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Environmental Impacts and Benefits of the End-of-Life of Building Materials: Database to Support Decision Making and Contribute to Circularity

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Abstract: This paper outlines a methodology for structuring a generic database of environmental impacts on the end-of-life phase of buildings, which can be used at the national level, in accordance with European standards. A number of different options are also considered for managing construction and demolition waste (CDW), as well as for promoting the circularity of materials in construction. The database structure has been developed for use by the main stakeholders who decide the disposal scenario for the main CDW flows, assess waste management plans, and identify the corresponding environmental aspects. The impact categories considered in this paper are global warming potential (GWP) and the abiotic depletion potential of fossil fuels (ADP (f.f.)). This lifecycle assessment (LCA) database further facilitates the identification of important information, such as possible treatments for CDW, or suppliers of recycled materials for use in new construction. Two demolition case studies were used to confirm the benefits of the proposed database. Two demolition scenarios are assessed—traditional and selective—in order to demonstrate the advantage of selective demolition in waste management. The results obtained from the environmental assessment of CDW flows demonstrate that the proposed database can be an important and useful tool for decision making about the end-of-life of construction materials, as it is designed to maximize their reuse and recycling. An innovative online platform can be created based on this database, contributing to the reduction of the environmental impacts associated with the end-of-life phase of buildings.

Keywords: CDW; circularity; end-of-life phase of buildings; environmental impacts

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1. Introduction

The construction sector is responsible for important environmental impacts, including energy consumption, the emission of atmospheric pollutants, and the generation of waste [1,2].

The construction and demolition waste (CDW) that is generated at building sites is one of the most significant sources of waste in the world [3]. This is mainly due to the significant volume of waste generated, but also because of the hazardous nature of that waste. Potential environmental concerns arise from the inadequate treatment of waste, such as the contamination of soil and water resources, and uncontrolled landfills, which lead to a loss of resources due to the disposal of waste without the recovery of material and energy [3,4]. Therefore, CDW management is a sector where investment must be prioritized in order to promote sustainability [5–7]. For both environmental and economic reasons, the deconstruction of buildings at the end of their service life is gradually gaining importance in the demolition market, with the possibility of material recovery, reuse, and recycling, and for improving and transforming waste management into sustainable materials management [8]. Such treatment at the end-of-life phase of buildings of the materials that can be recovered promotes a circular economy in the construction sector, a more efficient use of natural resources, and the reduction of waste generation [9]. The introduction of these circular economy principles must be associated with the creation of new patterns of production and consumption, and with new strategies for saving energy.

Over the last two decades, the lifecycle assessment (LCA) approach has been used as the principal method for identifying and assessing the environmental impacts [2,10,11] of buildings. Many LCA studies have been undertaken, but most do not include an in-depth analysis of the end-of-life phase.

The main goal of this study is to develop and present a generic database of the environmental impacts of the end-of-life phase of buildings, with a consideration of the most important CDW flows and the promotion of their reuse or recycling. The database is designed for the Portuguese context and considers the two main alternatives, traditional demolition and deconstruction: this includes transport, recycling, incineration with energy recovery, and sending CDW to landfill.

Through this methodology, it is possible to make a comparative environmental impact analysis of the different options in CDW management. The proposed database is designed to be used by multiple stakeholders in the construction sector: for example, designers, construction companies, building owners, and CDW operators. The aim is to facilitate synergetic interaction between these actors and promote the adoption of the best practices in CDW management.

This paper is organized into six sections, including this introduction. Section 2 includes a literature review of previous studies on the assessment of the end-of-life phase, an analysis of the most important CDW flows, a review of the circularity of construction, and an assessment of the relevance of the proposed database in the national context. Section 3 describes the database methodology. Section 4 summarizes the development of the proposed database. Section 5 presents cases studies on the application of the database to confirm its benefits. Finally, the conclusion summarizes the advantages of this generic database.

2. Literature Review

LCA is a methodology that serves to assess the potential environmental impacts of a given system or product, considering energy and reagent consumption, as well as emissions, throughout its whole lifecycle [3]. Although the standards in force in Europe, EN 15804:2012+A2:2019 and EN 15978 [12,13], already define the different phases of a building's lifecycle, it is difficult to find studies that include all stages, and in particular the end-of-life stage. This is because the high level of uncertainty in the processes that will be used to dismantle buildings in the distant future makes outcomes difficult to predict [14–17], with a lack of data on the demolition, recovery, and recycling of materials [14]. Without information on the end-of-life phase of construction products, neither alternative impacts nor the end-of-service life of buildings can be accurately modelled, which makes the planning of recyclable and eco-efficient construction work complicated [18].

There is no doubt that CDW is a real problem, given that it represents 36% of the waste generated by economic and domestic activities in the European Union [19]. For this reason, the European Union has published directives that promote the efficiency and the rationality of the use of natural resources in order to reduce environmental impacts, particularly the emissions of greenhouse gases. To make the economy truly circular, it is necessary to take additional measures to achieve sustainable production and consumption, focusing on the entire lifecycle of products in order to preserve resources and close the whole cycle [7]. Some of the latest studies published on the end-of-life stage of buildings assess the impact of waste management. The goal of these studies was to evaluate the environmental impacts related to this phase of CDW in order to assess the best disposal or recovery scenarios given the quality of the waste materials, and to promote the circularity of construction [1,3]. Circular economy policies emphasize just how important end-of-life decisions about buildings are, and highlight the need for proper and careful modelling of this stage. In the construction sector, the main action that promotes the circular economy approach is the management of CDW as secondary material in order to avoid the extraction of raw materials and the disposal of waste in landfills [9]. European Union Directive 2008/98/EC [20] establishes a target for approximately 70% of CDW to be reused or recycled, making the disposal of 100% of demolition waste no longer possible in the European Union.

Recent European standards [12,13] define an end-of-life phase (C stage) and a supplementary LCA information module D, designated 'benefits and loads beyond the system boundary', which occur after the end of the service life of construction materials. The assessment of this stage should include the net impact and benefits related with the 3R potential (reuse, recovery and/or recycling) of CDW and other waste flows [15]. A construction product reaches its end-of-life phase when it is replaced, deconstructed, or dismantled from a building, and does not provide any additional functionality [15]. Depending on the product's end-of-life scenario, it can also occur at the end of a building's service life. Initially, all outputs in this phase are considered to be waste. This condition is changed when these outputs reach the 'end-of-waste state', i.e., the waste reaches the status of product or secondary raw material [13]. This state is achieved when there is a specific purpose and a market or a demand for such material, complying with the technical requirements for the specific purpose and meeting the legislative standards ([20], cited by [15]).

The environmental impact of a building's lifecycle has been recently studied by several authors [21–23]. The lack of environmental information with respect to demolition and deconstruction operations leads to the use of traditional demolition in most cases: it is the most common practice in Portugal. It is also the fastest approach, with financial costs being the easiest to justify [24]. Consequently, the level of circularity in the construction sector in Portugal is still low, although it does have great potential [25]. According to Martínez et al. [26], the selective demolition scenario is characterized by the separation of some waste into mono-materials that have great recovery potential. It must be designed, however, to take into account the pre-treatment processes required to increase their recovery potential, and the final disposal of waste that cannot be recovered. On the other hand, Martínez et al. [26] observe that most waste cannot be recovered in traditional demolition due to technical or economic constraints, and as a result it is sent to landfill. Selective demolition requires waste separation, which maximizes the reuse and the recycling of demolition waste and minimizes landfill operations. Martinez et al. conclude that incentives are needed to make selective demolition more attractive, e.g., by waste operators linking the price of disposal services to the purity of the aggregates delivered to their plants [8].

Several research studies have been conducted on selective deconstruction, including assessments of environmental and economic benefits [1,8,23,24,26]. Most of these studies concluded that the transportation of demolition waste for recycling operations and the transportation of non-recyclable waste to final disposal both play an important role in the selection of the demolition approach. [27]. Coelho and de Brito [24] stated that there are environmental benefits to core material separation in demolition operations and their recycling/reuse.

For all these reasons, LCA databases for assessing and comparing the environmental impacts of different demolition scenarios should be used to support stakeholder's decision making, thus facilitating the formulation of waste management plans at the design stage [26].

3. Methodology

As already mentioned, several databases for the calculation of an LCA for buildings are in use, but none are exclusively focused on the assessment of the environmental impacts of CDW at the end-of-life phase of buildings. The methodology proposed within this paper for the development of such a database relies on the concept of the circular economy, with the aim of contributing to the valorization of CDW and the prevention of the depletion of natural resources: these both reduce the environmental impacts associated with the end-of-life phase of buildings.

In order to develop a database, it is first of all necessary to define the goal and scope, then to define a system limit and a declared unit, and then to develop the detailed structure of the database.

The database proposed by this paper consists of static and dynamic data integrated into an online platform, which results in an interactive platform. The online platform is initially fed by a static database, which includes information of 'CDW' type, the valorization processes, and the calculation rules for environmental impact indicators present in the literature, which correspond to the back office of this platform. A dynamic database is produced through the introduction of data by users, with the location of the CDW, the quantity by type, the recovery processes, and the associated environmental impact. This will provide benefits for both stakeholders and the general community. This collective data integration will promote behavioural change that decreases the environmental impact associated with the end-of-life of buildings. This section describes the database audience and the methods used for environmental impact assessment. The methodology is organized in different steps, as shown in Figure 1.

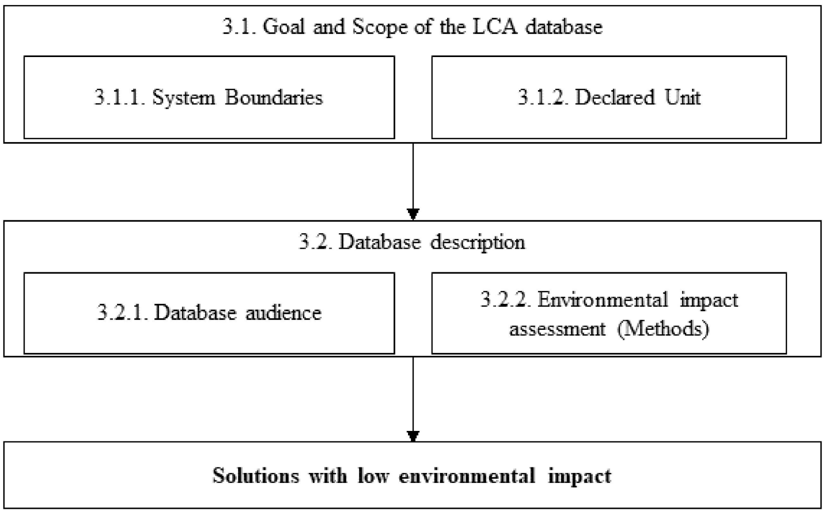

Figure 1. Database methodology flowchart.

3.1. Goal and Scope Definition

The definition of our goals and scope establishes the overall objectives of the LCA, and must be agreed before its application. As previously mentioned, the main goals of this study are to propose an LCA database to be applied in the context of the Portuguese CDW's market, and to identify the variables of the demolition process that significantly affect the environment. The LCA database is based on the relevant information required to undertake an environmental assessment at the end of a building's lifecycle, and aims to provide accessible information on the CDW market, thus helping the stakeholders in their decision-making process. This database also contributes to the correct assessment of the waste generated at the end-of-life of a building for both traditional and selective demolition scenarios, and presents alternatives for the recovery of that waste. This paper also intends to demonstrate the advantages of using this type of LCA database in maximizing the reuse and recycling of CDW (see Section 5).

First, it is necessary to design the database by defining the most relevant information. Data are collected regarding the most common wastes from the end-of-life phase of buildings, and identified using the European waste codes (EWC) and the possible recovery processes, in line with Directive 2008/98/EC [20].

Depending on the demolition scenario, different management routes for CDW can be analysed according to their potential for direct reuse, treatment feasibility and subsequent recycling, or final disposal. The associated environmental impact will be determined for each valorization process, namely the global warming potential (GWP) and the abiotic depletion potential of fossil fuels (ADP (f.f.)). With this analysis, several alternatives can be assessed, and the one with the lowest environmental impact can be selected.

The system boundaries and declared unit are defined next.

3.1.1. System Boundaries

To establish the system boundaries, all lifecycle phases to be included in the assessment need to be defined [28]. According to EN 15978 [12] the end-of-life of the system under study (a building) comprises several stages:

(i) selective demolition process (deconstruction) or the traditional demolition of building components;
(ii) collection of construction waste and on-site sorting process;
(iii) transport to the treatment plant for recycling/recovery processes or transport of mobile recycling plants; and/or
(iv) disposal of waste to landfill [27].

This methodology focuses on the building's end-of-life phase (stages C1–C4) and on the benefits beyond the boundary system (module D). The boundaries of the system under study are shown in Figure 2.

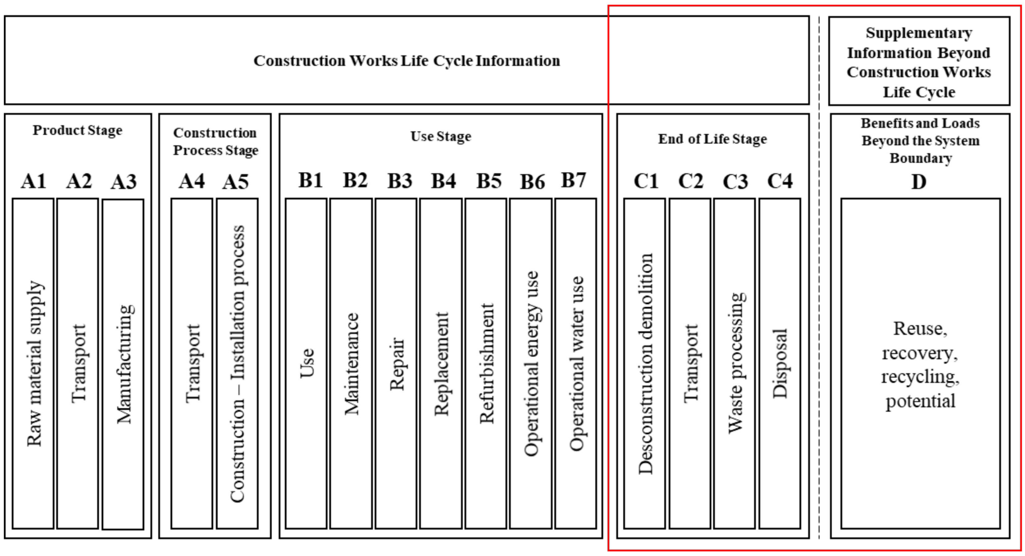

Figure 2. Lifecycle stages (proposed in [13])—definition of system boundaries.

3.1.2. Declared Unit

According to EN 15804+A2:2019 [13], a construction product can have several functions. Depending on the scope and goal, an environmental product declaration (EPD) can be related to a specific function, using a functional unit, or it may cover a range of functionalities, using a declared unit.

A declared unit is defined as the quantity of a construction product intended for use as a reference unit in an EPD [13]. The declared unit should be applied when a functional unit cannot be defined, e.g., when the function of the product cannot be described or when the precise function of the product is not declared or is unknown [13,18].

In studies that only consider the management of CDW in the end-of-life phase, a declared unit is considered instead of a functional unit when accounting for the impacts of the waste generated in demolitions activities. This unit expresses the waste generated in weight (kg or ton) to assess the environmental impacts of the various scenarios considered in management [1,3]. In the LCA database herein presented, the declared unit will be expressed in kg of waste.

3.2. Database Description

We intend to develop a public LCA database, for different types of users, in line with the objectives of the methodology presented here. The CDW consumer can also be a supplier, providing information to the database about the type/amount of CDW generated and/or if they want to acquire some type of CDW. As a result, a dynamic database for stakeholders and a CDW marketplace are generated. A description of the stakeholders and of the impact assessment method is set out below.

3.2.1. Database Audience

The dynamic database presented here is developed for a target audience which consists of all of the main construction stakeholders, including building designers, construction companies, building owners, and waste operators. By being so inclusive, it promotes transparent communication between these actors, making it possible to compare information on the environmental impact of CDW, and to demonstrate to key users the quantifiable benefits of their correct management. This approach allows each user to assess how they weight environmental impacts in their decision-making process. With updated information and georeferencing, this database helps the user access in real time and with up-to-date locations information on where they can acquire CDW for use in construction (as a consumer), or where to send it for treatment or landfill (as a waste generator).

In the database development, the audience is divided into three types of users: consumers, generators, and CDW operators. Inputs and outputs are different for each profile, as described in Table 1. They are essentially focused on: (i) the CDW's type, produced or requested (identified by the EWC); (ii) the identification of the recovery processes, used or available for use, according to Directive 2008/98/EC [20]; and (iii) the environmental impacts associated with user's choice—GWP or ADP (f.f.).

Table 1. Inputs/outputs from CDW generators, consumers, and operators.

User Profile	Decision Maker	Input	Output
CDW generator	• Designers • Construction companies • Building owners	• Location of CDW (demolition site) • Demolition scenario (traditional or selective) • Type of CDW generated • Quantity of CDW generated	• CDW description (information data) • Possibility of disposal for CDW • Associated environmental impact according to chosen destination (presented according to the associated activities: demolition scenario, transport, processing, avoided impact, and total impact)
CDW consumer	• Designers • Construction companies • Building owners	• Location of construction site that requires CDW • CDW type required, according to EWC • Quantity of CDW required	• CDW description (information data) • Location of existing CDW, with distance information • Quantity of existing CDW in each location • Info of the company that owns the CDW • Associated environmental impact according to the chosen company (presented according to the associated activities: transport, processing, and total impact)
CDW operator	• Operator as CDW supplier	• Type of stored CDW • Quantity of stored CDW • Recovery operations associated with CDW	• Associated environmental impact according to the associated activities of processing
	• Operator as CDW consumer	• Type of CDW required	• Location of demolition sites generating the CDW required • Distance from the identified demolition sites • CDW description • Associated environmental impact according to chosen demolition site (presented according to the associated activities: demolition scenario, transport, processing, avoided impact, and total impact)

3.2.2. Environmental Impact Assessment—Methods

For the assessment of environmental impacts, it is necessary to evaluate three activities associated with the recovery of CDW from the end-of-life phase of a building, namely:

(i) the type of demolition carried out;
(ii) the transport;
(iii) and the processing that the CDW undergoes, including a consideration of the environmental impact avoided by the use of these secondary materials.

The building's end-of-life stage should be studied in detail, and its environmental impacts and its 3R potential in particular. Even when one cannot be sure about the impacts avoided at this stage, their estimated quantification in this analysis is still important to ensure that the 'disassembly design' approach is rewarded ([29], cited by [15]). Through a specific 3R allocation procedure, European standards show the impacts that module D can have in LCA studies, by considering the potential benefits of avoiding the use of primary materials and the loads associated with the processes of recycling and recovery. The calculation of the net impacts related to this procedure follows these steps [13]:

- Calculation of the net output streams of secondary material from the product system: adding all output streams and subtracting all input streams of this type in each substage (C1 and C4), followed by the total calculation in stage C, and finally, the total of the product system;
- Calculation of impacts and potential benefits related to the processing of the net outflows calculated in the previous step: adding the impacts of the recycling and recovery processes beyond the boundary system limit (stage D), i.e., after the end-of-waste state, to the point of functional equivalence ('when secondary material or energy replaces primary production'), and subtracting the impacts related to 'substituting product production or generating energy from primary sources';
- Applying a justified value correction factor (to reflect the difference in functional equivalence when the output stream 'does not reach the functional equivalence of the replacement process').

The environmental impact of waste recycling (Ir) and transport (It) can be represented as: Ir + It (attributed to C2 and C3, respectively).

This operation avoids the impacts of the production of a similar new product (In—potential benefit in module D) and the impacts from waste treatment (Iw). Therefore, recycling should only be promoted if (Ir + It) < (In + Iw) because it will avoid an impact corresponding to (In + Iw – Ir – It). If the option is not to recycle, Iw must be included in the C4 substage.

The methodology used in this calculation should avoid double counting the recycling benefit ([29], cited by [15]). If recycling rates for the production and end-of-life stages are defined as rp and re, respectively, and Nf represents the net outflows, the '3R allocation procedure' defined in the European standard [15] can account for a reduction in environmental impacts. This reduction can be represented by three individual amounts ([15], adapted from [29]):

- (rp.(In-Ir)) at substage A1 (includes secondary material input processing and recycling processes). Only the impact of Ir is considered for the amount of secondary material used;
- (re.(Iw-It)), expressed by a reduced environmental impact (re.It instead of re.Iw), in the production system phase where the waste flow occurs;
- ((In-Ir) for Nf), this impact reduction being considered as impacts and benefits in module D, when recycling occurs after the end-of-waste state.

In conclusion, according to the literature [15,29,30], three important criteria were considered in the LCA calculation rules: reward the use of recycled products in the construction phase, reward the waste separation and subsequent recycling, and avoid double counting the benefits of recycling.

4. Database Development

As already mentioned, the proposed database includes static data, introduced in the back office of the online platform, and dynamic data resulting from its use. This use begins with the user—either a generator, consumer, or CDW operator—who introduces the requested data to achieve the intended objective, which can then be consulted by all users. After filling in the input data, the results are presented, along with the respective environmental impacts (Figure 3).

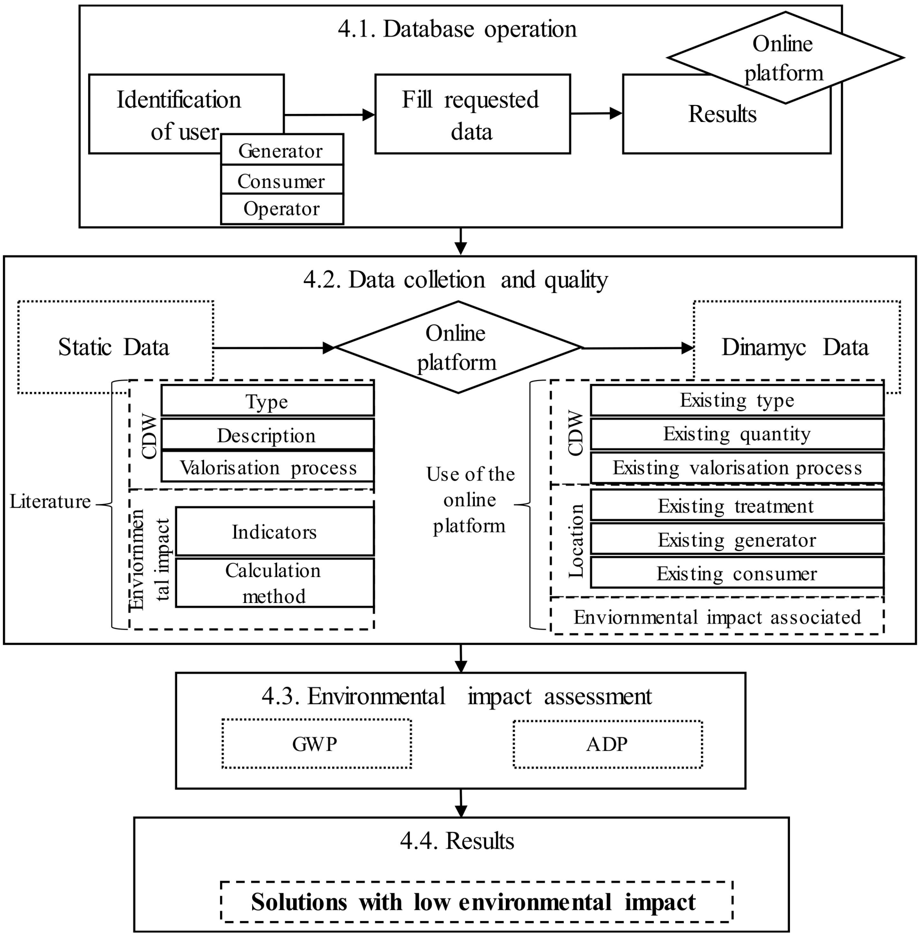

Figure 3. Database operating methodology.

This database aims to collect and gather information on the production of CDW (as outlined by the EWC) by quantifying and locating them in order to promote their use. Several valorization possibilities are presented, using the codification present in Directive 2008/98/EC [20]. The environmental impacts at the end-of-life phase of buildings associated with the production, use, recovery processes, transport, and disposal of CDW, namely the GWP and the ADP (f.f.), are then calculated. The CDW's production, storage, and usage locations will be georeferenced in order to promote the reduction of the environmental impact associated with transport, in particular the use or storage of waste closer to its production.

4.1. Database Operation

In this section, the functioning of the online platform that is supported by the database that we have developed will be described. This includes all of the operations which must be completed by the user, and in particular its registration. To access the online platform, it is necessary to register the user (U1) on the home page (U). This record consists of the identification of the type of user (designer, builder, owner, or CDW operator) (U1.1), their

TIN (U1.2), their address (U1.3), and the definition of the login elements (e-mail (U2.1) and password (U2.2)). In the case of the waste operator, a new window will open with a request for confirmation of the services that they perform (U1.1D). The platform manager validates all registrations and give access to the corresponding functionalities according to the type of user. Designers, contractors, and construction owners will have access to the Generator (B) and Consumer (C) profiles, while waste operators will have access to the Operator page (D). In the case of users who are already registered, access to the database requires that they log in (U2) using the email (U2.1) and password (U2.2) that were already defined during their registration (Figure 4).

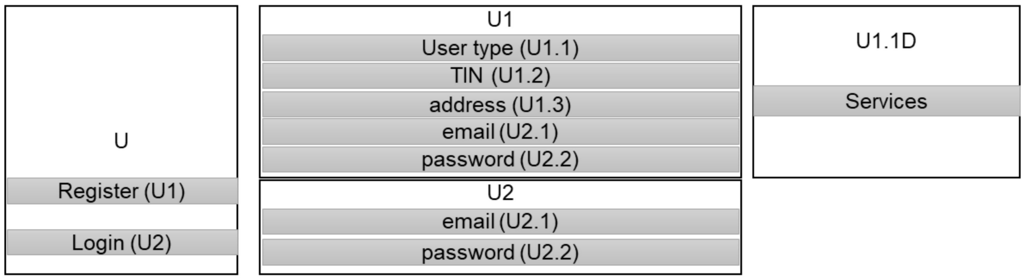

Figure 4. Online platform preview for user registration/login.

On the homepage (A) of the database, users must select one of the following options: (i) Generator (B), (ii) Consumer (C), or (iii) Operator (D). Depending on the option chosen, different pages will open with different inputs and outputs.

In the case of the generator profile (B), two options are given: create demolition work (B1), or—for users who have already created a demolition task in the database—edit demolition work (B2). After selecting the option to create demolition work (B1), a new page opens, where the user fills in the location (B1.1), the demolition scenario, whether the demolition is traditional or deconstructive (B1.2), and the type (B1.3) and the quantity (B1.4) of generated CDW. After selecting the option to edit work (B2), a new page opens, where the user chooses the demolition work where the CDW is being generated (B2.1). The user must then select the type of waste-generating activity, i.e., traditional demolition or deconstruction (B2.2), and the type (B2.3) and the quantity (B2.4) of generated CDW. From the information provided by the user, the description of the CDW (E1), the possible destinations (E2), and the corresponding environmental impacts (E3) are presented. The environmental impacts are quantified through GWP and ADP (f.f.) indicators and associated with the type of demolition (E3.1), transport for treatment plant (E3.2), processing of CDW (E3.3), avoided impact (E3.4), and total environmental impact (E3.5) (Figure 5).

In the consumer profile (C), the same options are also given: create work (C1) or edit work (C2). After selecting the option to create work (C1), a new page opens, and the user fills in the location (C1.1), the type of CDW required (C1.2), and the quantity (C1.3). After selecting the option edit work (C2), a new page opens, where the user chooses the work where the CDW are being generated (C2.1). Then the user fills in the required CDW type (C2.2) and quantity (C2.3). From the information provided by the user, a new page (F) opens, where the following information is shown: i) the description of the required and available CDW (F1), ii) the location of existing CDW (F2), iii) the amount of existing CDW (F3), iv) the information about the company holding CDW, including all available services (F4), and v) the environmental impacts (F5) associated with processing (F5.1), transport to the consumer location (F5.2), and the total impact (F5.3). Additionally in this case, the environmental impact is provided through the GWP and ADP (f.f.) indicators (Figure 6).

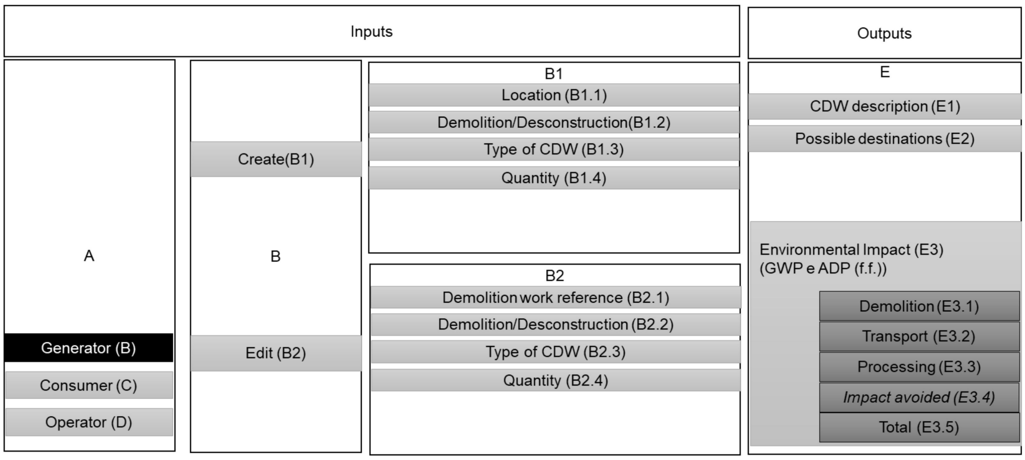

Figure 5. Online platform preview for the CDW generator profile.

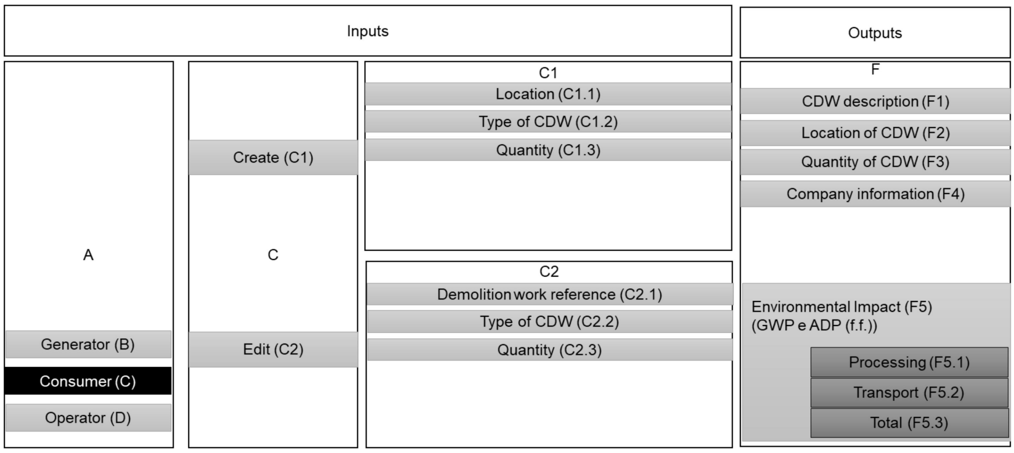

Figure 6. Online platform preview for the CDW consumer profile.

For the operator profile (D), two alternatives can be chosen: a treated CDW supplier (D1), or a CDW consumer for treatment (D2). After selecting the supply option (D1), a new page opens, where the user indicates the type of CDW owned (D1.1.), the quantity (D1.2), and the recovery processes that it has already been subjected to (D1.3). After filling in the requested information, the environmental impact (G1) associated with processing and the total environmental impact (G1.1) is provided, based on the GWP and ADP (f.f.) metrics. When the user wants to acquire CDW (D2), the CDW type (D2.1) should be provided. Then the location of the demolition works or other treatment sites (H1) that are generating these CDW, the distance (H2), the description of the CDW (H3), the environmental impact (H4) associated with the demolition process (or if it comes from a demolition site, H4.1), the transport undertaken from the supplier to the consumer/operator (H4.2), processing information (if it comes from another operator, H4.3), the impact avoided (H4.4), and the total impact (H4.5) are shown (Figure 7).

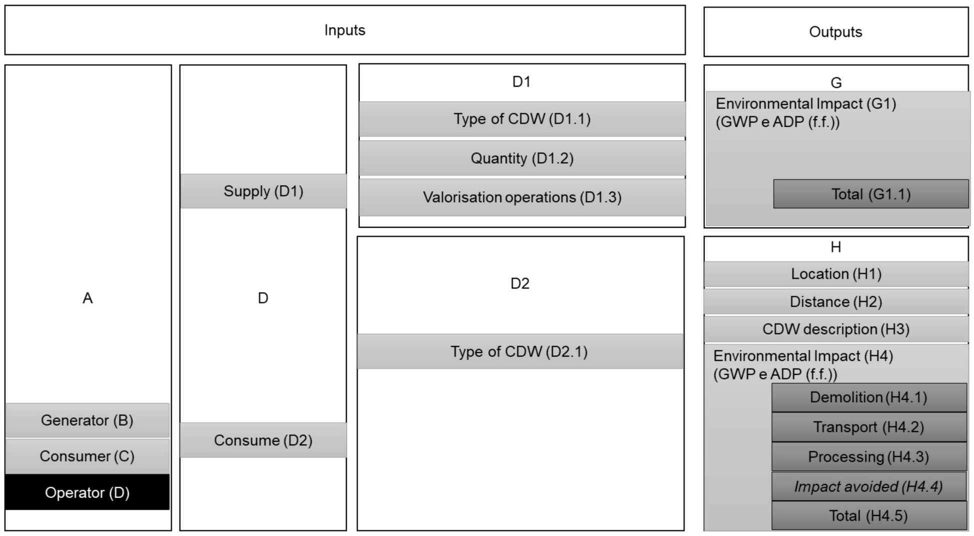

Figure 7. Online platform preview for the CDW operator profile.

On all pages referring to data entry there will be an option to "make data public", which the user must accept to give permission. If the user is looking for a certain type and quantity of CDW which is not available at that time, a window will appear asking if the user wants to receive notifications about the availability of the searched CDW.

4.2. Data Collection and Quality

After defining the types of waste, demolition scenarios, and environmental indicators to be evaluated, data must be collected. Data used in this work comes from generic databases and literature sources. For a given type of waste, it may be possible to find several different processes, representing the same general material in different products. Moreover, the same product can be related to different geographic areas, which highly influences the environmental impacts of each material [25]. It is therefore important to use a scientifically based method to select the most adequate dataset for each CDW for the Portuguese case [2]. With this information, the impacts of the main CDW management processes can be gathered and calculated.

For the database presented here, the European Waste Codes (EWC) are used to identify the type of CDW, where the different types of waste are fully defined by a six-digit code, and the valorization processes (disposal operations (D) and recovery operations (R)) follow Directive 2008/98/EC [20], except for some additional ones (e.g., onsite reuse).

Two indicators were collected to represent the environmental impacts (GWP and ADP (f.f.)) for each of the processes to be considered, which include CDW transport, sorting plant, recycling, incineration, and landfill. In addition, the impacts associated with the type of demolition (selective or traditional) were considered. For CDW transport, the distance to recycling and/or landfill must be calculated according to the location of the waste operators registered in the database. Since CDW is expresses in kilogram (kg), the transported volumes are calculated based on "loose" material densities, collected from Coelho and de Brito [24] and Silvestre et al. [15].

4.3. Environmental Impact Assessment—Indicators

In this database, the environmental impact is presented using the GWP (kg CO_2 eq.), belonging to the climate change (total) category, and ADP (f.f.) (MJ), from the depletion of abiotic resources (fossil fuels) category. These indicators represent the carbon footprint and embodied energy, respectively, and are considered to be the most important in terms of environmental impact assessment at the end-of-life phase of buildings, since the decarbonization of the building is a priority in Europe and the construction and retrofit of buildings results in a significant consumption of energy [31,32]. Therefore, these indicators provide a good basis for decision making.

The environmental impacts of the demolition/end-of-life of the product were quantified using the generic impacts obtained through the Ecoinvent database [33]. These represent average European values. The unit values of the traditional demolition impacts were collected from Coelho and de Brito [24] and Martínez et al. [26]. The method used is EC-JRC, as referred to in EN 15804+A2:2019 [13], using SimaPro software. The total GWP is the sum of three subcategories of climate change [13]:

- GWP (fossil)—This indicator accounts for GWP from greenhouse gas (GHG) emissions and removals from any process that involves oxidation or the reduction of fossil fuels, or emissions from materials containing fossil carbon through their transformation or degradation (e.g., combustion, incineration, landfilling, etc.). This indicator also accounts for GWP from GHG emissions, e.g., from peat and calcination, as well as GHG removals, e.g., from the carbonation of cement-based materials and lime;
- GWP (biogenic)—This indicator accounts for GWP from the transformation of CO_2 into biomass from all sources except native forests, because the transfer of carbon, sequestered by living biomass, from nature into the product system is declared as GWP (biogenic). This indicator also accounts for GWP from transfers of any biogenic carbon from previous product systems into the product system under study. This indicator also covers biogenic emissions into the air from biomass from all sources except native forests due to oxidation or degradation (e.g., combustion, solid waste disposal) as well as all transfers of biogenic carbon from biomass from all sources except native forests into subsequent product systems in the form of biogenic CO_2;
- GWP (luluc)—This indicator accounts for GHG emissions and removals (CO_2, CO, and CH4) originating from changes in the defined carbon stocks caused by land use and land use changes associated with the declared/functional unit. This indicator includes biogenic carbon exchanges resulting, e.g., from deforestation or other soil activities (including soil carbon emissions). For native forests, all related CO_2 emissions are included and modelled under this subcategory (including connected soil emissions, products derived from native forest, and residues). CO_2 uptake related to the carbon content of biomass entering the product system from native forests is set to zero. Impacts are declared in the modules where they occur.

The indicators are calculated for the different stages, taking into account the processes involved, the declared unit, and the type of CDW generated.

4.4. Results

The database presented here allows the assessment, in terms of environmental impact, of various types of treatment of CDW from the end-of-life of buildings, enhancing their use as a raw material. The environmental impact assessment is carried out using the two indicators already mentioned (GWP and ADP (f.f.)) for the different processes associated with each treatment possibility, which allows the user to choose the type of treatment with the least environmental impact. This will lead to the reduction of the environmental impact associated with the end-of-life of buildings, and will also promote a reduction of the extraction of natural resources through the presentation of recovery possibilities, such as the recycling and reuse of various CDW. As a result, less of these materials will go to landfill, helping attain the goals defined by the European Union in Directive 2008/98/EC [20]. In environmental terms, the database also demonstrates the benefits of opting for selective demolition instead of traditional demolition in order to increase the possibility of recovering CDW from the end-of-life of buildings.

The use of this database promotes the C2C (cradle to cradle) perspective on the lifecycle of building materials, maximizing their environmental performance and supporting the circular economy. The upcycling of CDW is also promoted, by transforming a cost (when disposing in a landfill) into a potential source of revenue (when recycling and/or reusing) after they have reached the end of their lifecycle. In summary, this database will help achieve sustainability in the construction sector by promoting the circularity of CDW and reducing the environmental impacts associated with the end-of-life phase of buildings.

5. Case Studies

After developing the methodology and structure for the database, it is necessary to confirm the benefits of using it. This section presents the practical application of the database in two different case studies: (i) the rehabilitation of a primary school, with the goal of promoting sustainability by reducing the environmental impact associated with the management of the CDW generated by the rehabilitation activities; and (ii) the end-of-life of a manufacturer's precast walls ('pre-wall' system), in order to assess the potential optimization of this solution in the design/production phase, and the future impacts at the end of its service life. In the case of both studies, only fixed treatment plants were considered.

5.1. Sustainable Rehabilitation

This case study looks at the rehabilitation of an old primary school located in Coimbra, Portugal, where the following CDW was expected to be generated:

- 170101: Concrete;
- 170107: Mixtures of concrete, bricks, tiles, and ceramics other than those mentioned in 170106;
- 170201: Wood;
- 170405: Iron and steel;
- 170802: Gypsum-based construction materials other than those mentioned in 170801.

In the design phase, the elimination of CDW with the codes 170101, 170107, and 170802, as well as the valorization of the CDW 170201 and 170405, is forecast, with no provision for recycling of any waste generated (Table 2).

Table 2. Forecast of the production of CDW in the rehabilitation activities of a primary school.

EWC	Quantity Produced (kg)	Quantity Produced (%)	Recycling Amount (%)	Recycling Operation	Recovery Amount (%)	Recovery Operations	Disposal Amount (%)	Disposal Operation
170101	37,500	29.6	0	Not applicable	0	Not applicable	100	D1
170107	14,000	11.0	0	Not applicable	0	Not applicable	100	D1
170201	4500	3.5	0	Not applicable	100	R1	0	Not applicable
170405	900	0.7	0	Not applicable	100	R4	0	Not applicable
170802	70,000	55.2	0	Not applicable	0	Not applicable	100	D1

R1—Use as fuel; R4—Metal recycling/reclaim; D1—Landfill.

The database outlines several waste-reception sites, different operations that can be carried out, and the impacts associated with each option. The user would choose the generator profile (B), and the option to create (B1) or edit work (B2). Then, the user would enter the location of the building (B1.1), the type of demolition performed (B1.2), the generated CDW code (B1.3), and the respective quantity of CDW (B1.4). After completing page B1, the user will be presented with a description corresponding to the CDW code (E1), a list with the possible destinations (E2), and with general information about the company, the location, and the possible recovery operations for this CDW. For each identified destination, the environmental impacts associated with the type of demolition, transport, and processing is presented, as well as the avoided and total impact. The options would be listed in ascending order, depending on the associated environmental impact. Figure 8 shows the final layout of the database (inputs) and the respective outputs, for the example of concrete (170101).

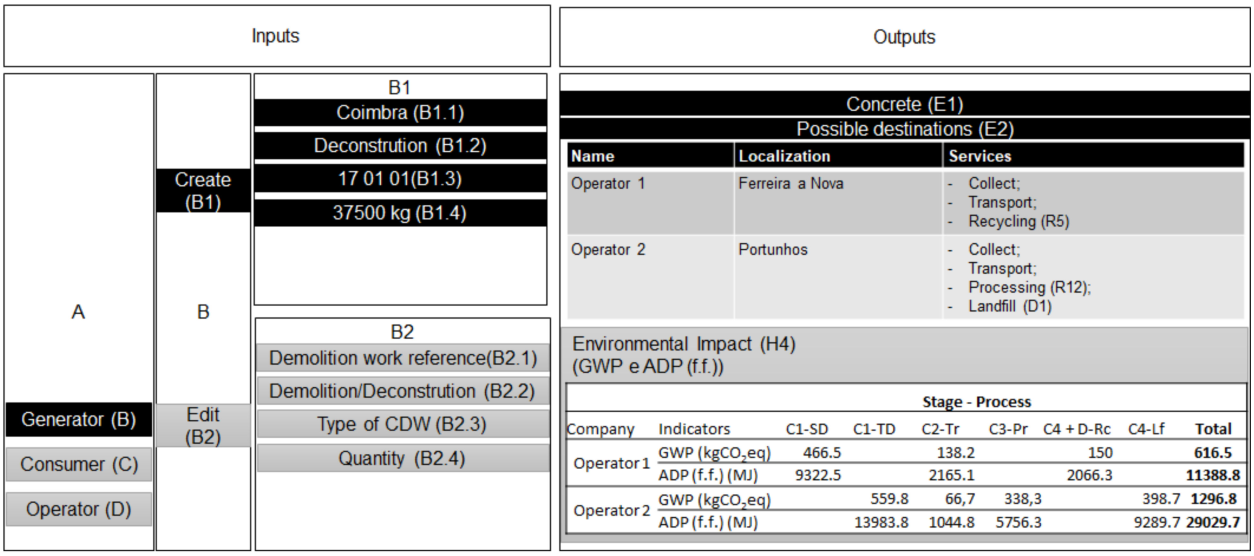

Figure 8. Example of filling the database with input and output, referring to waste 170101—Rehabilitation case study. Notes: R5: Inorganic subs. recycling/reclaim; R12: Exchange of waste for submission of R1 to R11; D1: Landfill; C1-SD: Stage C1-Selective demolition; C1-TD: Stage C1-Traditional demolition; C2-Tr: Stage 2-Transport; C3-Pr: Stage C3-Processing; C4 + D-Rc: Stages C4 and D-Recycling; C4-Lf: Stage C4-Landfill.

The possible destinations presented are the ones normally used for CDW in the Coimbra area, with operator 1 being a treatment plant and operator 2 being an inert materials' landfill. For a traditional demolition and landfill (Demolition Scenario 1), operator 2 is the choice, as this corresponds to a landfill of inert materials and to the activities usually carried out there. For selective demolition and subsequent recycling (Demolition Scenario 2), operator 1 was assumed, taking into account its characteristics, company activities, and objectives. In the first scenario, all CDW goes to landfill and, in the second scenario, all are valued: CDW identified as EWC 170101, 170107, 170405, and 170802 are subjected to a recycling process, and CDW identified as EWC 170201 are submitted to incineration (Figure 9).

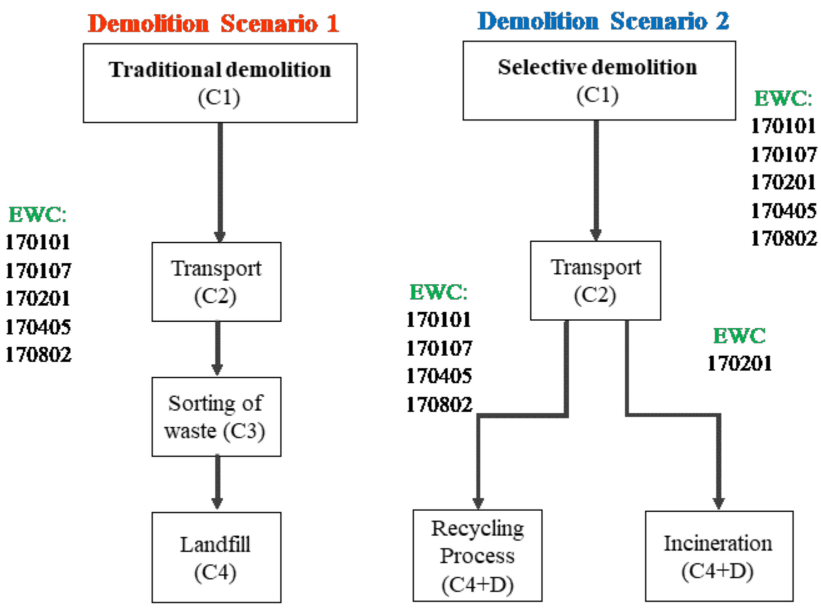

Figure 9. Demolition scenarios considered.

Results

In this case study, two potential destinations for the generated CDW and two indicators of environmental impacts are analysed. Considering the environmental impact associated with each destination and the different processes for each waste flow generated, it is possible to identify some relevant information. By analysing the GWP indicator, demolition (both selective and traditional) is the process that has the greatest weight in the overall impact of all waste generated, ranging from 39% to 66%, with the exception of waste 170201 (wood), where landfilling (with operator 2) is the process with the greatest weight in the overall impact. It is also possible to verify that transport (C2–Tr) is the process with the lowest environmental impact related to this indicator in the treatment of all waste generated during the rehabilitation. With wastes 170101, 170107, and 170802, sent to operator 1, demolition contributes more than 62% to the environmental impact. In the case of wastes 170201 and 170405, the demolition value is reduced, since the recovery process ranges between 45% and 55% of the total value. In the case of operator 2, with wastes 170101, 170107, 170405, and 170802, demolition has a value greater than 39%, with the exception of waste 170201, for which this figure is only 11%, as the landfill value is 81% (Figure 10).

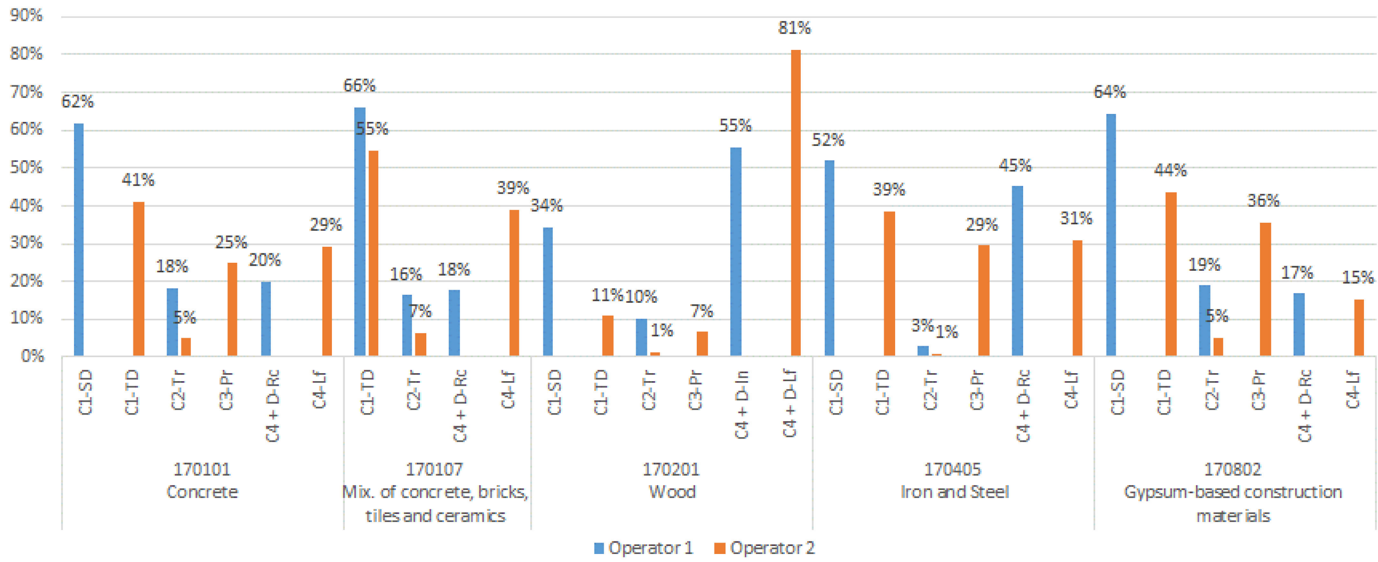

Figure 10. Weight of each process for each waste stream relative to the GWP indicator. Notes: C1-SD: Stage C1-Selective demoli-tion; C1-TD: stage C1-Traditional demolition; C2-Tr: Stage 2-Transport; C3-Pr: Stage C3-Processing; C4 + D-Rc: Stages C4 and D-Recycling; C4-Lf: Stage C4-Landfill; C4 + D-In: Stage C4-Incineration.

For the ADP (f.f.) indicator, the demolition process (both selective and traditional) is the one with the greatest value in the overall impact of all generated waste, ranging from 77% in the case of waste 170107 (operator 1 (C1–TD)) to 46% in the case of 170101 (operator 2 (C1–TD)) for traditional demolition. For the CDW from selective demolition, this process is also responsible for the greatest value in the environmental impact. Similarly, to the GWP indicator, transport is also the process with the least value in the environmental impact for the ADP (f.f.) indicator. In the case of wastes 170101, 170107, and 170802, sent to operator 1, demolition contributes to over 69% of the environmental impact, while for wastes 170201 and 170405, the value of demolition is reduced as the recovery process presents almost half the total value. For operator 2, for all waste types, demolition contributes to more than 46% of the associated environmental impact, meaning that this process has the greatest impact (Figure 11).

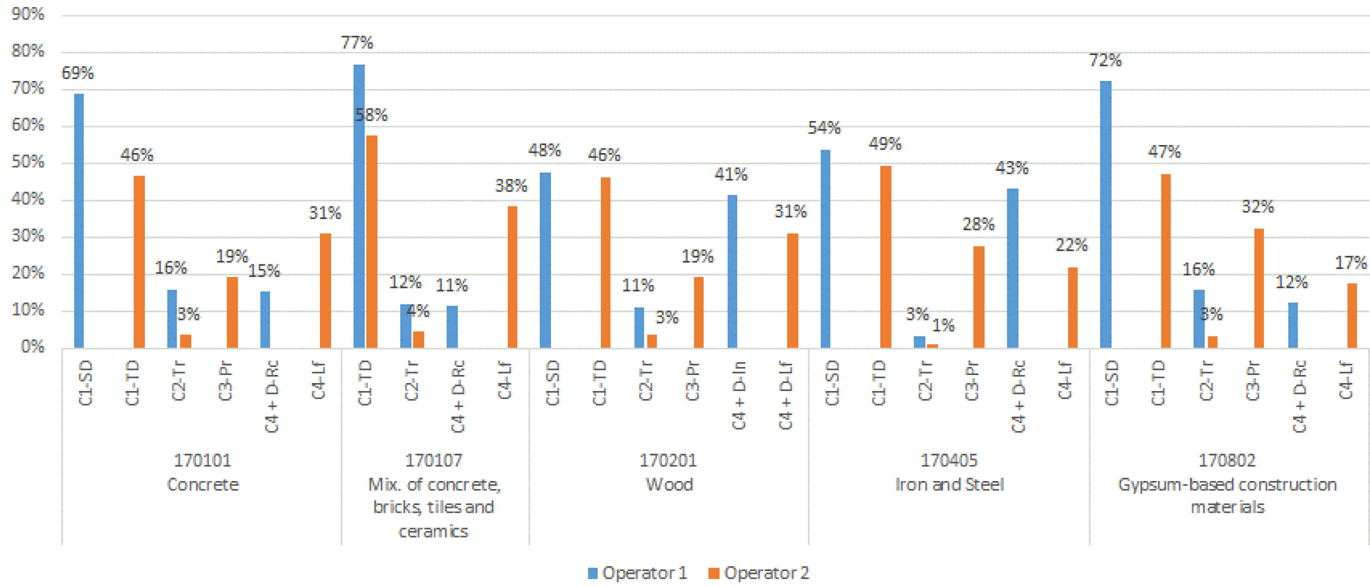

Figure 11. Weight of each process for each waste relative to the ADP (f.f.) indicator. Notes: C1-SD: Stage C1-Selective demolition; C1-TD: stage C1-Traditional demolition; C2-Tr: Stage 2-Transport; C3-Pr: Stage C3-Processing; C4 + D-Rc: Stages C4 and D-Recycling; C4-Lf: Stage C4-Landfill; C4 + D-In: Stage C4-Incineration.

Comparing the weight of the environmental impact associated with the two indicators at each stage and for each type of CDW in Figures 10 and 11, it is clear that the indicators present a difference of approximately 10% for most types of CDW, with the exception of wood (170201). This waste type presents higher differences, reaching 50% in stage C4 + D, corresponding to the landfill of operator 2.

Analysing the type of waste generated and the associated total environmental impact calculated for each operator, it is possible to identify that waste 170802 has the greatest value in the environmental impact, corresponding to 55% of the CDW quantity generated (Table 2). This is for both indicators GWP and ADP (f.f.), and for the two operators it ranges between 48% and 57% relative to the total environmental impact. Concrete (170101) corresponds to 30% of the CDW quantity generated (Table 2) and is the second waste type with the greatest impact, ranging between 27% and 29% for each indicator and for each destination. Iron and steel waste (170405) are the ones that produce the lowest environmental impact in both indicators and for both operators, corresponding to about 4%, because they represent 0.7% of the quantity of the CDW generated (Figure 12). If the impact per declared unit of each type of CDW is considered, it appears that the treatment referring to iron and steel CDW (170405) has the highest value in the total environmental impact compared to other types of CDW, being more than 93% of the total environmental impact for both indicators, for both types of treatment, and for both operator 1 and operator 2 (Figure 13).

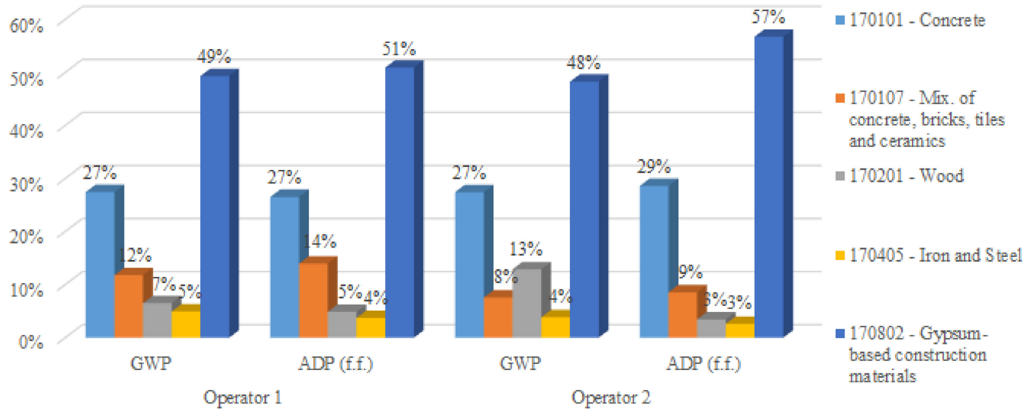

Figure 12. Weight of each type of CDW treatment in the environmental impact by indicator and operator.

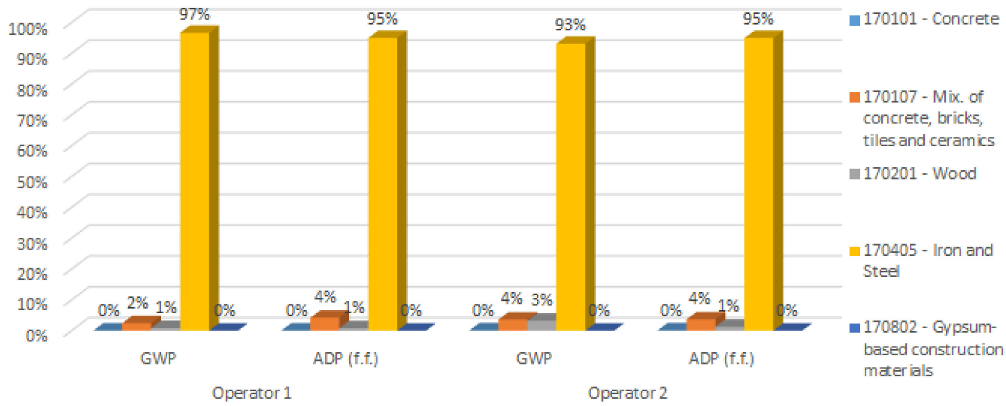

Figure 13. Weight of each type of CDW treatment—Impact per declared unit by indicator and operator.

In the case of the environmental impact for each indicator in stages C1, C2, and C4, it is possible to observe that, for most situations, the operator 1 option has lower environmental impact than operator 2, with the exception of transport, since operator 2 is located at about half the distance of operator 1. It is also possible to identify that stage C4 presents high differences in environmental impact for both indicators between both operators. At this stage, disposal by landfill substantially increases the environmental impact across both indicators compared to recycling. In the case of the GWP indicator, the CDW with the smallest difference at this stage is 170405, because the impact associated with disposal by landfill is similar to the impact associated with recycling it, while the one with the greatest difference is 170201. This difference is related to the fact that the impact of wood landfill is much greater than the impact associated with its incineration. Unlike the GWP indicator, for the ADP (f.f.) indicator the CDW with the smallest difference among the processes for this stage is 170201, because in this indicator the difference between the impact of wood landfill is similar to the impact associated with incineration. Moreover, the CDW types that present the greatest differences are 170101 and 170107, because in both CDW types the impact associated with disposal by landfill is far greater than the impact associated with its recycling. This analysis is performed taking into account only the weight of the environmental impact of each process at each stage per waste type (Figure 14).

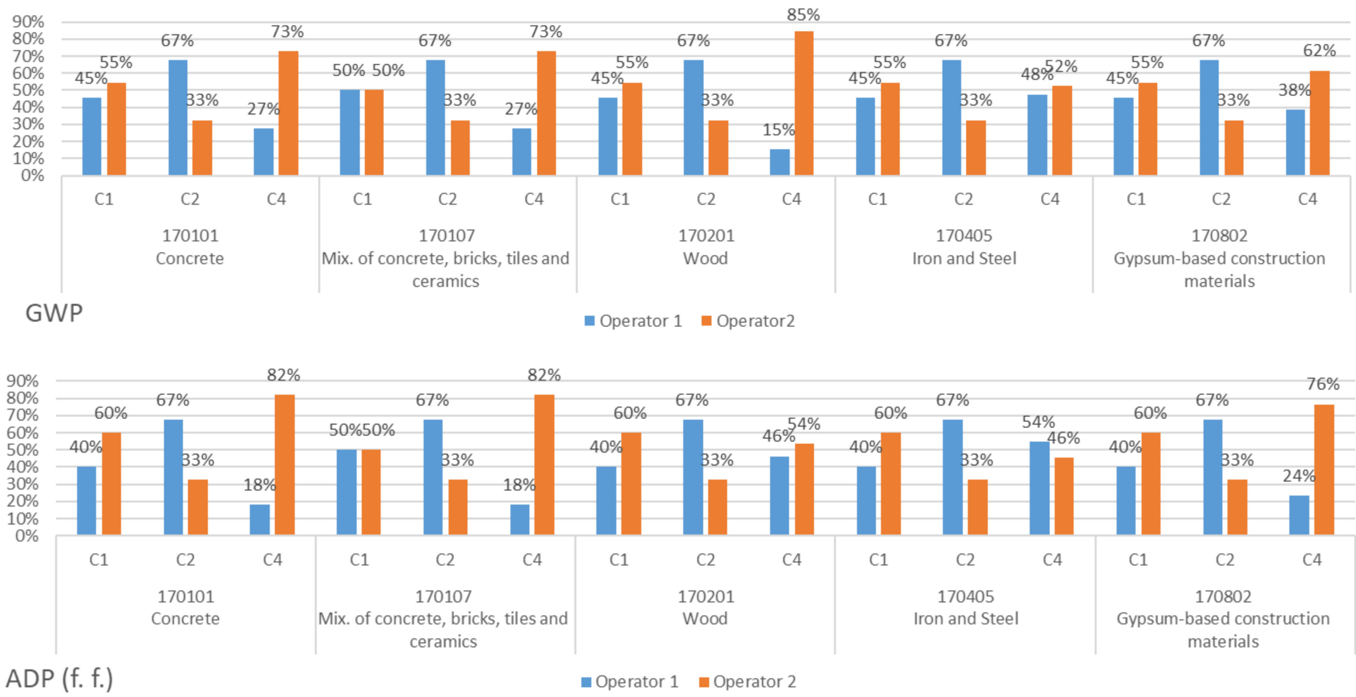

Figure 14. Comparison of the impacts associated with GWP (above) and ADP (f.f.) indicators (below) for each operator, stage and type of CDW.

Comparing both destinations, it appears that the environmental impacts related to the GWP and ADP (f.f.) indicators are lower for the operator 1 destination for the selective demolition and recovery processes, compared to the operator 2 option, which involves traditional demolition and subsequent deposit in landfill for all types of CDW. It can also be seen that CDW 170802 is the one with the greatest impact on both indicators, as previously mentioned. This is because this waste corresponds to about 55% of the amount of CDW generated (Table 2); for unitary impact, CDW 170405 is the one with the greatest environmental impact of the analysed CDW types (Figure 13). For the GWP indicator (Figure 15), it appears that the difference in the environmental impact of each type of CDW between the two operators (i.e., the ratio between operators) varies between 17% and 74%, depending on the waste treated. The smallest difference corresponds to CDW 170107 (17%), because, in both operators, the stage C1 is considered to be traditional demolition, which reduces the difference between the two treatment processes. The biggest difference is related to CDW 170201 (74%), because the impact associated with stage C4 is higher when the landfill option is chosen (operator 2) instead of incineration (operator 1), as previously mentioned. For the treatment of the remaining CDW generated, the greatest contribution to the environmental impact happens at stage C4, when disposal by landfill is chosen rather than recycling for CDW 170101 and 170802, while for CDW 170405, the greatest weight is related to stage C1, when traditional demolition is chosen instead of selective demolition, justifying the difference between the two types of treatment.

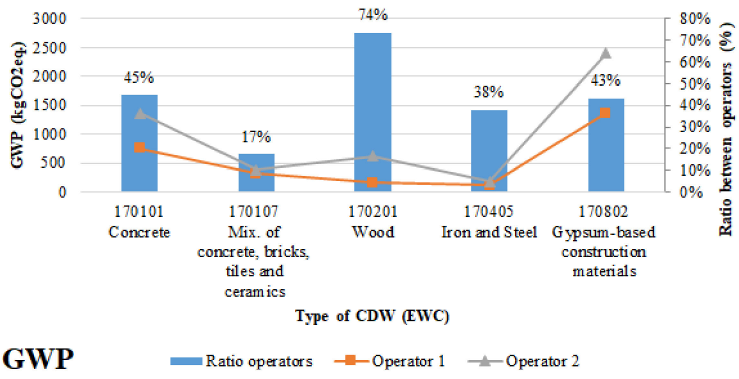

Figure 15. Comparison between the two operators for the GWP indicator.

In relation to ADP (f.f.) (Figure 16), the difference between the environmental impact associated with operator 1 and operator 2 (the ratio between operators) is also identified, ranging between 25% and 56%. The smallest difference is also with CDW 170107 (25%), for the same reason seen in the GWP indicator, because in both treatments it is considered to be traditional demolition. The biggest difference is associated with CDW 170802 (56%), where the environmental impact associated with this indicator increases substantially if landfill is chosen instead of recycling in stage C4. The same happens in the treatment of CDW 170101. For the treatment of the remaining generated CDW (170201 and 170405), the difference between the two processes in stage C1 is equal for the treatment of both, as seen in Figure 14, compared to stage C4: for CDW 170405, the impact associated with operator 1 is higher than that of operator 2, the opposite occurring with CDW 170201, but the weight of the processing (stage C3) is much higher in the case of CDW 170405 (see Figure 11), promoting a bigger difference between the impact generated in each operator with CDW 170405 compared to CDW 170201.

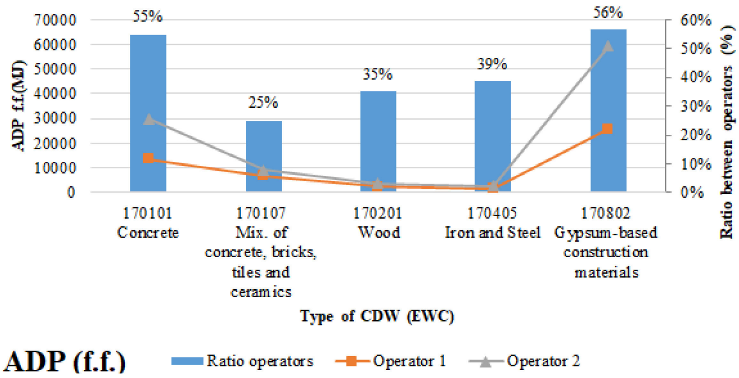

Figure 16. Comparison between the two operators for the ADP (f.f.) indicator.

From the analysed data, the operator 1 destination substantially reduces the environmental impact in the treatment of different types of CDW for both indicators GWP and ADP (f.f.), compared to operator 2.

5.2. 'Pre-Wall' System

In this case study, the generic database is applied to the use of a pre-cast concrete member, designated as a 'pre-wall'. The 'pre-wall' system consists of a structural wall solution for the construction of pre-cast buildings, characterized by two reinforced concrete panels connected by a light steel truss. These modules are produced in a factory and transported to the construction site, and are then assembled in situ by placing reinforcement in the connections between members after the core is cast. In addition to concrete and steel reinforcement, these members may also contain insulation materials in their constitution. The material quantities per m^2 of wall are presented in Table 3.

Table 3. Constitution of 'pre-walls', per m^2.

Material	Weight (kg)
Mixture of concrete	390
Metal (Steel)	12
EPS (optional)	2
Total	404

In this case study, two different solutions for this constructive system are considered:

(i) a solution without insulation material, with only steel reinforcement and concrete, with 20 cm of total thickness (Solution A); and

(ii) a similar solution, with an insulation layer (expanded polystyrene, EPS) in the 'pre-wall' core, with 5 cm thickness, with a total thickness of 25 cm (Solution B).

In addition, two demolition scenarios were addressed (presented in Figure 17):

- Traditional demolition (Scenario 1), considering the complete demolition of the walls and transport of the CDW to landfill;
- Selective demolition (Scenario 2), with dismantling on site and separation of different waste types for recycling, when possible, and with the contaminated materials that are impossible to separate being sent to landfill.

The two demolition scenarios were analysed for both solutions studied (A and B). In traditional demolition (Scenario 1), all CDW will be landfilled. For selective demolition (Scenario 2), Solution A considers that the concrete is totally separated from the steel, and that all the waste generated is recycled. For Solution B, since the 'pre-wall' core is concreted on site, and is in contact with the EPS, it is expected that the recovery of all of the material for recycling will not be possible in Scenario 2. An approach to recover 75% of EPS and 75% of concrete for recycling is then considered, with the remaining 25% being contaminated and sent to landfill (see Figure 17). Therefore, the generated CDW, with the respective EWC codes are: 170101 (concrete), 170106 (mixture of concrete/steel, contaminated with insulation), 170405 (steel reinforcement), and 170603 (EPS insulation material).

For calculation purposes, the same CDW operators of the previous case study are considered. The CDW landfill of Scenario 1 will be carried out by operator 2, located approximately 20 km from the demolition site; and Scenario 2 will be carried out by operator 1, located at about 40 km from the site. Tables 4 and 5 show, respectively, the values for solutions A and B, for each impact category assessed, and for each demolition scenario, per m^2 of wall.

From the results obtained, it can be seen that for demolition Scenario 1, Solution B has a greater environmental impact, despite not being significant, since it contains insulation material in its constitution that will be disposed by landfill. On the other hand, for Scenario 2, Solution B has an ADP (f.f.) value 63% lower than Solution A (ADP (f.f.) = 162.8 MJ and 60.0 MJ, respectively), which proves the recycling potential of the insulation material, although only 75% of all EPS material is considered to be recycled. Comparing the demolition scenarios, it can be seen that the adoption of a selective demolition approach allows a reduction of GWP between 43% and 53%, and a reduction of ADP (f.f.) between 52% and 83%, compared to Scenario 1, even when a longer destination for waste treatment for Scenario 2 is adopted. These figures confirm that selective demolition is advantageous in terms of environmental impacts, and deconstruction is particularly important because it allows the reintroduction of recycled/reused material in new constructions [24].

Table 4. Environmental impacts, by category—solution A (without EPS insulation).

Impact Category	Units	Demolition		Transport		Processing	Recycling	Landfill	TOTAL		% Reduction
		Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 1	Scenario 2	
GWP	$kgCO_2eq./m^2$	6.8	5.6	0.8	1.5	4.2	2.2	4.9	16.6	9.4	43
ADP (f.f.)	MJ/m^2	163.1	108.7	11.3	23.3	69.8	30.8	104.5	348.6	162.8	53

Note: Colors only to differentiate the results for each scenario according with Figure 17.

Table 5. Environmental impacts, by category—Solution B (with EPS insulation).

Impact Category	Units	Demolition		Transport		Processing	Recycling	Landfill		TOTAL		% Reduction
		Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2 (75%)	Scenario 1	Scenario 2 (25%)	Scenario 1	Scenario 2	
GWP	$kgCO_2eq./m^2$	14.4	12.0	0.7	1.5	4.4	−3.0	5.2	1.1	24.7	11.6	52
ADP (f.f.)	MJ/m^2	164.1	109.4	11.3	23.3	70.3	−97.0	105.0	24.3	350.7	60.0	83

Note: Colors only to differentiate the results for each scenario according with Figure 17.

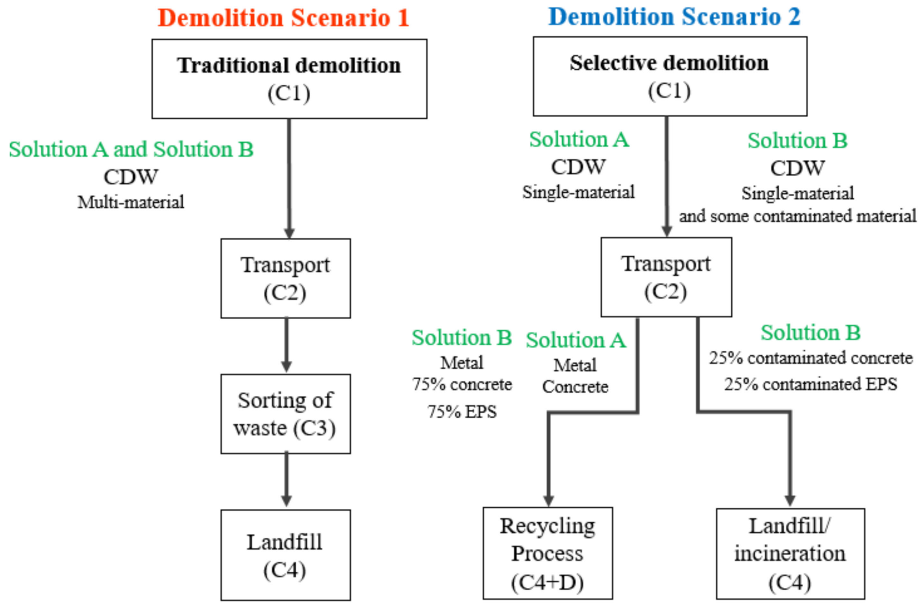

Figure 17. Definition of the demolition scenarios.

Using the database, the building designer can optimize the 'pre-wall' system in order to obtain a solution with the least possible environmental impact at the end of its service life. After creating a waste generator profile (B), defining the demolition site location (B1.1) and the demolition scenario adopted (B1.2), the user must choose the generated CDW and the respective quantity (B1.3 and B1.4) (see Figure 5). The outputs presented by the LCA database are the list of possible treatments and/or landfill destinations, with the location and distance, and the possible waste recovery operations. Finally, the database can calculate the environmental impacts associated with these operations.

5.3. Discussion

The methodology for the development of the LCA database proposed in this paper models the recording and collection of the most important information from CDW, in order to help users reduce the environmental impacts of waste at the end-of-life stage of buildings. At the same time, it promotes the incorporation of recycled materials in future constructions. In fact, for both case studies, there is a significant benefit in choosing processes that contribute to the recycling of CDW.

The rehabilitation case study (Section 5.1) demonstrates that the weight of transport as part of the environmental impact associated with the treatment of CDW is quite reduced. In most situations, the type of demolition is responsible for the greatest contribution to the environmental impact, across both indicators. For the two destination options analysed, there is a reduction in the environmental impact of 45% for GWP and 52% for ADP (f.f.) for the selective demolition and waste recycling option, compared to traditional demolition and subsequent landfill. The analysis of the environmental impacts also shows that stages C1 (demolition scenario) and C4 (recovery of CDW) are, in general, the ones that make the greatest contribution to the environmental impact associated with the treatment of all CDW types analysed, for both indicators.

In the 'pre-walls' case study (Section 5.2), the database is used by the designer/manufacturer to develop the waste management plan during the design and conception phases. This allows them to assess the environmental impacts of several options for the recovery of waste generated at the end-of-life phase, and to evaluate the level of material reuse and/or recycling involved in this solution. Solution B demonstrates that it is not possible to reuse the complete module, since it is mainly made of concrete and insulation material which cannot be separated and is considered to be contaminated material. Similar to the previous case study, selective demolition proved to be advantageous over traditional demolition, with a reduction in GWP and ADP (f.f.) up to about 52% and 83% respectively. This database is therefore an important tool to support decisions during the design and production phase, in order to obtain a solution that not only fulfils its function, but also contributes to the reduction of the ecological footprint by decreasing the consumption of primary resources through the use of recycled material in the prefabrication sector.

6. Conclusions

The literature review shows that there are comparatively fewer lifecycle assessments that focus on the end-of-life stage of buildings, and that currently there is no LCA tool for the CDW market in Portugal or internationally. This paper is an attempt to fill these gaps, specifically for the end-of-life phase of buildings and the CDW generated, thereby promoting a C2C perspective.

At present, decisions about waste from the end-of-life phase of construction are mainly made based on the distance to the treatment or disposal site, and on the associated costs. Using this database, the respective environmental impacts can be calculated and a more sustainable choice can be made, contributing to the sustainable management of materials, as referenced in Directive 2018/851 [7]. The benefits identified should have a huge impact in the way that the main operators in the construction sector work. This should be the main driver to create a new and dynamic online platform, which can be constantly updated by its users.

By being developed using existing knowledge from previous studies (static data) and data provided in real time by stakeholders (dynamic data), the proposed database will promote better sustainable management of construction materials based on the circular economy, with advantages both for the end-of-life phase of buildings and new products, which will have benefits for all stakeholders and for the wider community. The two case studies in this paper have validated the database methodology proposed and confirm the benefits of using it. An online platform for CDW will improve the interaction between all stakeholders in the construction sector, and will create a greater awareness of its environmental impact and of the need to reuse and recycle material. Therefore, it will promote the reduction of the environmental impact of the sector. This interaction results in a new and complete database that promotes the valorization of CDW, taking into account the environmental impact of the existing end-of-life alternatives.

The combination of environmental and economic impacts allows the choice of the most sustainable and economical solutions. The current database only considers environmental impacts but, for the future, it is necessary to include the economic impact to have better and more holistic decision making in waste management.

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