Comparative Economic Sustainability of Commonly used Flat Roofs in Portugal

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Abstract. The construction of new buildings as well as its retrofitting processes should be ruled by sustainability concepts considered since the design and project phases. The materials and the construction processes used at each stage have a direct influence on the sustainability of the final solution at all parts of the “before use” stage of a building life cycle, namely: “pre-construction”, “product” and “construction process”. The aim of this paper is to compare three different construction solutions for flat roofs, commonly used in Portuguese buildings regarding their economical sustainability. All the solutions have the same functional equivalent, i.e. they are designed to have similar thermal, acoustical and fire protection performance. In order to evaluate the economical sustainability of the different construction solutions, the EcoSust methodology, based on the European standards framework, will be applied. According to this methodology the result of the economic performance is expressed in monetary units and the result of the sustainability performance by an index of economical sustainability (A+, A, B, C, D, E).

1. Introduction

The EcoSust model [1] is based on an LCA for assessing the economic sustainability of buildings, following the European construction sustainability framework as defined by EN 15643-1:2010 [2], EN 15643-4:2012 [3] and EN 16627:2015 [4], which, in turn, is based on the European Standards framework developed by CEN / TC 350 "Sustainability of construction works", proposes a system for assessing the sustainability of buildings based on life cycle analysis (LCA). The approach has been developed to systematically assess the economic performance of a building within the concept of sustainability. The methodology follows the principle of modularity, where aspects and impacts that influence economic performance and building sustainability index during the “before use phase”, are assigned to the categories in which they occur. The hierarchical structure of the methodology directs the flow of information relating to aspects and impacts that influence the economic performance of the indicators, modules and stages of the life cycle, based on the quantification of the 65 parameters defined for the EcoSust methodology [1]. The parameters provide accurate information for indicators from observable or measurable data from the project or existing building.
This paper aims to present the methodology and calculation of the reference values (benchmarks) for the parameters of the hierarchical structure of EcoSust methodology, applied to a set of three construction solutions for flat roofs, in order to evaluate and compare their economical sustainability. The construction solutions represent different possible scenarios for flat roofs: a) an inverted roof in which the waterproofing layer is beneath the thermal insulation. The membrane is therefore protected by the insulation from the expansion and contraction caused by weather fluctuations, such as frost and solar radiation. The membrane is also protected from damage by traffic on the roof, such as people walking and equipment movement; b) an intensive green roof that can sustain trees, shrubs, irrigation, benches and walkways, drainage and root protection layers; and c) an insulated metal deck flat roof in which the insulation layer is placed above the structural decking made of trapezoidal steel profiles. A vapor control layer beneath the insulation is required to prevent moisture, and the waterproofing system is placed over the insulation to completely wrap it. All the three flat roofs solutions show the same performance concerning thermal and acoustical insulation and show similar fire resistance protection. It is expected to grade the three flat roof solutions concerning their economic sustainability. To apply the EcoSust methodology regarding the evaluation of the three flat roofs solutions, a building with simple geometry and similar construction solutions for all elements, except for the flat roofs, was defined. The three different flat roofs types correspond to the three studied solutions.

2. Characterization of the flat roofs

2.1. Construction solutions

The construction solutions regarding the flat roofs to be analyzed are the following (see Figure 1):

- Solution 1 – The flat roof corresponding to solution 1 (inverted roof) is to consist of a 20 cm solid reinforced concrete slab (SR), under a 10 cm-thick fill layer consisting of an expanded clay coat (FP), a layer of bituminous waterproofing membrane on a surface primer (I) covered by a geotextile mat (CS). The geotextile layer (CS) is placed under a 16 cm-thick slab of thermal insulation made of extruded polystyrene foam-XPS (IT), covered by another geotextile mat (CSa) and a 12 cm-thick rolled pebble layer on top (P).
- Solution 2 – The flat roof corresponding to solution 2 (intensive green roof) is to consist of a 20 cm solid reinforced concrete slab (SR), under a 10 cm-thick fill layer consisting of an expanded clay coat (FP), a layer of bituminous waterproofing membrane on a surface primer (I) covered by a geotextile mat (CS). The geotextile layer (CS) is placed under a 14 cm-thick slab of thermal insulation made of extruded polystyrene foam-XPS (IT), covered by another geotextile mat (CSa), a permeable membrane with a filter made on rigid plastic (D), a geotextile layer used, not only for retain the finest materials but to promote the natural growing of the vegetation (Fi), and a 25 cm-thick topsoil layer covered with vegetation and plants (P).
- Solution 3 – The flat roof corresponding to solution 3 (insulated metal deck flat roof) is to consist of a structural decking in ribbed galvanized steel section with 26 cm (SR), covered by a 16 cm-thick slab of thermal insulation made of mineral wool-MW (IT), and a bituminous waterproofing membrane with mineral granules to make up the self-protective top layer (I).

![Diagram](image1.png)  ![Diagram](image2.png)  ![Diagram](image3.png)

**Figure 1.** Vertical sections (Solutions 1, 2 and 3).
2.2. Functional performance of the flat roofs
Table 1 synthesizes the functional performance for the three analyzed flat roofs. The overall behavior concerning thermal insulation, sound insulation and fire resistance for the three flat roofs is approximately the same. The figures included in Table 1 were provided by the manufacturers through laboratory tests or calculated based on technical scales. Therefore, the sustainability performance in comparative terms for the three solutions can be performed using EcoSust model. The U-values for the three flat roofs are calculated based on the method described in NP EN ISO 6946:2017 [5]. The method follows a methodology for the calculation of the thermal resistance and thermal transmittance supported on the electrical analogy.

The weighted Sound Reduction Index (Rw) for the three flat roofs was obtained by using the method described in NP EN 20140-3:1998 [6] and NP EN ISO 717-1:2013 [7]. This metric is assumed to be an important parameter for laboratory comparison of different building construction elements, such as façade walls, windows, pavements and roofs. The Rw index is calculated based upon a 1/3 octave band frequency range, between 100 Hz and 3150 Hz. The fire resistance classification for the three flat roofs was calculated in compliance with NP EN 13501-2:2016 [8]. This European standard employs values that result from smoke leakage and fire resistance essays that are considered in compliance with the application field of the test method.

| Solution | U-value (W/m²·K) | Rw (dB) | Fire-Resistance duration (minutes) |
|----------|------------------|--------|-----------------------------------|
| Solution 1 | ≈ 0.3 | ≈ 60 | >120 |
| Solution 2 | ≈ 0.3 | ≈ 60 | >120 |
| Solution 3 | ≈ 0.3 | ≈ 60 | ≈ 120 |

2.3. Necessary resources for each constructive solution
The unitary costs for solutions 1, 2 and 3 of the resources were built based on a publication of the Portuguese National Civil Engineering Laboratory (LNEC) [9], which is an accurate and widely used source in Portugal. In Table 2, the cost of resources for the construction of one square meter of each flat roof solution is presented. The description for the materials, their quantities and unitary costs are not presented due to the article size limitations.

| Resource | Solution 1 Cost (€) | Solution 2 Cost (€) | Solution 3 Cost (€) |
|----------|---------------------|---------------------|---------------------|
| Water    | 0.015               | 0.010               | 0.010               |
| Energy   | 0.160               | 0.015               | 0.060               |
| Labor    | 21.290              | 20.870              | 11.110              |
| Equipment| 0.050               | 0.050               | 0.080               |
| Materials| 32.350              | 33.320              | 31.070              |
| TOTAL    | 53.870              | 54.270              | 42.330              |

3. Comparative analysis
The assessment of economic performance and the level of economic sustainability of a residential building during the design phase, based on the expected behavior for the entire building life cycle should be made for the four phases of the lifecycle of a building. Each phase of the lifecycle is divided into stages, modules, indicators and parameters. For the moment, EcoSust is developed only for the “before use phase”. The object of assessment is the building, including its foundations and landscaping within the building perimeter [1]. Table 3 shows the hierarchical structure of the method (stages, modules, indicators and parameters) that corresponds to the before use phase.

At each level, information is obtained by aggregation of information at the lower level. EcoSust assesses the performance and economic sustainability of buildings, the result of economic performance is expressed in monetary unit and the sustainability in an economic sustainability index
(A+, A, B, C, D, and E), where "E" the means lowest economic sustainability and "A+" the higher economic sustainability.

| Level 1 Stages | Level 2 Modules | Level 3 Indicators | Level 4 Parameters |
|----------------|-----------------|--------------------|--------------------|
| Pre- construction Stage (PC) | A0: Site and associated fees and counselling | A0.1: Cost of purchase and rental incurred for the site or any existing building. | P1 to P3 |
| Product Stage (EP) | A1: Supply of raw materials | A0.2: Professional fees related to the acquisition of land. | P4 to P8 |
| | A2: Transport of raw materials | A1.1: Cost of raw materials. | P9 |
| | A3: Manufacturing | A2.1: Cost of transportation of raw materials. | P10 |
| Construction process Stage (EC) | A4: Transport | A3.1: Cost of transformation raw materials. | P11 |
| | A5: Construction-installation process | A4.1: Cost of transport of materials and products from the factory gate to the building site. | P12 |
| | | A4.2: Cost of transport of construction equipment such as site accommodation, access equipment and cranes to and from the site. | P13 |
| | | A5.1: Costs with exterior works and landscaping works. | P14 to P20 |
| | | A5.2: Cost of storing products including the provision of heating, cooling, humidity etc. | P21 |
| | | A5.3: Cost of transportation of materials, products, waste and equipment within the site. | P22 |
| | | A5.4: Cost of temporary works including temporary works off-site as necessary for the construction. | P23 |
| | | A5.5: Cost on site production and transformation of a product. | P24 to P27 |
| | | A5.6: Cost of heating, cooling, ventilation, humidity control, etc. during the construction process. | P28 to P29 |
| | | A5.7: Cost of installation of the products into the building including ancillary materials. | P30 to P32 |
| | | A5.8: Cost of water used for cooling, of the construction machinery or on-site cleaning. | P33 |
| | | A5.9: Cost of waste managing processes of other wasters generated on the construction site (RCD). | P34 to P36 |
| | | A5.10: Transportation cost of waste RCD. | P37 |
| | | A5.11: Costs of commissioning and handover related cost. | P38 to P44 |
| | | A5.12: Cost for professional fees related to work on de project. | P45 to P48 |
| | | A5.13: Costs of the taxes and other costs related to the permission to build and inspection or approval of works. | P49 to P64 |
| | | A5.14: Incentives or subsidies related to the installation. | P65 |

3.1. Application of the methodology

The methodology was applied to a multifamily residential building located in the Porto region, on an appropriate building site located in a low density urban allotment. The lot of land destined to the construction of the building was acquired for the amount of € 723,840. In order to prepare the construction of the building it was necessary to carry out some infrastructure works related to earthmoving, road paving, peripheral containment and structures of soil support, hydraulic and electric infrastructures, public street lighting, telecommunications and gas facilities. Consequently, the cost of the building comprises the building itself plus the outside arrangements and infrastructures. The building consists of an underground floor for car parking, a ground floor and 3 more stories destined to housing apartments. The building has 29 apartments of the type T0, T1, T2 and T3 with a gross construction area of 2320 m². The structure of the building is a reinforced concrete structure resting on shallow foundations. The slabs are of prefabricated concrete. The solutions for the flat roofs are the three previously described. The interior finishes are the following: the coverings of floors are ceramic in the kitchens and bathrooms, and totally wood surfaced in bedrooms, living rooms and halls. The common areas of the building, mainly the corridors and stairs are covered with natural stone. The
partition walls of kitchens and bathrooms are covered with tiles and the remaining walls are covered with sprayed plaster painted with clear plastic paint. The façade walls are rendered and painted. For building installations conventional construction materials were applied: PVC-U for ventilation, wastewater and rainwater drainage, PPR (Polypropylene) for water piping system and copper in the natural gas piping system. The study involved a comparative analysis of the results of the assessment of economic performance and economic sustainability of the building for the three constructive solutions of flat roofs with similar performance. The original solution (Solution 1) is said to be the “basic solution” and corresponds to the described building. The flat roof has a total area of 845 m².

3.2. Results
The results of the evaluation of the economic performance of the building in the “before use phase”, for each of the three constructive solutions considered in this study are presented in Tables 4, 5 and 6, expressed in monetary units. These values correspond to the direct and indirect costs that occur within the boundary of the building, associated with all stages of the “before use phase”.

| Table 4. Economic performance for the level 1 attributes: before use phase (€) |
| Phase: | Before use phase | Total Cost |
|-------|-----------------|------------|
|        | Pre-construction | Product | Construction process |        |
| Solution 1 | 793711 | 659911 | 1325329 | 2778950 |
| Solution 2 | 793711 | 660092 | 1321179 | 2774982 |
| Solution 3 | 793711 | 619163 | 1077885 | 2490759 |

| Table 5. Economic performance for the Level 2 attributes: stages (€) |
| Stages: | Pre-construction | Product | Construction process |
| Modules: | A0 | A1 | A2 | A3 | A4 | A5 |
| Solution 1 | 793711 | 133766 | 178354 | 347791 | 227230 | 1098099 |
| Solution 2 | 793711 | 133803 | 178403 | 347887 | 227293 | 1093887 |
| Solution 3 | 793711 | 125506 | 167341 | 326316 | 212314 | 865571 |

| Table 6. Economic performance for the Level 3 attributes: modules (indicators A0.1 to A5.14) (€) |
| Modules: | Indicators: | A0 | A0.1 | A0.2 | A1 | A1.1 | A2 | A2.1 | A3 | A3.1 | A4 | A4.1 | A5 | A5.1 | A5.2 | A5.3 | A5.4 |
| Solution 1 | 739340 | 54371 | 133766 | 178354 | 347971 | 227230 | 146995 | 8918 | 10701 | 156060 |
| Solution 2 | 739340 | 54371 | 133803 | 178403 | 347887 | 227293 | 147036 | 7850 | 9420 | 156103 |
| Solution 3 | 739340 | 54371 | 125506 | 167341 | 326316 | 212314 | 865571 |

The normalized values (NV) and the sustainability index for the three solutions is presented in Tables 7 and 8.

| Table 7. Stages and phases: normalized values normalized and sustainability index. |
| Stages: | Solution 1 | Solution 2 | Solution 3 |
|        | NV | Index | NV | Index | NV | Index |
| Pre-construction | 0.640 | B | 0.640 | B | 0.640 | B |
| Product | 0.106 | C | 0.106 | C | 0.182 | C |
| Construction process | 0.286 | C | 0.302 | C | 0.440 | B |
| Phase: Before use phase | 0.362 | C | 0.371 | C | 0.461 | B |
By converting the monetary costs for the three solutions into normalized values, the converted



• EcoSust methodology has attributed a score “B” for the sustainability index regarding the pre-construction stage. This stage is strongly related to the cost determined by the purchasing of the land. This cost doesn’t depend on the value for the acquisition of construction materials, neither on the cost of the construction processes specified on the design of the building and applied during the construction works. The assessment of the economic performance regarding this stage determined a value of 793 711€, regardless the value of 2 490 759€, while for Solution 1 and 2 the total cost is 2 778 950€ and 2 774 982€, respectively. By converting the monetary costs for the three solutions into normalized values, the converted results give for Solutions 1 and 2 the values of 0.362 and 0.371, respectively, which represent a sustainability index “C” for both situations, while for Solution 3 the value of 0.461 is obtained, corresponding to a sustainability index “B”.

• Regarding Level 2, which corresponds to the “stages” level, the applied methodology attributed a score “B” for the sustainability index regarding the pre-construction stage. This stage is strongly related to the cost determined by the purchasing of the land. This cost doesn’t depend on the value for the acquisition of construction materials, neither on the cost of the construction processes specified on the design of the building and applied during the construction works. The assessment of the economic performance regarding this stage determined a value of 793 711€, regardless the construction solution applied. The sustainability index "C" is calculated for the “product stage”, which is associated with the material/product costs from the “raw material supply” to the “construction site gate”. The normalized values obtained for Solution 1 and Solution 2 is 0.106, and for Solution 3 is 0.182. The “construction stage” is associated with the costs related to the processes necessary for the construction of the building – 1 325 329€, 1 321 179 € and 1 077 885€, respectively for the solutions for flat roofs 1, 2 and 3. The normalized value obtained for Solution 1 is 0.286, for Solution 2 is 0.302, and for Solution 3 is 0.440, corresponding, respectively, to sustainability indexes "C", "C" and "B".

• Modules A2 (Transport of raw materials) and A5 (Construction-installation process) show an improvement in the sustainability index when applying Solution 3 when compared to Solution 1. In module A2 the index improves from “D” to “C”, while on module A5 the index increases from “C” to “B”.

EcoSust methodology has proved to be a viable solution for comparison of different scenarios regarding the economic sustainability of buildings.

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4. Conclusions

The analysis of the results regarding the evaluation of the performance and the economical sustainability of the building, taken as a case study, allows the following conclusions:

- The results obtained for the assessment of the economic performance of the building in the “before use phase” shows that Solution 3 obtains the best results. In fact, Solution 3 represents a total cost of 2 490 759€, while for Solution 1 and 2 the total cost is 2 778 950€ and 2 774 982€, respectively. By converting the monetary costs for the three solutions into normalized values, the converted results give for Solutions 1 and 2 the values of 0.362 and 0.371, respectively, which represent a sustainability index “C” for both situations, while for Solution 3 the value of 0.461 is obtained, corresponding to a sustainability index “B”.
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