.04  | 0.01 | 0.05  | 120.1    | 31.7   | 151.8    | 0.4%   | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| <i>Mineral wool, 60 mm thick</i>                                             | <i>m<sup>2</sup></i> | 3058.8 | 0.0% | 5.0% | 5.19  | 0.17 | 5.37  | 15,883.5 | 531.6  | 16,415.1 | 45.6%  | 4.0 | 5.0 | 4.0 | 4.3 | -    |
| <b>Suspended ceilings in wet zones</b>                                       | <b>m<sup>2</sup></b> | 628.6  | -    | -    | 11.67 | 0.85 | 12.52 | 7333.2   | 536.5  | 7869.7   | 100.0% | -   | -   | -   | 4.5 | 0.5% |
| <i>Tapered edge moisture-resistant plasterboard, 12.5 mm</i>                 | <i>m<sup>2</sup></i> | 628.6  | 0.0% | 5.0% | 2.02  | 0.60 | 2.62  | 1267.3   | 377.9  | 1645.2   | 20.9%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| <i>Galvanised steel ceiling channel</i>                                      | <i>m<sup>2</sup></i> | 628.6  | 0.0% | 5.0% | 4.11  | 0.07 | 4.18  | 2585.1   | 42.9   | 2627.9   | 33.4%  | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| <i>Joint filler</i>                                                          | <i>m<sup>2</sup></i> | 628.6  | 0.0% | 5.0% | 0.04  | 0.01 | 0.05  | 24.7     | 6.5    | 31.2     | 0.4%   | 5.0 | 5.0 | 4.0 | 4.7 | -    |
| <i>Mineral wool, 60 mm thick</i>                                             | <i>m<sup>2</sup></i> | 628.6  | 0.0% | 5.0% | 5.50  | 0.17 | 5.67  | 3456.2   | 109.2  | 3565.4   | 45.3%  | 4.0 | 5.0 | 4.0 | 4.3 | -    |
| <b>Base coat plastering and fine cement skim coat on stair-well ceilings</b> | <b>m<sup>2</sup></b> | 280.3  | 0.0% | 5.0% | 3.72  | 0.09 | 3.81  | 1042.7   | 24.2   | 1066.9   | 100.0% | 5.0 | 4.0 | 5.0 | 4.7 | 0.1% |
| <b>Total</b>                                                                 |                      | -      | -    | -    | -     | -    | -     | 41,776.1 | 3171.6 | 44,947.7 |        |     |     |     | 4.5 | 3.1% |

Note. Bold entries represent the main construction categories, standard entries represent the construction systems, and italicised entries represent the constituent materials forming each construction system.

### 3.8. EC Calculation for Waterproofing Systems

Waterproofing systems are applied in several parts of the building to protect against water and moisture ingress. Bituminous waterproofing systems are used in the roof, balconies, landscaped areas, circulation zones and basement walls, each adapted to the specific exposure conditions of these elements.

In interior wet areas, such as kitchens, laundries and sanitary facilities, waterproofing is provided through cementitious waterproof coatings applied to the substrate.

The resulting EC calculations for the waterproofing systems considered in the study are presented in Table 36.

**Table 36.** EC for waterproofing systems.

| Element                                                                                                             | Unit           | MQ    | WR    |       | CF (kgCO <sub>2</sub> /Unit) |      |       |          | EC (kgCO <sub>2</sub> ) |          |              | Data Reliability |     |     |       | EC Share |
|---------------------------------------------------------------------------------------------------------------------|----------------|-------|-------|-------|------------------------------|------|-------|----------|-------------------------|----------|--------------|------------------|-----|-----|-------|----------|
|                                                                                                                     |                |       | A1–A3 | A4    | A1–A3                        | A4   | A1–A4 | A1–A3    | A4                      | A1–A4    | System Share | C1               | C2  | C3  | Score |          |
| Roof waterproofing system                                                                                           | m <sup>2</sup> | 818.0 | -     | -     | 44.54                        | 3.86 | 48.39 | 36,429.7 | 3156.4                  | 39,586.1 | 100.0%       | -                | -   | -   | 4.6   | 2.7%     |
| Lightweight concrete screed layer (1–5 mm grain size)                                                               | m <sup>2</sup> | 818.0 | 2.0%  | 2.0%  | 20.69                        | 2.60 | 23.29 | 16,924.2 | 2129.5                  | 19,053.7 | 48.1%        | 5.0              | 5.0 | 4.0 | 4.7   | -        |
| Bituminous emulsion                                                                                                 | m <sup>2</sup> | 818.0 | 10.0% | 10.0% | 0.24                         | 0.02 | 0.26  | 192.5    | 17.0                    | 209.5    | 0.5%         | 2.0              | 4.0 | 4.0 | 3.3   | -        |
| Rigid mineral rock wool 120 mm thick                                                                                | m <sup>2</sup> | 818.0 | 5.0%  | 5.0%  | 18.48                        | 0.94 | 19.42 | 15,116.6 | 768.0                   | 15,884.6 | 40.1%        | 5.0              | 5.0 | 4.0 | 4.7   | -        |
| Two-layer bituminous waterproofing system with a 3 kg/m <sup>2</sup> base sheet and a 4 kg/m <sup>2</sup> top sheet | m <sup>2</sup> | 818.0 | 0.0%  | 10.0% | 5.13                         | 0.30 | 5.43  | 4196.3   | 242.0                   | 4438.3   | 11.2%        | 4.0              | 5.0 | 4.0 | 4.3   | -        |
| Balcony waterproofing system                                                                                        | m <sup>2</sup> | 173.5 | -     | -     | 34.50                        | 3.32 | 37.82 | 5985.6   | 575.8                   | 6561.4   | 100.0%       | -                | -   | -   | 4.6   | 0.5%     |
| Lightweight concrete screed layer (1–5 mm grain size)                                                               | m <sup>2</sup> | 173.5 | 2.0%  | 2.0%  | 20.69                        | 2.60 | 23.29 | 3589.7   | 451.7                   | 4041.3   | 61.6%        | 5.0              | 5.0 | 4.0 | 4.7   | -        |
| Bituminous emulsion                                                                                                 | m <sup>2</sup> | 173.5 | 10.0% | 10.0% | 0.24                         | 0.02 | 0.26  | 40.8     | 3.6                     | 44.4     | 0.7%         | 2.0              | 4.0 | 4.0 | 3.3   | -        |
| Rigid mineral rock wool 50 mm thick                                                                                 | m <sup>2</sup> | 173.5 | 5.0%  | 5.0%  | 8.30                         | 0.39 | 8.69  | 1439.2   | 67.9                    | 1507.1   | 23.0%        | 5.0              | 5.0 | 4.0 | 4.7   | -        |
| Two-layer bituminous waterproofing system with a 3 kg/m <sup>2</sup> base sheet and a 4 kg/m <sup>2</sup> top sheet | m <sup>2</sup> | 173.5 | 0.0%  | 10.0% | 5.13                         | 0.30 | 5.43  | 890.1    | 51.3                    | 941.4    | 14.3%        | 4.0              | 5.0 | 4.0 | 4.3   | -        |
| Geotextile separation layer                                                                                         | m <sup>2</sup> | 173.5 | 0.0%  | 10.0% | 0.15                         | 0.01 | 0.16  | 25.9     | 1.3                     | 27.2     | 0.4%         | 4.0              | 5.0 | 4.0 | 4.3   | -        |

|                                                                                                                           |                |        |       |       |       |      |       |          |        |          |        |     |     |     |     |      |
|---------------------------------------------------------------------------------------------------------------------------|----------------|--------|-------|-------|-------|------|-------|----------|--------|----------|--------|-----|-----|-----|-----|------|
| Patio water-proofing system                                                                                               | m <sup>2</sup> | 195.0  | -     | -     | 22.40 | 2.73 | 25.13 | 4367.5   | 532.2  | 4899.7   | 100.0% | -   | -   | -   | 4.7 | 0.3% |
| <i>Lightweight concrete screed layer (4–12.5 mm grain size)</i>                                                           | m <sup>2</sup> | 195.0  | 2.0%  | 2.0%  | 5.22  | 0.59 | 5.81  | 1018.0   | 114.7  | 1132.7   | 23.1%  | 5.0 | 5.0 | 5.0 | 5.0 | -    |
| <i>Bituminous emulsion</i>                                                                                                | m <sup>2</sup> | 195.0  | 10.0% | 10.0% | 0.12  | 0.01 | 0.13  | 22.9     | 2.0    | 25.0     | 0.5%   | 2.0 | 4.0 | 5.0 | 3.7 | -    |
| <i>Polyester-reinforced bituminous membrane</i>                                                                           | m <sup>2</sup> | 195.0  | 0.0%  | 10.0% | 1.75  | 0.20 | 1.95  | 341.3    | 39.0   | 380.2    | 7.8%   | 2.0 | 4.0 | 5.0 | 3.7 | -    |
| <i>Lightweight expanded clay aggregate drainage layer</i>                                                                 | m <sup>2</sup> | 195.0  | 0.0%  | 10.0% | 15.00 | 1.92 | 16.91 | 2924.2   | 373.6  | 3297.8   | 67.3%  | 4.0 | 5.0 | 5.0 | 4.7 | -    |
| <i>Geotextile separation layer</i>                                                                                        | m <sup>2</sup> | 195.0  | 10.0% | 10.0% | 0.31  | 0.02 | 0.33  | 61.0     | 2.9    | 64.0     | 1.3%   | 4.0 | 5.0 | 5.0 | 4.7 | -    |
| Ground floor circulation water-proofing system                                                                            | m <sup>2</sup> | 41.4   | -     | -     | 10.62 | 0.90 | 11.52 | 439.0    | 37.3   | 476.3    | 100.0% | -   | -   | -   | 4.8 | 0.0% |
| <i>Lightweight concrete screed layer (4–12.5 mm grain size)</i>                                                           | m <sup>2</sup> | 41.4   | 2.0%  | 2.0%  | 5.22  | 0.59 | 5.81  | 215.9    | 24.3   | 240.2    | 50.4%  | 5.0 | 5.0 | 5.0 | 5.0 | -    |
| <i>Bituminous emulsion</i>                                                                                                | m <sup>2</sup> | 41.4   | 10.0% | 10.0% | 0.12  | 0.01 | 0.13  | 4.9      | 0.4    | 5.3      | 1.1%   | 2.0 | 4.0 | 5.0 | 3.7 | -    |
| <i>Two-layer bituminous water-proofing system with a 3 kg/m<sup>2</sup> base sheet and a 4 kg/m<sup>2</sup> top sheet</i> | m <sup>2</sup> | 41.4   | 0.0%  | 10.0% | 5.13  | 0.30 | 5.43  | 212.1    | 12.2   | 224.4    | 47.1%  | 4.0 | 5.0 | 5.0 | 4.7 | -    |
| <i>Geotextile separation layer</i>                                                                                        | m <sup>2</sup> | 41.4   | 0.0%  | 10.0% | 0.15  | 0.01 | 0.16  | 6.2      | 0.3    | 6.5      | 1.4%   | 4.0 | 5.0 | 5.0 | 4.7 | -    |
| Retaining wall waterproofing system                                                                                       | m <sup>2</sup> | 831.9  | -     | -     | 1.87  | 0.21 | 2.08  | 1553.7   | 175.0  | 1728.7   | 100.0% | -   | -   | -   | 3.0 | 0.1% |
| <i>Bituminous emulsion</i>                                                                                                | m <sup>2</sup> | 831.9  | 10.0% | 10.0% | 0.12  | 0.01 | 0.13  | 97.9     | 8.6    | 106.5    | 6.2%   | 2.0 | 4.0 | 4.0 | 3.3 | -    |
| <i>Polyester-reinforced bituminous membrane</i>                                                                           | m <sup>2</sup> | 831.9  | 0.0%  | 10.0% | 1.75  | 0.20 | 1.95  | 1455.8   | 166.4  | 1622.2   | 93.8%  | 2.0 | 3.0 | 4.0 | 3.0 | -    |
| Interior wet zones water-proofing system                                                                                  | m <sup>2</sup> | 1781.7 | -     | -     | 7.79  | 0.11 | 7.90  | 13,879.1 | 198.5  | 14,077.7 | 100.0% | -   | -   | -   | 4.2 | 1.0% |
| <i>Single-component water-proofing mortar</i>                                                                             | m <sup>2</sup> | 1781.7 | 0.0%  | 5.0%  | 7.32  | 0.11 | 7.43  | 13,041.8 | 192.5  | 13,234.3 | 94.0%  | 4.0 | 5.0 | 4.0 | 4.3 | -    |
| <i>Alkali-resistant glass fibre mesh</i>                                                                                  | m <sup>2</sup> | 1781.7 | 0.0%  | 10.0% | 0.47  | 0.00 | 0.47  | 837.4    | 6.0    | 843.4    | 6.0%   | 3.0 | 3.0 | 4.0 | 3.3 | -    |
| Total                                                                                                                     |                | -      | -     | -     | -     | -    | -     | 62,654.6 | 4675.2 | 67,329.8 |        |     |     |     | 4.5 | 4.7% |

Note. Italicised entries represent the constituent materials forming each construction system.

### 3.9. EC Calculation for Building Constructive Elements

To facilitate the interpretation of the EC results, Table 37 summarizes the cradle-to-site carbon footprint of each building constructive element, together with its reliability analysis score and contribution to the total EC.

**Table 37.** EC analysis for building constructive elements.

| Element                                       | CF (kg CO <sub>2</sub> e) |           | CF (kg CO <sub>2</sub> e/m <sup>2</sup> ) |       | Reliability Analysis Score | EC Share |
|-----------------------------------------------|---------------------------|-----------|-------------------------------------------|-------|----------------------------|----------|
|                                               | A1–A3                     | A4        | A1–A4                                     | A1–A4 |                            |          |
| Earthworks and aggregates                     | 843.7                     | 31,352.6  | 32,196.3                                  | 5.1   | 5.0                        | 2.2%     |
| Ready-mix concrete                            | 570,532.9                 | 15,765.9  | 586,298.9                                 | 92.3  | 5.0                        | 40.5%    |
| Reinforcement and structural steel elements   | 152,309.3                 | 9669.4    | 161,978.7                                 | 25.5  | 5.0                        | 11.2%    |
| Masonry                                       | 147,861.0                 | 21,738.5  | 169,599.5                                 | 26.7  | 4.7                        | 11.7%    |
| Exterior cladding                             | 54,819.0                  | 4606.4    | 59,425.4                                  | 9.4   | 4.1                        | 4.1%     |
| Infill and floor levelling                    | 171,574.7                 | 8928.1    | 180,502.8                                 | 28.4  | 5.0                        | 12.5%    |
| Floor finishes                                | 68,298.4                  | 3061.6    | 71,360.0                                  | 11.2  | 4.8                        | 4.9%     |
| Wall finishes                                 | 22,495.6                  | 953.7     | 23,449.4                                  | 3.7   | 4.9                        | 1.6%     |
| Plasterboard linings, partitions and ceilings | 83,934.2                  | 10,522.4  | 94,456.6                                  | 14.9  | 4.6                        | 6.5%     |
| Waterproofing systems                         | 62,654.6                  | 4675.2    | 67,329.8                                  | 10.6  | 4.5                        | 4.7%     |
| Total                                         | 1,335,323.5               | 111,273.8 | 1,446,597.3                               | 227.8 | 4.9                        | 100%     |

## 4. Discussion

### 4.1. Framework Applicability and Overall Results

The methodological framework adopted in this study, combining detailed MQT with carefully selected CFs, enabled a systematic and transparent assessment of EC across the analysed construction systems. By structuring the analysis within the cradle-to-site stages (A1–A4), the approach provides a coherent representation of how different materials and assemblies contribute to the overall environmental profile of the building. Beyond the specific case study, this framework demonstrates its applicability as a practical tool for conducting consistent and context-sensitive EC assessments in similar construction contexts.

A key aspect of this study is the explicit definition and transparency of the calculation process and system boundaries. Attention is given to clearly documenting data sources, assumptions, and included processes, providing full clarity on what is incorporated within the LCA scope. This addresses a common limitation in existing studies, where insufficient methodological transparency hinders interpretation and comparability of results. By explicitly defining boundaries and inputs, the proposed framework enhances reproducibility and reduces ambiguity in EC assessments.

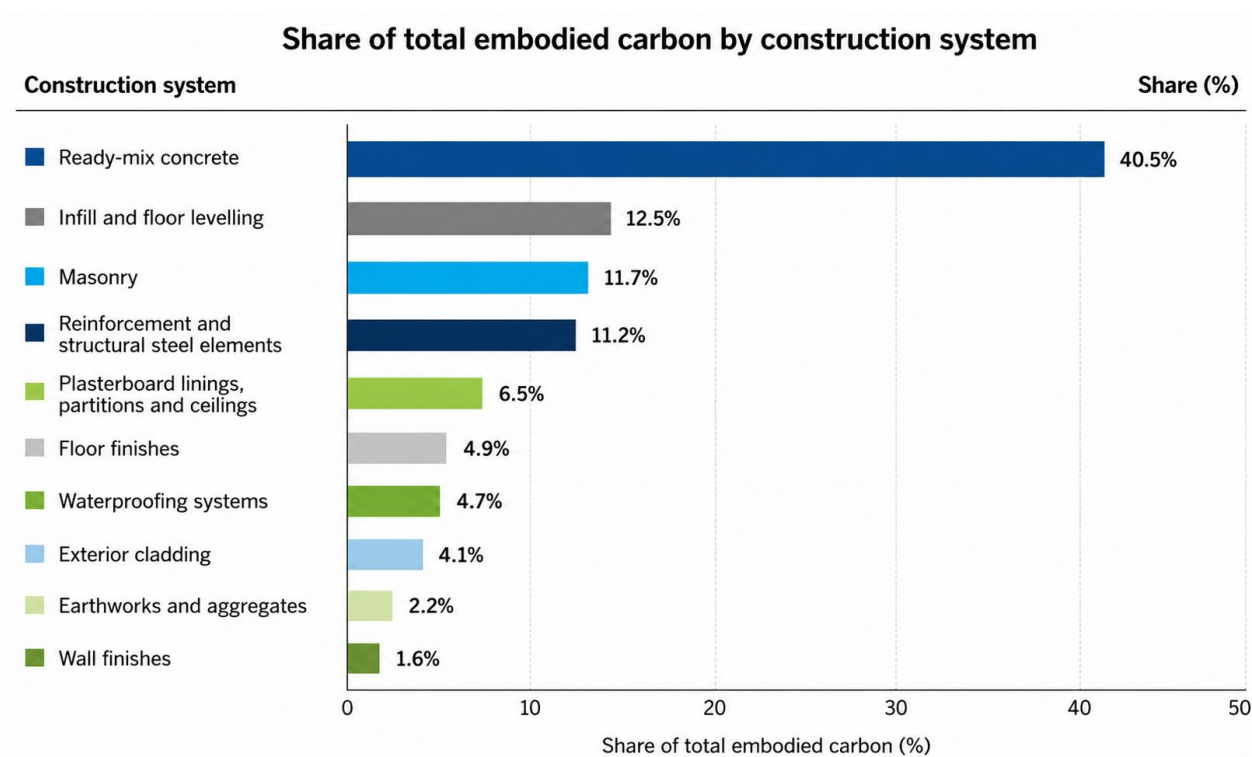
The results indicate that the product stage (A1–A3) accounts for 1,335,324 kg CO<sub>2</sub>e, equivalent to 210.3 kg CO<sub>2</sub>e/m<sup>2</sup>. This value is lower than the embodied carbon benchmarks reported for residential buildings in Europe, where A1–A3 impacts are approximately 340 kg CO<sub>2</sub>e/m<sup>2</sup> when considering the baseline scope and around 400 kg CO<sub>2</sub>e/m<sup>2</sup> when optional scopes, such as interior finishes, building services and external works, are included [84]. The difference may be attributed to project-specific factors, including material specifications, structural design, construction practices, and the adopted system boundaries. Furthermore, benchmark datasets often represent a wide range of residential buildings with varying levels of complexity and material intensity.

The transport stage (A4) contributes an additional 111,274 kg CO<sub>2</sub>e (17.5 kg CO<sub>2</sub>e/m<sup>2</sup>), resulting in a total cradle-to-site impact of 227.8 kg CO<sub>2</sub>e/m<sup>2</sup>. Although transport emis-

sions are not negligible, the results confirm that the product stage remains the dominant contributor to embodied carbon emissions. Overall, the obtained values remain within a plausible range for residential construction while indicating a lower embodied carbon intensity than the European benchmark values reported in the literature.

#### 4.2. Emission Hotspots: Cement-Based Materials

As shown in Figure 2, a clear concentration of emissions is observed within a limited number of material categories. Ready-mix concrete emerges as the primary hotspot, accounting for approximately 40% of total A1–A4 emissions. This dominance is consistent with existing studies and can be explained by the high cement content and the large volumes required in RC structures. Similar trends are observed in other cement-based systems, such as masonry and infill and levelling layers, which together contribute a significant additional share. These findings reinforce the critical role of cement-intensive materials in shaping the EC profile of buildings and highlight the potential impact of strategies aimed at reducing cement content or substituting clinker-intensive binders.



**Figure 2.** Share of total EC of the building constructive elements and their relative contributions for stages A1–A4 of the LCA.

#### 4.3. Contribution and Role of Secondary Contributors to EC

Non-structural systems also play a relevant role in the overall EC profile. Infill and levelling systems, particularly lightweight concrete screeds incorporating regranulated EPS, contribute significantly due to their extensive application across floor areas and their relatively high specific EC. When combined with associated layers such as polyethylene membranes and self-levelling screeds, these systems represent a notable share of total emissions. This highlights that non-structural solutions, despite their functional advantages, may carry a considerable environmental burden. Alternative solutions with lower cement content or reduced material intensity therefore represent a relevant opportunity for emission reduction.

In addition to concrete-based systems, other materials also contribute significantly to EC. Reinforcing steel accounts for approximately 11% of total emissions. Despite its lower mass relative to concrete, its high specific carbon intensity results in a disproportionate impact. This effect is also observed in lightweight assemblies such as gypsum partitions, where galvanised steel profiles contribute a substantial share of emissions relative to their mass. These findings highlight the importance of considering both MQ and carbon intensity when evaluating EC contributions.

#### *4.4. Data Limitations and Implications for Low-Carbon Construction*

The analysis also highlights persistent challenges related to data availability and reliability. While many materials are supported by high-quality and geographically relevant EPDs, others require the use of proxies due to the absence of suitable datasets. Such limitations introduce uncertainty and increase the effort required for data selection, highlighting the need for broader and more consistent publication of EPDs within the construction sector. Despite these constraints, the overall reliability assessment yields a high average score (4.9 out of 5), reflecting the effort made to ensure geographical and material representativeness.

Overall, the study demonstrates that combining detailed material quantification with a structured evaluation of environmental data enables a robust and transparent assessment of EC. The proposed framework not only supports the identification of key emission hotspots but also provides a practical basis for informing design decisions, material selection, and procurement strategies aimed at reducing the environmental impact of residential buildings.

## **5. Conclusions**

This study developed and applied a structured LCA framework to quantify the EC of a multifamily residential building in Faro, Portugal, focusing on the cradle-to-site stages (A1–A4). By integrating detailed MQT with CFs derived from EPDs and peer-reviewed sources, the framework enables a transparent, systematic, and context-sensitive assessment of embodied emissions. Beyond the specific case study, the proposed approach constitutes a practical and replicable methodology that can be applied to similar construction projects, particularly in contexts where geographically representative environmental data are limited.

The results show that EC is highly concentrated in a limited number of material categories. Cement-based systems, particularly ready-mix concrete, dominate the overall impact, accounting for approximately 40% of total A1–A4 emissions, while reinforcing steel contributes around 11%. Together with masonry and infill and levelling systems, these materials represent more than 75% of total embodied emissions. These findings confirm that the greatest potential for reducing EC lies in optimising structural systems, reducing cement content, improving concrete mix designs, and evaluating alternative binders or structural strategies.

A key methodological contribution of this study is the application of a structured approach for CF selection under conditions of data uncertainty. The use of the AHP enabled the evaluation of multiple datasets and supported the selection of a representative emission factor for ready-mix concrete.

The study also provides practical insights for design and material selection. While structural materials dominate total emissions, non-structural systems such as infill and levelling layers can contribute significantly due to their widespread application and material composition. Finishing materials, although less significant in terms of mass, exhibit considerable variability in carbon intensity, indicating that targeted material substitution can achieve incremental reductions in EC. In addition, composite systems such as ETICS

demonstrate that cumulative effects across large surface areas can result in a meaningful environmental impact, reinforcing the need to evaluate construction systems holistically.

Limitations related to data availability remain a critical challenge. Although the reliability assessment yielded a high overall score (4.9/5), achieving this required extensive effort to identify suitable datasets, particularly for materials lacking locally representative EPDs. The high overall reliability score was also influenced by the weighted nature of the assessment, in which materials with greater contributions to total EC had a larger influence on the final score. Since the major EC contributors, such as ready-mix concrete and reinforcing steel, were generally supported by robust environmental data, materials with lower reliability scores had a comparatively limited impact on the overall assessment. The absence of specific EPDs for common materials such as ready-mix concrete in Portugal highlights the need for improved data availability and standardisation. Expanding the publication of geographically relevant EPDs would significantly enhance the accuracy, efficiency, and comparability of EC assessments.

The transferability of the proposed framework depends on the availability of sufficiently detailed material quantity data and representative environmental datasets, preferably derived from verified EPDs or peer-reviewed literature developed under comparable standards. In addition, the use of consistent system boundaries and adequate project documentation is essential to ensure meaningful application across different construction contexts. Although the framework was developed and demonstrated within the Portuguese construction context, its underlying methodology may be adapted to other building projects through an appropriate assessment of data representativeness and reliability. Furthermore, the framework has the potential to be extended beyond embodied carbon to other environmental indicators reported under EN 15804.

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