

## Article

# Development of an Eco-Design Tool for a Circular Approach to Building Renovation Projects

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**Abstract:** Considering the construction sector's impact on the environment, it is necessary amongst other measures to change the way in which new construction or renovation projects of buildings are designed and how solutions are proposed and integrated. Nowadays, an effort is being made by designers to implement more sustainable and circular design in buildings, but because of the lack of tools that can provide designers with knowledge about the impacts of the solutions to be chosen, the sustainability factor does not enter in the decision-making process as a key factor. In this sense, the development of an eco-design tool and procedure for the decision-making process will allow designers to integrate into the design phase a circular design methodology and, in a practical way, will also promote sustainability and circularity concepts as a decision factor in the construction of buildings. The present work introduces an eco-design tool that was developed to integrate circularity and sustainability information into building-renovation projects. This tool enables the evaluation and comparison of solutions based on information provided by Environmental Product Declarations (EPD) or other LCA-based calculations as well as life cycle costing information, through the generation of radar graphics that simplify the overall analysis at the decision moment. The tool was tested in a simple case study of a building renovation process and allowed designers to understand the environmental and economic impacts that each competing solution carries, either related to the materials removed from the building or to the materials coming into the buildings being renovated. In this test application, the eco-design tool proved to be able to gather quantitative information regarding environmental and economic impacts, facilitating designers to access knowledge on the different solutions impacts and help them to make a design choice based on sustainability and circularity considerations.

**Keywords:** eco-design; sustainability; circular; renovation; construction



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## 1. Introduction

The construction industry is still dominated mainly by a linear economy model, which results in the consumption of high volumes of raw materials and generates large amounts of waste that are sent to landfill disposal [1,2]. On the other hand, the construction sector is an intensive consumer of other resources (energy and water) in the diversified manufacture and assembly processes that it involves related to the several construction materials and activities associated with this value chain. Therefore, this problem must be seriously addressed and discussed around the world, due to the scarce resources and due to the environmental impacts and resource consumption caused by the construction industry. In this regard, supported decisions on sustainability issues at the design stage will contribute to the efficiency of the resources used, and a circular economy model has proved to be a

more sustainable practice that enhances the reduction of the use of new materials, with the promotion of recycling and reuse practice [3–5]. Camana et al. [4] focus on the implications on the local waste management policies, while Hossain et al. [5] in their work point out the trends and challenges that the circular economy approach brings to sustainable construction. There are some studies that also highlight the advantages of implementing a circular model in the construction sector, supporting it with case studies that demonstrate the different approaches used [6,7]. The circular model is characterised by being a regenerative system that through the optimization and valorisation of materials creates loops that extend the life of the materials [8,9]. The opportunity for material recovery and valorisation is best achieved when choosing a deconstruction strategy [10,11], and this choice along with the possible waste outflows must be defined early in the design phase [12,13]. To understand the possible outflows of wastes and the impact that they imply, it is essential to carry out the characterization of the construction and demolition waste (CDW) in a design phase, given the differences in the constructive systems of buildings at the national level, influenced by the building year and the area in which it is located [14,15]. Although it is important for designers to consider the products' end-of-life in their decision [12], there is a need to implement this circular way of thinking in an earlier stage, by incorporating the assessment of the environmental impact on the product life cycle.

The European Standard *EN 15643 (2014) Sustainability of construction works: Assessment of the sustainability of buildings* [16], which proposes a system for assessing the sustainability of buildings based on their life cycle, is based on the assessment of the environmental, social, and economic performance of a building. To apply this standard, it is necessary to consider solutions with the same technical characteristics and functional aspects, to be able to compare them. The *EN 15643 (2014)* standard does not establish reference values or performance levels; it only allows for the comparison of results between assessments of solutions. At an environmental level, this standard proposes the environmental assessment based on the information given by the Environmental Product Declaration (EPD) and assumes the building life cycle assessment.

There is some useful research regarding resource consumption, namely of energy consumption that shows the potentialities of the building's energy simulation in improving its behaviour, leading also to less impact on the environment [17,18]. There is some software that can be used to do building energy simulation (Energy Plus, Design Builder and others), making it possible for designers to have knowledge about the energy and water consumption of the building. However, this software does a simulation based on resource consumption in the usage phase and does not consider the whole life cycle of the building products or systems. Moreover, it does not allow designers to consider the environmental impact in order to implement a more sustainable and circular design approach, namely, to compare solutions and draw conclusions about the ones with the least impact on the environment.

Based on these issues, the goal was to rethink the “business as usual” project design methodology and to start implementing sustainability and circularity concepts as a significant factor in the design stage decision process. This was carried out by the development of an eco-design tool that analyses data information on two pillars of sustainability, the environmental and economic ones, as well as introduces circularity considerations, which allow us to compare solutions from this point of view.

## 2. Eco-Design Tool Development

This eco-design tool is an instrument that was developed with the aim of allowing the comparison of environmental and economic indicators of different competing constructive solutions in an easier and faster way. It accomplishes this by providing the results of data analysis in a graphical way, considering the information of each solution so that different solutions can be compared and decisions about them can be more easily reached. The purpose of this tool is to enable designers to have knowledge about the environmental and

economic impacts of the competing solutions that they are considering for the project design, so that they can achieve a more sustainable project and contribute to the circular model.

The development of the eco-design tool was based on criteria proposed by the European Standard EN 15643 (2014), whereby the tool will assess the environmental and economic dimensions separately, based on life cycle considerations and only allowing comparisons between solutions within the same functional categories.

### 2.1. Environmental Dimension Assessment

The assessment of the environmental dimension is made by analysing information provided by life cycle analysis reports that gather information on the environmental impact, the consumption of resources (energy, water and materials) and the possible materials outflows, such as the ones supporting the Environmental Product Declarations (EPD). As the information provided by verified EPDs may consider several stages of the material's life cycle, this tool manages to synthesize useful information to analyse and compare different solutions for the same system or product category.

The parameters that will be gathered and analysed by the eco-design tool are the information that is provided by the environmental assessment of the materials on EPDs [19], which includes parameters related to environmental impact, resources consumption and waste outflows.

There are several active EPD database platforms referring to construction products registered in different countries, which may be considered to make it easier to gather the information needed for the assessment of the environmental dimension. Just to refer to some of them, there is Environdec in Sweden, BRE in the UK, IBU-EPD in Germany, DAPHabitat in Portugal and DAPconstrucción in Spain. These systems and many others are acknowledged members of a European association of EPDs registration program operators (EcoPlatform—<https://www.eco-platform.org>), which organized a list of EPDs that may be assessed through their EcoPortal.

For the environmental dimension, the eco-design tool considers two material flows for the assessment named as: (i) *output materials*, regarding the materials that are being removed; and (ii) *input materials*, regarding the materials that are being chosen for the new building or to replace existing ones in an existing building renovation.

#### (i) Output materials information:

The proposed tool involves an assessment of the quantity of wastes that is going to be generated in the new construction or renovation process and to which waste outflow it is going to be sent. From a circular model perspective, the following waste or materials outflows were considered: reuse, repair, recycling, energy valorisation and landfill disposal. This will provide quantitative information for each material that is going to be evaluated in two different stages, in the design phase and in the execution phase. This will also allow the monitoring of the waste management processes and the obtaining, at the end of the work, of the deviation between the estimated quantities of the generated waste (design phase) and the real quantities the construction has generated (execution phase).

#### (ii) Input materials information:

Regarding the materials that are coming into the construction site, the tool does a quantitative assessment of the parameters that describe: (i) the environmental impacts, namely the depletion of abiotic resources (elements and fossil fuels), soil and water acidification, ozone layer depletion, global warming, eutrophication and photochemical ozone formation; (ii) the resource consumption, specifically the total use of renewable primary energy resource, the total use of non-renewable primary energy resources, the use of secondary material, the use of secondary renewable fuels, the use of non-renewable secondary fuels and the net use of fresh water. It also does a qualitative analysis of the possible future outflows of the waste that is generated during the life cycle of the product that is being analysed for selection. By placing the values of the life cycle parameters taken from EPDs

(or other LCA-based reliable sources) in the tool, it allows the project design team to assess and compare different construction products or systems.

As the main goal of this eco-design tool is to obtain a quick and accessible reading on any specific comparison by displaying the values of the different parameters of each solution under evaluation, it turned out that the best way to display them for the final objective of making a fast decision was the “radar” type graphics. Since the different parameter data values may vary significantly, in terms of keeping a comparable scale, the tool was made to enable a normalisation of the values of each parameter to obtain a single scale for all parameters, and by doing so, the resulting interpretation is more facilitated and helpful for a quicker decision.

In this work, this procedure was carried out for a simple case study, both for the assessment of environmental impacts and for the assessment of resource consumption. In the end, this eco-design tool will provide a comparison that will help to decide which solution has the least environmental impact as well as information on the economic impact. Hence, the project design team can decide based on a multicriteria approach and have the freedom as such to value some particular parameters or cost, depending on the designer criteria.

## 2.2. Economic Dimension

The evaluation of the economic feature in this tool is performed based on the criteria of life cycle cost (LCC) of a building and is targeted at the cost analysis of the competing solutions that are coming into the construction site. Because the tool will assess materials or construction system solutions and not the whole building, an adaptation of the assessment process for the analysis was necessary. Hence, the costs that are going to be considered in this economic evaluation are the maintenance cost and the cost of acquisition of the material or construction system, which also includes material, labour and equipment usage costs. This adaptation of the life cycle cost was made assuming that this tool enters in the design phase as a decision support tool, acting only as a comparison between competing solutions. As the design cost itself would be identical for any case, it was not considered for the overall comparison.

Regarding the end-of-life cost, it was considered that over long lifetimes (>50 years) the end-of-life scenarios can vary significantly, and new valorisation solutions may arise that would change the foreseen scenario. Accordingly, it was decided not to consider this cost as a quantitative factor in this decision procedure.

To evaluate the total cost of the maintenance of the solution over the entire lifecycle, it is necessary to identify the elements under maintenance, as well as their maintenance actions. Then, for each action, information regarding their respective frequency and costs are needed to calculate the lifecycle maintenance cost, using the following equation:

$$\text{Action life cycle maintenance cost} = \frac{\text{Cost of Action (€)} * \text{Estimated lifetime (years)}}{\text{Frequency (years)}} \quad (1)$$

After evaluating the cost of each maintenance action that the system needs during the building’s life cycle, the total maintenance cost of the system over the lifetime of the building will be assessed.

## 3. Methodology

The application of the eco-design tool should provide the designer team qualified information about the environmental impacts of different constructive solutions, together with economic data so that the decision-making process on competing solutions can be accomplished considering these factors that integrate sustainability and circularity concepts, among other reasons the team wants to favour.

In a circular methodology way of thinking, this tool can be introduced in a design phase, both in new construction projects or in renovations on existing buildings, having in mind that before applying the tool, all the building’s material information should be

thoroughly mapped and provided in what is known as the red and yellow drawings and in the materials quantity maps, so this information can be used in the overall assessment. The red and yellow drawing plans are information given and used by designers to express, in yellow, the demolitions and, in red, the changes that will be made in the project.

In renovation projects, the interventions are made with specific goals based on the inspection and diagnosis of the building, either to correct defects identified in the building or to improve the building's indoor comfort conditions (acoustic insulation or energy consumption). The developed eco-design tool will enter in a phase where the intervention proposal is made, and the technical properties of the materials are defined. This tool will also gather the technical properties of the competing solutions described in the preliminary project, but it will only be considered in the decision-making phase of the project. The tool does not aim to decide for itself which solution but aims to provide additional information and help to the designer, since he or she will face a complex multicriteria-based decision.

For the assessment of the output materials, the ones being removed from the building, the eco-design tool accounts for the type of waste generated, its quantities and the waste content that is going for each outflow stream. The information needed by the tool to analyse these inputs will be found in: (1) project information (quantity map and red and yellow drawings/plans) regarding the list of the type of waste that is going to be produced and respective quantities; (2) EPDs or other database information, regarding the amount of waste material that may go to each outflow stream. With this information gathered, it is possible to calculate the quantity of each material that can go to each outflow stream, enabling better waste management in terms of reuse or recycling policy.

For the assessment of the input materials, the competing solutions to be chosen for the renovation actions, the tool allows us to compare the different ones, classified in the same functional categories (walls, roof, insulation, windows, pavements, claddings, structural, etc.). For doing the environmental analysis, information is needed about the material's technical properties, which may be found in the project information, and its environmental impacts and resource consumption, which may be found in their respective EPDs (see Figure 1) or other LCA-based reports.

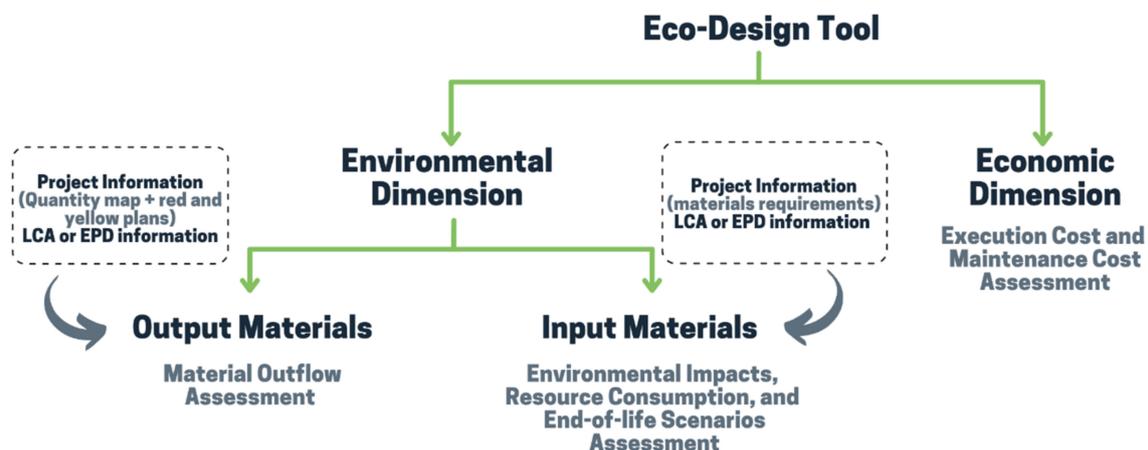


Figure 1. Eco-design tool schematics.

#### 4. Case Study

This work was framed in a project (*UAveirogreenbuilding*) where its main concern was the development and testing of how to integrate circularity principles in construction or renovations on buildings, using as pilot cases some buildings from the Aveiro University (Portugal) campus. The first pilot case, focused on in this paper, was the Central Technical Zone (CTZ), a 12,330 m<sup>2</sup> building more than 30 years old that needed refurbishment and functional adaptation. One of the goals of this project was the development and validation of an eco-design tool that could also incorporate circular principles in its operation and that

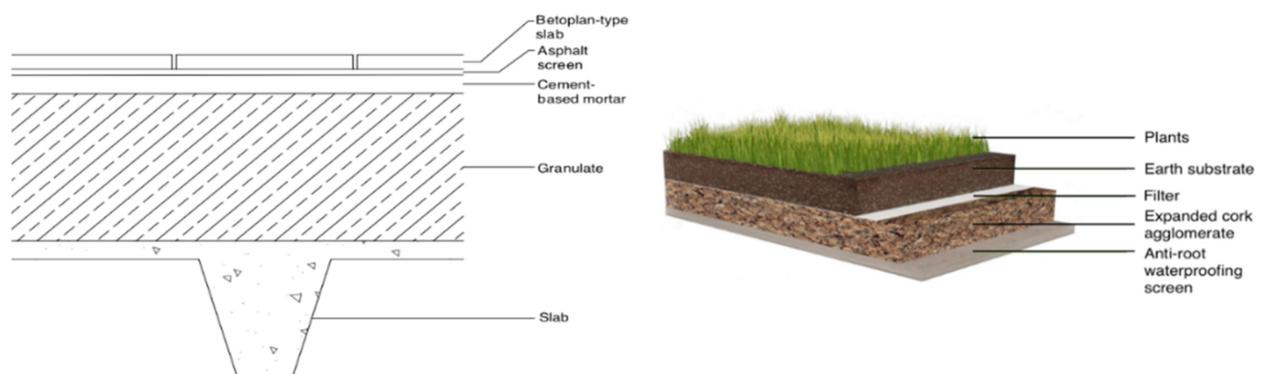
would give the designer teams an early-stage design decision that could contribute for a more sustainable construction.

This eco-design tool was developed and tested through this first case study of renovation of the roof constructive system of the CTZ building at the University of Aveiro, located in its Central Square of the Santiago Campus (see Figure 2).



**Figure 2.** Central Technical Zone building localization in the University Campus.

The objective was to support the decision process on the lowest environmental impact solutions. Two approaches were considered, one involving the refurbishment of the existing roofing system, replacing the damaged coating elements (Betoplan slabs) that will be sent for recycling or reuse, and another one considering the replacement of the original roofing system with a new green roof solution (Figure 3). This second option will also involve removing the current roof system, including the Betoplan slabs and supporting materials, except the concrete supporting slab that will remain in place to support the new green roof system. This last solution will also involve considering the respective recycling or reuse scenario.



**Figure 3.** Existing roof system (left) and green roof system (right) no scaled schemes [20].

The interventions planned by the design team for this building renovation will also involve creating new and larger openings in the current roof, which will allow more natural light to enter the interior spaces and improve indoor air quality and change the existing covering of the roof for a green roof system. Figure 4 shows the space of the central technical zone (CTZ) building that will be assessed by the eco-design tool in this test. The roof of this building serves as a public accessible square in the university campus

and its renovation must preserve this functionality. The evaluation of the environmental and economic parameters was performed for the two different solutions explained above (Figure 3). The results of this assessment allowed the comparison of the environmental performance and economic values of the solutions under consideration and enabled the decision-making team to consider what is more sustainable: maintaining the existing solution or implementing a new green roof system? In either one of the two situations, the roof slab will require maintenance. Accordingly, this element will not be considered in the assessments, but rather only its top concrete/mortar screed will be assessed.



**Figure 4.** CTZ building roof area to be assess by the eco-design tool.

For the environmental assessment, the French INIES database of EPDs was used, since it is an extensive platform that had all the necessary declarations for this specific assessment, but others can be used. This one was chosen here in order not to collect EPDs from different databases, as their calculation method may vary and thus consistency is maintained.

#### 4.1. Refurbishment of the Existing Roof System

For the output materials to be removed from the building, it was considered that only the original Betoplan slabs, a stone-cement composite, would be replaced, since a considerable number of existing slabs are damaged with cracks and efflorescences. The fact that only the replacement of this roof element is considered is because the inspection of the remaining supporting elements showed they were in a good state of conservation. The materials that will be removed for the roof openings to be wider were also considered as construction and demolition waste to be accounted for and managed in terms of final disposal.

Regarding these output materials, Table 1 shows the amount associated with the types of output streams that each element engages. These amounts resulted from the information provided by the EPDs, in the part referring to the outflows, where the quantity of material that will be reused, repaired, recycled, recovery or sent to landfill is given by the unit of measure of each material. Through these values, it is possible to have the amounts of each outflow of the different materials.

**Table 1.** Evaluation of Outflows of Outbound Materials (keeping the Existing Roof System).

Waste Type	Reuse	Repair	Recycling	Energy Recovery	Landfill	Quantity (m <sup>2</sup> )
Betoplan-type slab	44%		56%			5877.6
Cement-based mortar					100%	648.7
Asphalt screen	5%		95%			648.7
Lightweight Granulate			100%			648.7

From Table 1 it is possible to conclude that, by keeping the existing roof system with a total of 5877.6 m<sup>2</sup> of Betoplan slabs, 2597.9 m<sup>2</sup> of them would go for reuse and 3279.7 m<sup>2</sup> for recycling, while 648.7 m<sup>2</sup> of cement-based mortar would go to landfill, 33.1 m<sup>2</sup> of asphalt mesh would be reused and 615.6 m<sup>2</sup> would go for recycling, together with 648.7 m<sup>2</sup> of lightweight expanded clay granulates also going for recycling.

For the evaluation of the input materials, the EPDs of the constituent elements were used to obtain the parameter values of the environmental impacts and resource consumption of the existing roofing system, adding for each parameter the values of all the elements regarding it. Tables 2 and 3 present the values of environmental impacts and consumption of system resources, respectively. In this system, the possible material outflows are indicated in Table 4.

**Table 2.** Existing Roof System: Environmental Impact Assessment of Input Materials.

Solution	Environmental Impacts						
	Global Warming Potential (kg CO <sub>2</sub> Equiv.)	Depletion of the Ozone Layer (kg CFC 11 Equiv.)	Acidification (kg SO <sub>2</sub> Equiv.)	Eutrophication (kg (PO <sub>4</sub> ) <sup>3-</sup> Equiv.)	Photochemical Ozone Formation (kg C <sub>2</sub> H <sub>4</sub> Equiv.)	Abiotic Depletion Potential for Minerals and Metals Resources (kg Sb Equiv.)	Abiotic Depletion Potential for Fossil Resources (MJ, P.C.I.)
Existing roof system	$2.58 \times 10^2$	$2.12 \times 10^{-5}$	$9.96 \times 10^{-1}$	$1.13 \times 10^{-1}$	5.03	$4.41 \times 10^{-3}$	$3.18 \times 10^3$

**Table 3.** Existing Roof System: Resource Consumption Assessment of Input Materials.

Solution	Resource Consumption					
	TRR (MJ, P.C.I.)	TRNR (MJ, P.C.I.)	MS (kg)	CSR (MJ, P.C.I.)	CSNR (MJ, P.C.I.)	Net Use of Fresh Water (m <sup>3</sup> )
Existing roof system	$2.90 \times 10^2$	$3.50 \times 10^3$	$8.06 \times 10^1$	$2.37 \times 10^2$	$1.07 \times 10^2$	$7.68 \times 10^{-1}$

TRR = total use of renewable primary energy resources; TRNR = total use of non-renewable primary energy resources; MS = use of secondary material; CSR = use of secondary renewable fuels; CSNR = use of non-renewable secondary fuels; Fresh water = use of net fresh water value.

**Table 4.** Existing Roof System: Possible Outflows.

Waste Type	Reuse	Repair	Recycling	Energy Recovery	Landfill
Betoplan-type slab	X		X		
Cement-based mortar					X
Asphalt screen	X		X		
Granulate (Leca)			X		

The acquisition cost to be considered is related to the Betoplan slabs acquisition, its labour and equipment costs. Thus, an acquisition cost of €223,348.00 was assumed, obtained by multiplying the area with the cost per m<sup>2</sup> of the solution. The maintenance cost (Table 5) is based on the maintenance actions recommended in the Building Use and Maintenance Manual (CYPE) and the respective costs. For the purpose of calculating the maintenance cost, it was considered that the system will have 60 years of life span.

To estimate the cost of replacing existing damaged elements, the total area was multiplied by a factor that takes in account the reduction of the number of damaged elements, a factor that was obtained through an estimate based on the current situation. This aims to foresee a situation in which there is a reuse of elements that are still in a good state of conservation, assuming that the same material will be available 30 years later. The cost of maintaining the existing system per year was calculated to be €11,855.52 at current prices.

**Table 5.** Maintenance Cost Calculation: Existing Roof System.

Maintenance Source Element	Maintenance Action	Frequency (Years)	Cost of Action (€)	Lifecycle Maintenance Cost of the Action (€)
Betoplan-type slab	Visual inspection	5	350.00	4200.00
Betoplan-type slab	Periodical cleaning the slabs (dry or wet) with neutral detergents diluted in warm water	2	20,101.39	603,041.76
Betoplan-type slab	Replacement of damaged elements	30	37,224.80	74,449.60
Water drainage system	Visual inspection	1	350.00	21,000.00
Water drainage system	Cleaning of pavement siphons	0.5	72.00	8640.00
Total				711,331.36

#### 4.2. Replacing the Existing Roof with a Green Roof System

In the output materials, the filling and finishing materials for the existing roof were considered as demolition waste in the entire intervention area. As in the previous solution, the amounts of each output stream resulted from the information provided by the environmental declarations for each product.

From Table 6 it is possible to conclude that, in a total of 5877.6 m<sup>2</sup> of slabs, 2597.9 m<sup>2</sup> of slabs will go for reuse and 3279.7 m<sup>2</sup> for recycling, and also that 5877.6 m<sup>2</sup> of cement-based mortar will go now to landfill, 299.8 m<sup>2</sup> of asphalt mesh will be reused while 5577.8 m<sup>2</sup> will be recycled and, finally, 5877.6 m<sup>2</sup> of lightweight expanded clay aggregates will also go for recycling.

**Table 6.** Evaluation of Outflows of Outbound Materials (Replacing the Existing Roof System).

Waste Type	Reuse	Repair	Recycling	Energy Recovery	Landfill	Quantity (m <sup>2</sup> )
Betoplan-type slab	44%		56%			5877.6
Cement-based mortar					100%	5877.6
Asphalt screen	5%		95%			5877.6
Lightweight Granulate			100%			5877.6

To assess the input materials, the EPDs related information about the elements that make up all the green roof system were used to obtain the parameters values for the environmental impacts and resource consumption. Tables 7 and 8 present the values of environmental impacts and consumption of system resources, respectively. The possible material outflows for the green roofing system are indicated in Table 9, which acts only as additional information to support the designer.

**Table 7.** Green roof System: Environmental Impact Assessment of Input Materials.

Solution	Environmental Impacts						
	Global Warming Potential (kg CO <sub>2</sub> Equiv.)	Depletion of the Ozone Layer (kg CFC 11 Equiv.)	Acidification (kg SO <sub>2</sub> Equiv.)	Eutrophication (kg (PO <sub>4</sub> ) <sup>3−</sup> Equiv.)	Photochemical Ozone Formation (kg C <sub>2</sub> H <sub>4</sub> Equiv.)	Abiotic Depletion Potential for Minerals and Metals Resources (kg Sb Equiv.)	Abiotic Depletion Potential for Fossil Resources (MJ, P.C.I.)
Green roof system	−2.66 × 10 <sup>2</sup>	1.35 × 10 <sup>−5</sup>	8.00 × 10 <sup>−1</sup>	1.82 × 10 <sup>−1</sup>	4.65 × 10 <sup>−2</sup>	5.30 × 10 <sup>−5</sup>	2.19 × 10 <sup>3</sup>

**Table 8.** Green Roof System: Resource Consumption Assessment of Input Materials.

Solution	Resource consumption					Net Use of Fresh Water (m <sup>3</sup> )
	TRR (MJ, P.C.I.)	TRNR (MJ, P.C.I.)	MS (kg)	CSR (MJ, P.C.I.)	CSNR (MJ, P.C.I.)	
Green roof system	$7.37 \times 10^2$	$1.42 \times 10^3$	0.00	0.00	0.00	$9.18 \times 10^{-1}$

TRR = total use of renewable primary energy resources; TRNR = total use of non-renewable primary energy resources; MS = use of secondary material; CSR = use of secondary renewable fuels; CSNR = use of non-renewable secondary fuels; Fresh water use = use of net fresh-water value.

**Table 9.** Green Roof System: Possible Outflows.

Waste Type	Reuse	Repair	Recycling	Energy Recovery	Landfill
Earth substrate					X
Filter type Floradrain® FD 25-E					X
Expanded cork agglomerate (ICB)			X	X	
Anti-root waterproofing screen					X

From Table 9, it is possible to see that the ICB have recycling and energy recovery as possible outflows while all other constituent materials can only be sent to landfills now. The acquisition cost to be considered will be the acquisition cost of all the materials that constitute the green roof system, plus the cost of labour and equipment. Thus, the cost of acquiring the green roofing system was assumed to be €215,512.00, this being the cost associated with 2/3 of the total area of intervention, previously identified. The assumed purchase price was obtained by multiplying the area with the cost per m<sup>2</sup> of the solution in the CYPE Price Generator. As there will have to be circulation zones in the roof of CTZ building, the solution assumes that these areas will have slabs that were kept as coating if they were in good condition after inspection.

The maintenance cost (Table 10) is based on the maintenance actions advised by the Green Roofs Technical Guide and the associated costs. For the purposes of calculating the maintenance cost, it was considered that the system has 60 years of useful life. The estimation of the cost of maintaining the existing system per year is €20,601.55.

**Table 10.** Maintenance Cost Calculation: Green Roofing System.

Maintenance Source Element	Maintenance Action	Frequency (Years)	Cost of Action (€)	Life cycle Maintenance Cost of the Action (€)
Vegetation Areas	Visual inspection	1	350.00	21,000.00
Vegetation Areas	Cleaning, cutting, removing dried flowers, and fertilizing	1	4427.79	265,667.52
Vegetation Areas	Scarification and surface treatments (fertilization, use of organic matter, etc.)	2	626.94	18,808.32
Vegetation Areas	Control of weed plants, pests and diseases	2	1175.52	35,265.60
Constructive Elements	Visual inspection	1	350.00	21,000.00
Constructive Elements	Inspection and regulation of irrigation facilities	1	431.02	25,861.44
Constructive Elements	Removal of vegetation in areas without substrate, protection areas without vegetation	1	858.13	51,487.78
Total				1,236,093.22

Within the scope of the environmental assessment, through the standardisation performed for the parameters of environmental impacts and resource consumption, results are shown through radar type graphs to allow an easier and faster comparison between the two competing solutions, according to the previous parameters (Figures 5 and 6), meaning, comparing life cycle impacts of the existing roof system with a green roof system.

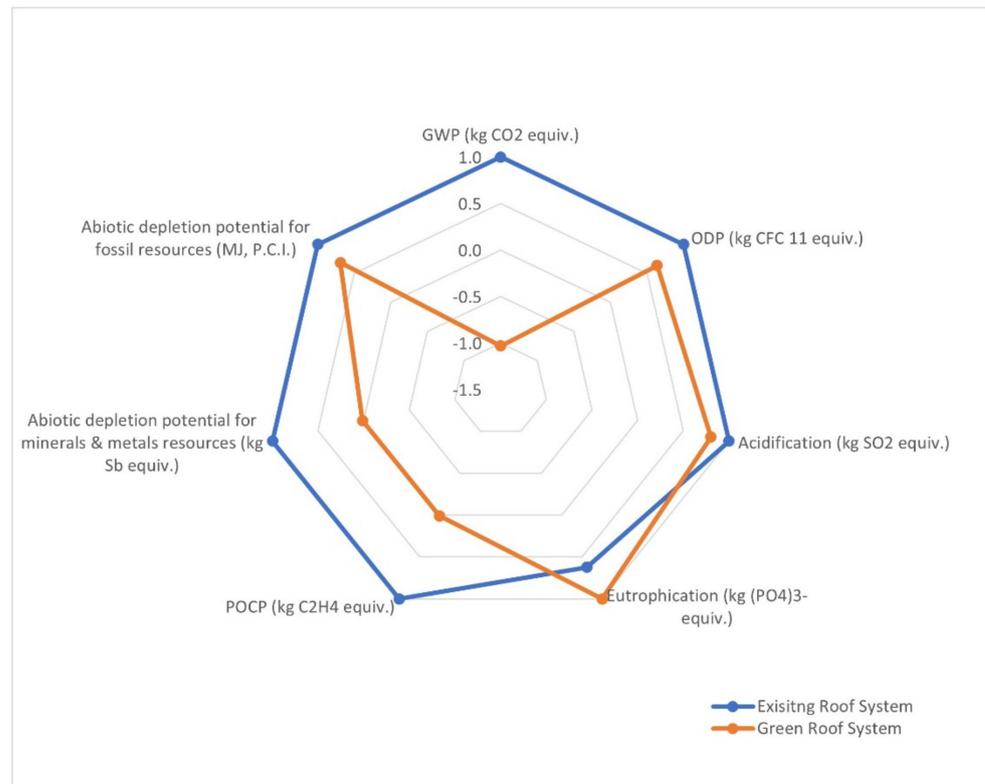


Figure 5. Environmental Impacts Assessment of competing roof solutions.

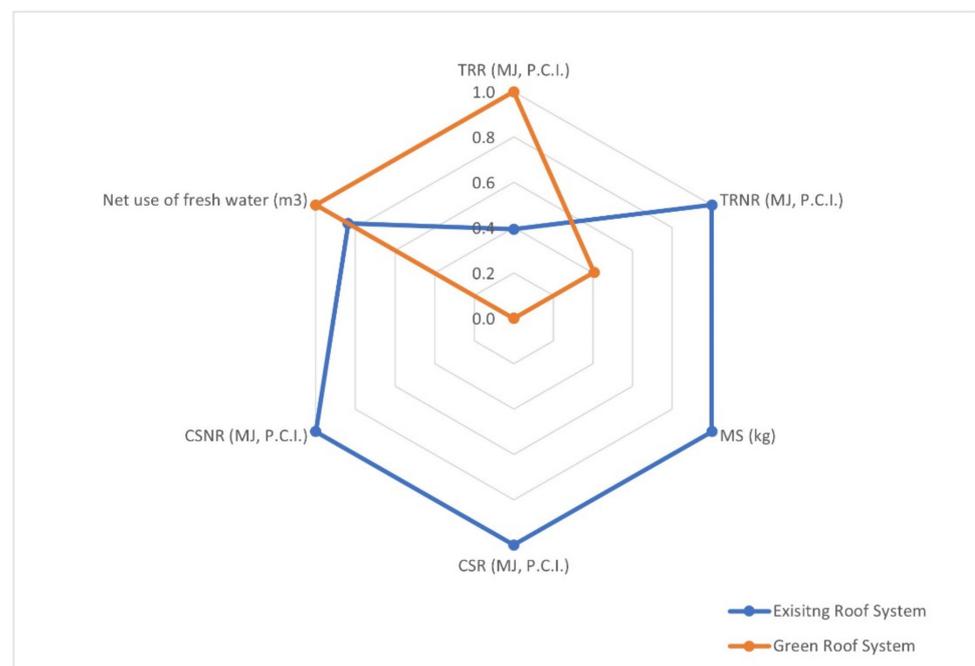
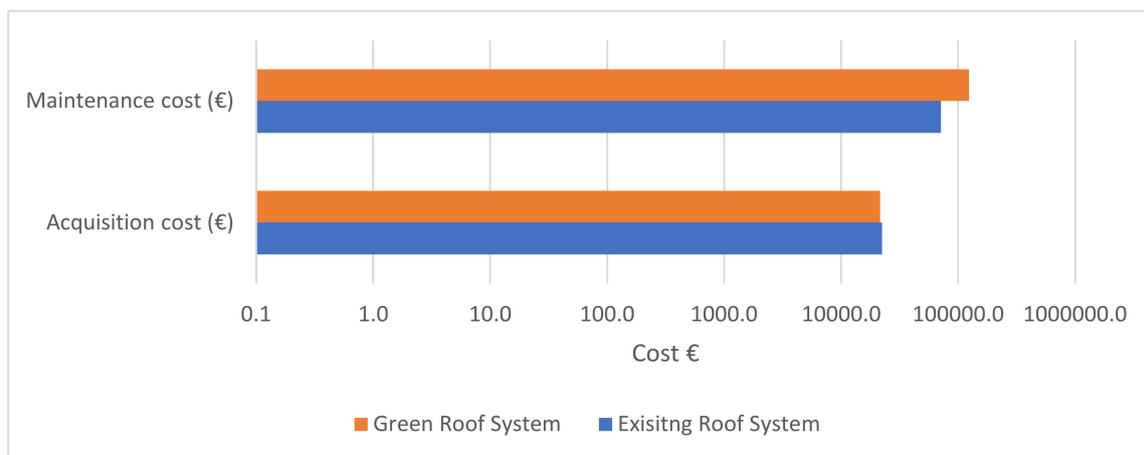


Figure 6. Resource Consumption Assessment of competing roof solutions.

According to the environmental impact (see Figure 5), the existing roofing system has a larger area than the green roofing system; therefore, the solution that contributes the most to the lowest environmental impact will be the green roof system. Regarding the resource consumption (see Figure 6), the existing coverage system also has a larger area compared to the green coverage system area; therefore, the solution that contributes the most to less consumption of resources is also the green roofing system. Nonetheless, it is important to highlight that replacing the existing roof system will produce a larger quantity of waste compared to the solution of maintaining the existing roof system. However, most of the materials that constitute the existing roof system can be reused and/or recycled, thus avoiding landfill disposal, according to the EPDs information of each material.

In the context of economic assessment (see Figure 7), it is possible to conclude that the acquisition cost of the green roof is lower than a new slab, considering that 1/3 of the amount of the existing covering will be used to make the sidewalks on top of the green roof. In terms of maintenance costs, as the green roof will need several gardening actions, its maintenance cost becomes greater than the maintenance cost of the existing roof system.



**Figure 7.** Economic Assessment of competing roof solutions.

## 5. Conclusions

To create more circular design projects, the eco-design tool and methodology was created to support decision-making through the evaluation of the environmental and economic impact of solutions that belong to the same functional categories, integrating circularity concepts. When tested in a case study for validation, this tool showed up to be efficient, in the sense that it provided results on the analysis of several data information, synthesised in graphics that are easily interpreted by the designers. Through the comparison of the competing solutions area of impact, in this case study, it was possible to conclude which was the less impacting solution, and that turned out to be the replacement of the existing roof system for a green roof system. This solution would generate more waste because more materials would be removed but will have less environmental impact and less resource consumption than keeping the existing one. Furthermore, this eco-design tool groups the possible outflows of each material, which can be used in the waste valorisation and management plan.

Regarding the economic assessment carried out in this case study, it was possible to conclude that implementing a green roof system would have less cost than replacing the existing roof finishing, although the maintenance cost of the green roof system would be higher because of the gardening works needed, but no maintenance actions are needed in comparison with the existing system.

Once again, it is important to highlight that this eco-design tool only gives information regarding the economic and environmental impact, so that designers can make a choice based on circularity and sustainability concepts and use a life cycle approach. In the

end, the eco-design tool that was developed and tested can be easily implemented in any project analysis, not giving the designer much more work than usual and not being time-consuming, but simultaneously it changes the project methodology perspective, making it more circular and sustainable. The lack of automatization in the process of gathering the EPDs/LCA information is still a limiting factor but the increasing number of digital EPDs together with BIM approaches may in the future facilitate the work with the eco-design tool. Regarding future work, this methodology will be tested and applied in the refurbishment of five other buildings at the University of Aveiro Campus, so it will be possible to validate in a much larger scale what will allow us to recognize its drawbacks and to improve its functionalities.

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