sustainability

Article

Environmental Performance of Deconstructable Concrete Beams Made with Recycled Aggregates

Lucas Caon Menegatti [1], Letícia Ikeda Castrillon Fernandez [1], Lucas Rosse Caldas [1], Marco Pepe [2,3], Francesco Pittau [4], Giulio Zani [5], Marco Carlo Rampini [5], Julien Michels [6], Romildo Dias Toledo Filho [1] and Enzo Martinelli [2,3,*]

[1] Department of Civil Engineering, Universidade Federal do Rio de Janeiro, Ilha do Fundão-Cidade Universitária, Rio de Janeiro 21941-594, Brazil
[2] Department of Civil Engineering, University of Salerno, Via Giovanni Paolo II 132, 84084 Fisciano, Italy
[3] TESIS srl, Via Giovanni Paolo II 132, 84084 Fisciano, Italy
[4] Department of Architecture, Built Environment and Construction Engineering (DABC), Politecnico di Milano, via Ponzio 31, 20133 Milano, Italy
[5] Department of Civil and Environmental Engineering (DICA), Politecnico di Milano, Piazza Leonardo Da Vinci 32, 20133 Milano, Italy
[6] Re-fer AG, Riedmattli 9, 6423 Seewen, Switzerland; jmichels@re-fer.eu
* Correspondence: e.martinelli@unisa.it

Citation: Menegatti, L.C.; Castrillon Fernandez, L.I.; Caldas, L.R.; Pepe, M.; Pittau, F.; Zani, G.; Rampini, M.C.; Michels, J.; Toledo Filho, R.D.; Martinelli, E. Environmental Performance of Deconstructable Concrete Beams Made with Recycled Aggregates. *Sustainability* **2022**, *14*, 11457. https://doi.org/10.3390/su141811457

Academic Editor: Jorge de Brito

Received: 1 August 2022
Accepted: 9 September 2022
Published: 13 September 2022

Abstract: The construction sector is one of the most energy-intensive and raw-material-demanding human activities and, hence, contributes a significant share of greenhouse gas emissions. As a matter of principle, making the construction sector "greener" is one of the main challenges for policy makers, private companies and the scientific community. For this reason, one of the most promising actions is based on recycling Construction and Demolition Waste (CDW) and converting them into secondary raw materials for the construction sector itself. Moreover, the reduction of the environmental impact can be further amplified through the optimization of the production, assembly and deconstruction/reuse procedures and through the maximization of the service life. In this aim, the present work aims at analyzing the environmental performance of duly sized and designed prefabricated Decontructable and Reusable Beam (DRB) incorporating with Recycled Concrete Aggregates (RCA) assembled by means of an innovative system based on a memory®-steel prestressing technique. The environmental performance is evaluated through Life Cycle Assessment with a cradle-to-gate approach: the analysis of 16 midpoint impact categories was conducted using the methodology proposed by EN15804. In this context, three allocation scenarios for avoided impacts due to reuse (100-0, 50:50 and 0-100) were considered, and a sensitivity analysis was performed. It was verified that due to the higher amount of post-tensioning required for the innovative shape memory alloy steel bars, the DRBs present inferior environmental performance than the Ordinary Beams (ORB). However, when analyzing the reuse scenarios, it was observed that the DRB could have considerably lower impacts, depending on the type of allocation procedure adopted in LCA modeling. This study brings as the main contribution an evaluation and some design guidelines for the development of circular concrete structures based on the principles of Design for Deconstruction (DfD) and the prefabricated process.

Keywords: Recycled Concrete Aggregate (RCA); Recycled Aggregate Concrete (RAC); Design for Deconstruction (DfD); reuse; recycling; Circular Economy (CE); Life Cycle Assessment (LCA)

1. Introduction

The linear take-make-dispose approach present in the traditional construction industry has become an unsustainable system regarding environmental issues. About 7% of the world's carbon dioxide emissions come from the cement industry [1]. Added to this, there is still great concern about the extraction of raw materials and the large amount of unexploited Construction and Demolition Waste (CDW) [2,3]. There are also studies that analyze the feasibility of using natural by-products as aggregates for concrete, such as wood shavings [4], bamboo waste [5], rice husk [6] and palm oil clinker [7]. In this way, it becomes urgent and necessary to adopt strategies and policies that aim to reduce the carbon footprint, preserve natural resources, reuse and recycle waste that normally do not have a proper End-of-Life (EoL). The recycling of CDW and the reuse of building components are potential strategies to promote the Circular Economy (CE) in the construction sector [8].

A widely discussed recycling technique is the use of CDW for the production of Recycled Concrete Aggregates (RCA) so that they can later be used as raw material for Recycled Aggregate Concrete (RAC) [9]. Therefore, the RCA is reintroduced into the construction processes, closing the material's loop. Over the last two decades, several researchers [2,3,9–15] have investigated the properties of RCA and its use for concrete production.

When it comes to sustainability issues, it is important to carry out a Life Cycle Assessment (LCA) to verify the real impacts avoided by using RCA [16]. LCA is a powerful, widely adopted methodology for quantifying, evaluating and comparing the environmental impact of any kind of product along its life cycle that has also been applied to the construction sector [17].

Grabois et al. [18] analyzed the performance of RCA mortars through different impact categories and observed that high levels of Natural Aggregate (NA) replacement by RCA was less detrimental to the environment and that the RCA evaluation was strongly influenced by long transport distances. Transport distance is also mentioned by Dias et al. [19] as a crucial parameter in RCA LCA.

Bennett et al. [20] conducted LCA to quantify the Global Warming Potential (GWP) of several mixtures from the literature that incorporate both recycled aggregate and a range of Supplementary Cementitious Materials (SCM) types. They observed that replacing NA with RCA resulted in small changes in CO_2 emissions, while the greatest gains in terms of sustainability were attributed to partial replacement of cement with SCM. After analyzing several studies, Xing et al. [16] also confirmed this fact, attributing better environmental performance to recycled concrete with SCM incorporation.

Regarding the reuse of constructive components, Design for Disassembly/Deconstruction (DfD) is considered one of the main CE reuse practices [21]. The DfD concept relies on the idea that products and components can be easily separated and reassembled [22]. Thereby, when applied to the construction sector, the DfD aims to consider the EoL of the entire construction or of its components in the initial design stage [23,24]. Crowther [25] also highlights that this consideration of disassembly in the design and conception phase can lead to a higher potential for reuse and upcycling.

The application of DfD tends to be more challenging in concrete structures than in other construction systems (such as in steel and wood systems) due to the monolithic connections between the structural components [26–28]. According to Figueira et al. [29], the most common structural connections in DfD concrete structures are steel plates and bolt systems. However, the authors point out that this type of connection can imply stress concentrations in the concrete region close to the bolts. Vandervaeren et al. [30] highlighted that careful LCA analysis should be carried out to verify the environmental performance of DfD solutions since even when including some DfD principles, construction may not be effectively dismantled or easy to maintain. Even though there are European standards (EN 15978:2011 [31] e EN 15804:2012 + A2:2019 [32]) for building

LCA, this analysis has deficiencies, mainly in the modeling of the benefits when using DfD components [30,33].

On the element and component scale, Eckelman et al. [34] compared different floor systems using LCA, considering different reuse scenarios and uncertainty analysis. Eberhardt et al. [35] evaluated different allocation approaches to verify the sustainability performance of four different elements (concrete column, timber column, recyclable roof felt and window with a reusable frame). Xiao et al. [36] analyzed the effect of the use of recycled aggregates on the seismic behavior of DfD beam-column connections under cyclic loading, performing LCA to verify the performance of materials regarding carbon emission. Cai et al. [37] investigated the structural behavior of demountable bolted joints under cyclic loads to verify the feasibility of using these connections in earthquake-prone DfD buildings, but only from the mechanical perspective (without performing an LCA study). Vandervaeren et al. [30] developed an LCA methodology that considers the interdependence of elements during the deconstruction stage, comparing the results obtained for a simple pavilion with the results calculated based on the methodology presented in EN 15978:2011.

Regarding the application of DfD to whole buildings, Eberhardt et al. [38] present a case study of a Danish office with a concrete DfD structure, in which 11 environmental impact categories were analyzed. Rasmussen et al. [39] compared a house building designed according to the reuse/recycle of elements based on the DfD methodology, in which elements and components are designed to be reused after their first EoL. Xia et al. [40] conducted a case study of a concrete structure built in Shanghai, China, using recycled aggregate concrete associated with DfD. Joensuu et al. [33] analyzed the effects of LCA methodological choices for three buildings with the same layout, but with different structural solutions: conventional construction, wooden structures and hybrid building with DfD structures. The main contribution of this study was to confirm the reliability of a new LCA method to account for the benefits of DfD.

Temporary constructions, such as galleries and exhibition pavilions, have great potential for the application of DfD, given their short lifespan. To investigate the potential benefits of these temporary structures designed with DfD principles, Arrigoni et al. [41] carried out an LCA study of a temporary pavilion built for EXPO Milan 2015. Toniolo et al. [22] present a case study of an exhibition area, using DfD principles applied to the carbon footprint assessment methodology.

In light of the foregoing, it is observed that the benefits provided by applying the two CE strategies (recycling and reuse) in a combined way are not yet widely explored, especially for concrete structures. Therefore, the aim of this study was to evaluate the sustainable performance of a DfD beam produced with recycled aggregates combined with an innovative memory®-steel prestressing technique on site. The latter is a new type of steel alloy able to prestress itself upon heating. This simple execution process, using iron-based shape memory alloy systems, offers new possibilities for modular construction when compared to traditional post-tensioning systems. The proposed innovative solution has the potential to become helpful for practical application in the coming future. In fact, the simple execution process, using iron-based shape memory alloy systems, offers new possibilities for modular construction. The whole system can innovate the future construction method, which is eco-friendly both from a raw material perspective—use of RAs for modular elements to be reused several times upon repetitive construction/deconstruction—and in terms of connecting elements—the memory®-steel, which can be recycled or even reused upon deconstruction. The target building typology is that of highly modular structures, demanding high construction speed and the possibility of reconversion of internal spaces.

Studies found in the literature did not evaluate any structural element with the technology presented here, even more considering environmental aspects. Therefore, the environmental performance of the DfD beam was also compared with a conventional beam, by performing an LCA analysis through 16 impact categories and different reuse allocation approaches for the quantification of benefits when reuse and recycling are considered CE strategies.

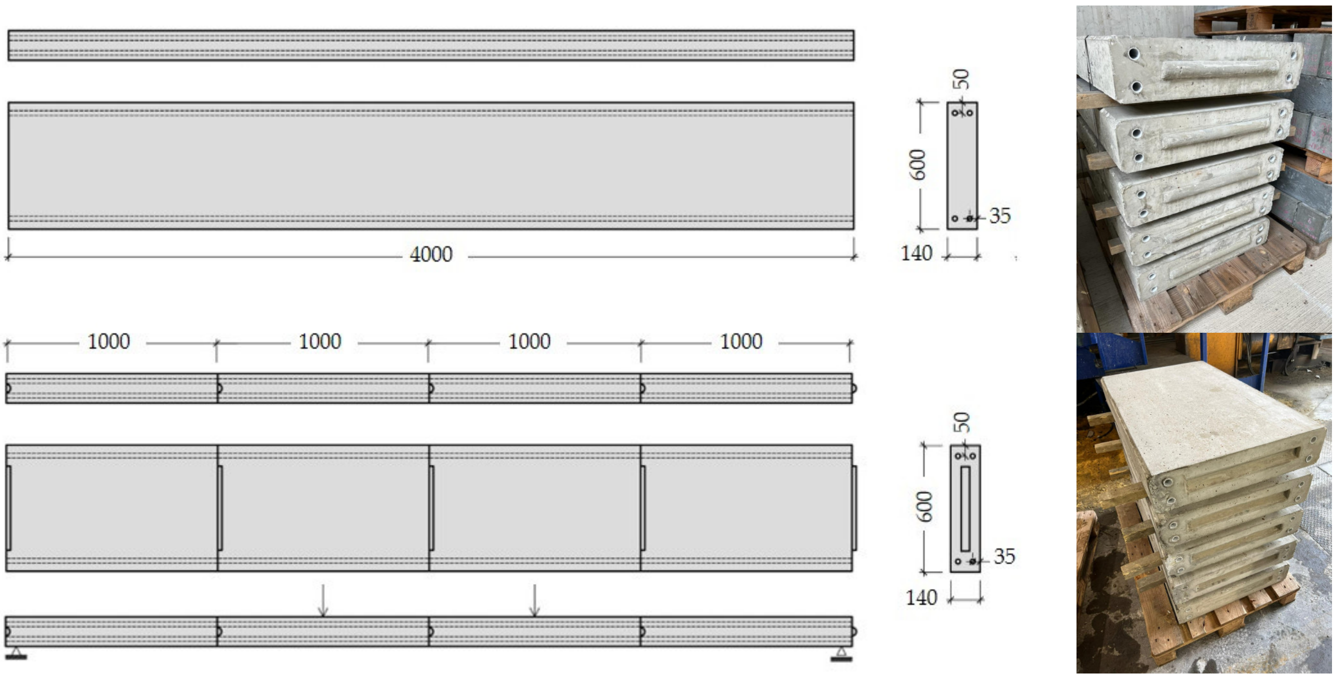
This study brings as the main scientific contribution the presentation of an innovative technology that allows deconstruction and reuse of concrete beams and its relation with environmental performance. Finally, some environmental design guidelines for the development of circular concrete structures, based on reuse and recycling strategies, are described. It will bring valuable information for material manufacturers, building constructors, researchers and other players in the construction sector.

2. Materials and Methods

The Materials and Methods section is divided into two subsections: (1) description of the studied beams and (2) LCA.

2.1. Description of the Studied Beams

Full-scale representative prototypes for the next-generation prefabricated elements developed throughout the whole study were produced and tested; details related to the dimension and connection systems of the produced beams are reported in Figure 1.



(**a**) (**b**)

Figure 1. Studied beams: (**a**) Ordinary Beam (ORB) with natural reference concrete and Deconstructable and Reusable Beam (DRB) with recycled aggregate concrete; (**b**) details regarding the connection system for DRB. Note that nominal dimensions are expressed in mm.

More specifically, two high-strength (C60) precast concrete modular (1 m length) beams (made of four modular elements) incorporating 100% of coarse RCAs and reinforced with the innovative memory®-steel (iron-based shape memory alloy) prestressing techniques (www.re-fer.eu (accessed on 1 July 2022)) were produced (see Figure 1b), called here Deconstructable and Reusable Beam (DRB). In addition, two reference ordinary (made with natural aggregates) prestressed (ordinary steel) and precast concrete (C60) beams (4 m length) were also produced (see Figure 1a), called ORdinary Beam (ORB).

The concrete mixture proportioning was based on the mix-design method recently proposed in the literature by Pepe et al. [42], which takes into account the specific peculiarities of the recycled particles, such as the Attached Mortar (AM) content leading to higher water absorption capacity, and lower particle density for coarse particles [42]. As a matter of principle, using a specific mixture proportioning method warranty, in the case of 100% replacement of natural coarse aggregates with the companion RCAs, the desired compressive strength at 28 days is not compromised [14,43].

Table 1 reports the concrete mixture proportioning of both RAC and reference concrete mixtures (for 1 m of beam); meanwhile, the geometric characteristics and details regarding the DRB connection system are shown in Figure 1. The table evidences the higher amount of steel (8 kg) employed in the case of DRB in comparison with the ORB (less than 3 kg). This is attributed to the different types of prestressing steel employed in the two systems analyzed herein. More specifically, the re-fer rebars R18 (iron-based shape memory alloy) require a greater area in comparison with the traditional prestressing system in order to achieve the target prestressing force. On the other hand, R18 re-fer rebars have higher deconstruction potential in comparison with the traditional system.

Table 1. Material composition of the evaluated beams (for 1 m of beam with section 14 × 60 cm).

Materials		ORB (kg)	DRB (kg)
Concrete	Natural sand 0/3 mm	51.02	51.02
	Natural coarse aggregates 0/12 mm	36.21	36.21
	Natural coarse aggregates 8/15 mm	58.43	-
	Recycled Concrete Aggregates 8/16 mm	-	52.42
	Filler	8.23	8.23
	Cement type CEM I 52.5R	31.27	31.27
	Superplasticizer	0.54	0.54
	Water	14.81	15.88
Steel	Ordinary steel rebars	9.44	9.44
	Prestressing steel strands	2.92	-
	re-fer re-bars R18	-	8.00

2.2. Life Cycle Impact Assessment (LCA)

LCA is a methodology composed of four iterative phases [44,45]: (1) definition of objective and scope; (2) Life Cycle Inventory analysis (LCI); (3) Life Cycle Impacts Assessment (LCIA); and (4) interpretation.

2.2.1. Objective, Scope and Functional Unit

The objective of this study was to evaluate and compare the environmental performance of two structural concrete beams, the DRB and ORD. The results obtained can be used to show the benefits and potential of environmental impact reduction when recycling and reuse are considered as a design strategy.

Regarding geographical coverage, the study was developed considering the European context. The scope of this research covers the following stages: (A1) raw material acquisition, (A2) transportation and (A3) processing and manufacturing of composites, according to the organization of the EN 15804:2019 [32], which is normally called "from the cradle-to-gate". In addition, since recycling and reuse will be evaluated, module D—Benefits and loads beyond the system boundary—is included in the analysis. Two benefits are accounted for: the avoided impacts due to the final disposition of aggregate mass in an inert landfill and the natural aggregate extraction.

The functional unit is one of the basic requirements of LCA studies. According to ISO 14040 [45], the functional unit can be defined as "quantified performance of a product system for use as a reference unit". A beam has a structural application; the beams evaluated in this study can be used as structural components for residential or commercial buildings. Thus, the Functional Unit (FU) was defined as "1 m of beam with section 140 × 600 mm that is composed of concrete with 60 MPa of compressive strength". A service life of 50 years of the beam is considered.

2.2.2. Life Cycle Inventory (LCI)

The data for the beams LCI were partially obtained from experimental research carried out by the authors, and the continuous data were obtained from the Ecoinvent v. 3.7.1 databases that accompany the SimaPro and the scientific literature. The detailed data and datasets are described in Table 2. Regarding the construction/assembly stages, in this research, it was supposed that all energy and materials were disregarded, as well as the waste generation. Considering that most materials are readily available and this study is based on a European context, the transportation distances were fixed at 100 km [46].

Table 2. Data used in the LCI.

Material/Activity	Dataset	Source
Cement	Cement, Portland {Europe without Switzerland} production	Ecoinvent v.3.7.1
Sand	Sand {RoW}∣ sand quarry operation, extraction from riverbed	Ecoinvent v.3.7.1
Gravel	Gravel, crushed {RoW} production	Ecoinvent v.3.7.1
Recycled aggregate	Literature data	Borghi et al. [47]
Filler	Limestone, crushed, for mill {RoW} production	Ecoinvent v.3.7.1
Superplasticizer	Plasticiser, for concrete, based on sulfonated melamine formaldehyde {GLO} production	Ecoinvent v.3.7.1
Water	Tap water {Europe without Switzerland} market for	Ecoinvent v.3.7.1
Ordinary steel rebars	Reinforcing steel {Europe without Austria} reinforcing steel production	Ecoinvent v.3.7.1
Prestressing steel strands/re-fer re-bars	Literature data	EPD: Hjulsbro Steel AB [48]
Electricity	Electricity, medium voltage {Europe without Switzerland} market group for	Ecoinvent v.3.7.1
Concrete dosage plant	Literature data	Souza et al. [49]
Transportation	Transport, freight, lorry 16–32 metric ton, euro5 {RER} market for	Ecoinvent v.3.7.1
Inert landfill	Inert waste, for final disposal {RoW} treatment of inert waste, inert material landfill	Ecoinvent v.3.7.1

2.2.3. Life Cycle Impact Assessment (LCIA)

The EN15804 method (EN 15804 +A2 Method V1.01/EF 3.0 normalization and weighing set) is the Life Cycle Impact Assessment (LCIA) method used, being the most recent. This method is classified as the midpoint, and the following impact categories are calculated: 1—Climate change (CC); 2—Ozone depletion (OD); 3—Ionizing radiation (IR); 4—Photochemical ozone formation (PO); 5—Particulate matter (PM); 6—Human toxicity, non-carcinogenic (HT-nc); 7—Human toxicity, carcinogenic (HT-c); 8—Acidification (AC); 9—Eutrophication, freshwater (EF); 10—Eutrophication, marine (EM); 11—Eutrophication, terrestrial (ET); 12—Ecotoxicity, freshwater (EC); 13—Land use (LU); 14—Water use (WU); 15—Resource use, fossils (RF); 16—Resource use, minerals and metals (RM).

As a second analysis, when the reuse benefits were evaluated, to facilitate the interpretation of results, a single score indicator (in Pt) from the EN 15804 + A2 Method V1.01/EF 3.0 normalization and weighing set was used.

2.2.4. Beam Reuse Scenarios

Based on the reviewed literature, we see that there is no accordance in terms of methodologies to account for benefits and avoided impacts [33]. Therefore, we used the concept of EN 15804 present in "module D—Benefits and loads beyond the system boundary" and the evaluation of different allocation scenarios, as presented in Figure 2. Three allocation scenarios were used in this research: the 100-0 (cut-off), 50:50 (equal share) and 0-100 (end-of-life recycling). The 100-0, also called the cut-off approach, is the simplest one, where the benefits do not go to a second life but remain associated only with the first one. The 50:50 approach is normally used for reuse and recycling, where the impacts are equally divided between all the cycles sharing the product. Finally, the 0-100 approach, in which all the benefits go to the second life cycle [35,38,50]. Although all the life cycles can be considered, in our research, only the A1–A3 stages were accounted for according to the definition of the goal and scope presented before. This kind of beam can be used for temporary projects (around 5 years of service life) or conventional ones (around 50 years of service life). In our research, we considered the application for conventional projects with 50 years of service life.

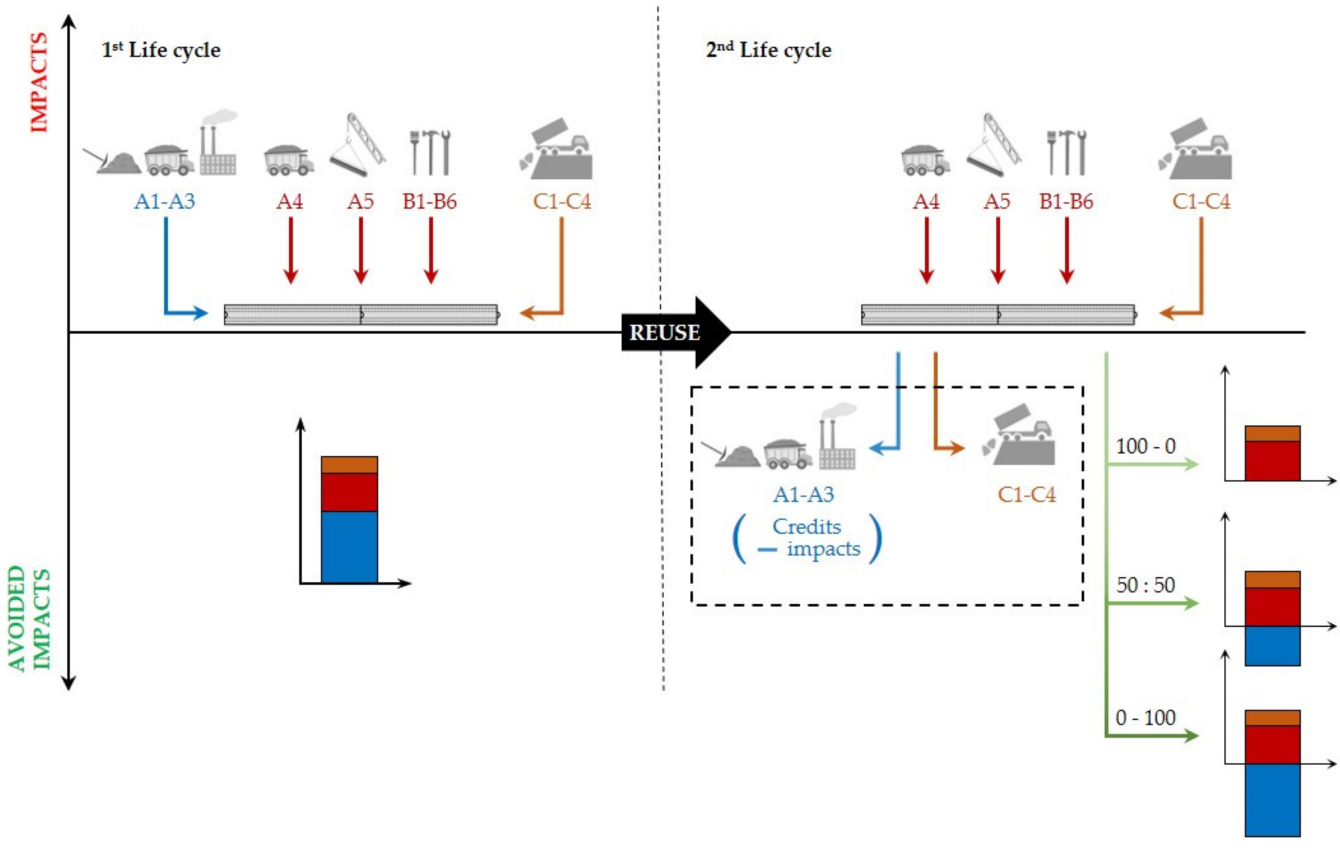


Figure 2. Scheme for evaluation of different scenarios for the account of reuse benefits considering different allocation approaches.

2.2.5. Sensitivity Analysis

A sensitivity analysis was made for three premises adopted in this research to increase the robustness of the study.

- Steel data: use of the dataset of Ecoinvent for the three types of steel.
- Sand extraction processes data: sand quarry operation and sand extracted from riverbed.
- Recycled aggregate processing plant: a plant based on diesel and other with electricity, based on the studies of Borghi et al. [47] and Coelho and de Brito [51].

3. Results

3.1. Overall Results

This section summarizes the results obtained in the LCIA of 1 m of the studied beams for ORB (Figure 3a) and DRB (Figure 3b): all the numerical results obtained herein are reported in Appendix A. These results show the cumulative contribution of materials and activities defined in the LCI for each impact category considered. Based on these figures, it can be seen that most of the contribution to potential impacts refers to ordinary and prestressing steel for ORB (34–97%) and ordinary and post-tensioning steel for DRB (48–98%). As expected, cement is another material that presents significant contributions to the impact categories in both beams (1–50%). Other similar studies have already seen the great influence of the environmental impacts of cement [52–54]. In addition, transportation is an activity with smaller contributions compared to previous materials, but with notable participation in most impact categories (0.2–13%).

Regarding Figure 3, it is also possible to note that steel is the major contributor to the human toxicity categories, carcinogenic and non-carcinogenic, presenting percentages between 86–94% for HT-nc and 97–98% for HT-c [55]. In the EN 15804 LCIA model, we have two types of human toxicity, one is carcinogenic (HT-c), and the other is non-carcinogenic (HT-nc). Human toxicity (carcinogenic and non-carcinogenic) is an impact category that accounts for the adverse health effects on human beings caused by the intake of toxic substances present in the environment [32]. For HT-c, a great part of the steel impact comes from the process of obtention and use of coke as fuel during pig iron production, according to the data used in the LCA modeling. This occurs due to the liberation of carcinogen substances, such as ammonia, sulfides and hydrogen cyanides [56]. On the other hand, for HT-nc, most of the impact comes from the sinter production process, which liberates an excessive amount of dust [57].

Therefore, the amount of steel used in beams must be reduced (without affecting the technical performance) to improve their environmental performance. It is also important to discuss the quality of steel data since it has a great influence on the final results. In this study, data from Ecoinvent for an EPD were used since primary data are not available, limiting the resolution of results, especially for prestressing steel strands and re-fer rebars. However, this is a common limitation in LCA studies, and when more specific data are available, new modeling should be performed. In the sensitivity analysis, it is possible to see when different data for steel are used, which is also a way to evaluate the influence of this material and reach more robust and reliable conclusions [58]

In terms of land use, sand is the material with the largest share of influence in this category—46% for both beams, which is expected, considering the process of obtention of sand that normally severely affects the natural landscape and environment [59]. The potential impacts generated by gravel in ORB showed a general level of relevance, but not so high, being in the range of 0.5–11%. For DRB, the impacts related to gravel decreased significantly (staying between 0.1–4%) as the coarser portion of the aggregates were replaced by recycled aggregates; however, in this case, the potential impacts caused by processing recycled aggregates were included in the modeling, which presented a variation from 0.2% to 4%. Concerning the concrete dosage plants, they showed not-so-significant contributions in both beams—staying in the range of 0.1–3%, since the main impact of cementitious materials comes from the calcination process and production of Portland cement [54]. Likewise, the other materials (e.g., filler, superplasticizer and water) do not significantly influence the results obtained in the life cycle modeling in general.

The avoided impacts related to the use of recycled aggregates in place of coarse aggregates are exhibited as negative values in the DRB graph (Figure 3b). Note that this is an important assessment, as these avoided impacts have amplitudes comparable to the sum of the transportation of all materials considered in modeling, e.g., for ozone depletion, transportation provides 12% of the total impacts while avoided impacts are 11%. These findings agree with previous studies from the literature [60,61].

In Figure 4, the avoided impacts are discretized in the processes that compose them, which are: natural aggregate extraction, final disposition in landfill, transportation of natural aggregates and transportation to landfill. In general, the participation of each process in each impact is quite similar. Some exceptions are that for the IR, HT-c, EF, WU and RM categories, the extraction of natural aggregates is clearly the most relevant process, as already verified in the studies of Hossein et al. [61]; and, for the LU category, the final disposition in landfill collaborates with the most significant share.

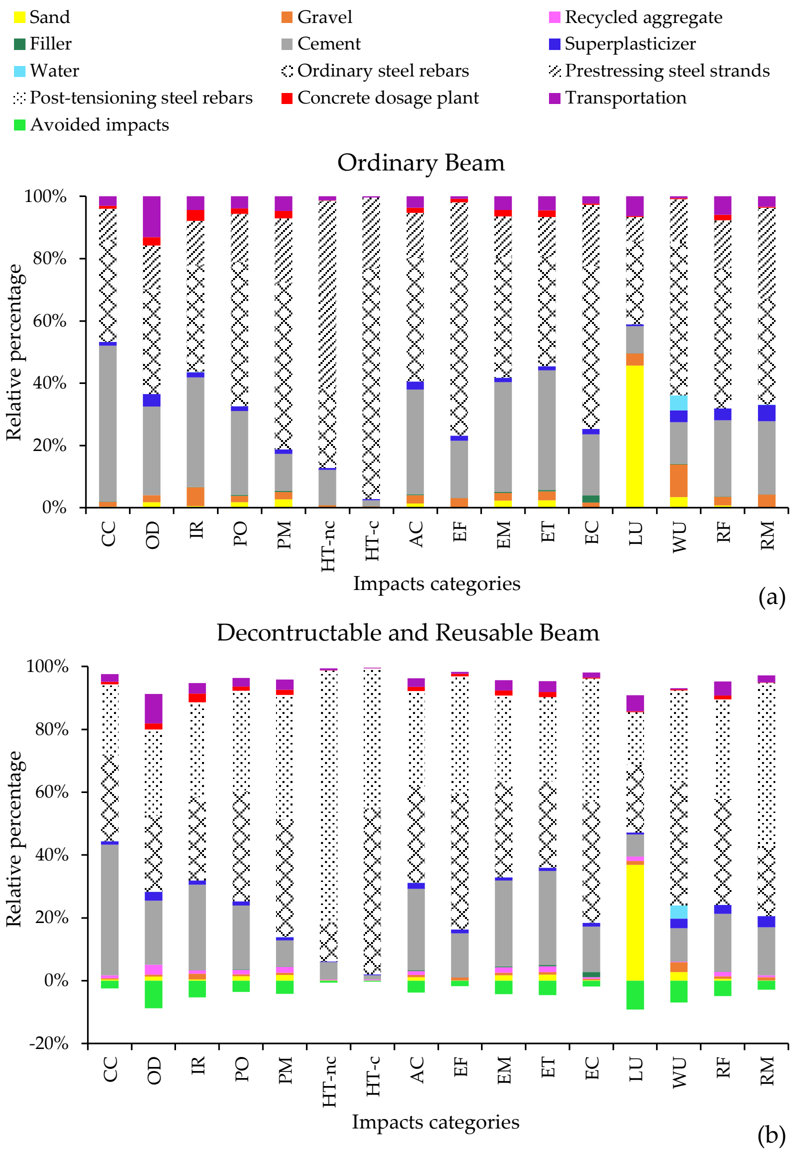


Figure 3. Potential environmental impacts of the life cycle of 1 m of (**a**) Ordinary Beam and (**b**) Deconstructable and Reusable Beam, presented as a cumulative percentage. CC—Climate change; OD—Ozone depletion; IR—Ionizing radiation; PO—Photochemical ozone formation; PM—

Particulate matter; HT-nc—Human toxicity, non-carcinogenic; HT-c—Human toxicity, carcinogenic; AC—Acidification; EF—Eutrophication, freshwater; EM—Eutrophication, marine; ET—Eutrophication, terrestrial; EC—Ecotoxicity, freshwater; LU—Land use; WU—Water use; RF—Resource use, fossils; RM—Resource use, minerals and metals.

In this study, recycled materials were used as coarse aggregate replacements. However, they can be used to replace fine aggregates or even cement. Since cement was another hotspot for most of the evaluated impacts, the replacement of it with recycled materials can generate greater benefits. The recycled concrete as powders can reduce the amount of cement as a filler material [62] or even a pozzolanic material, in this case recycling from calcined-clay waste [63,64].

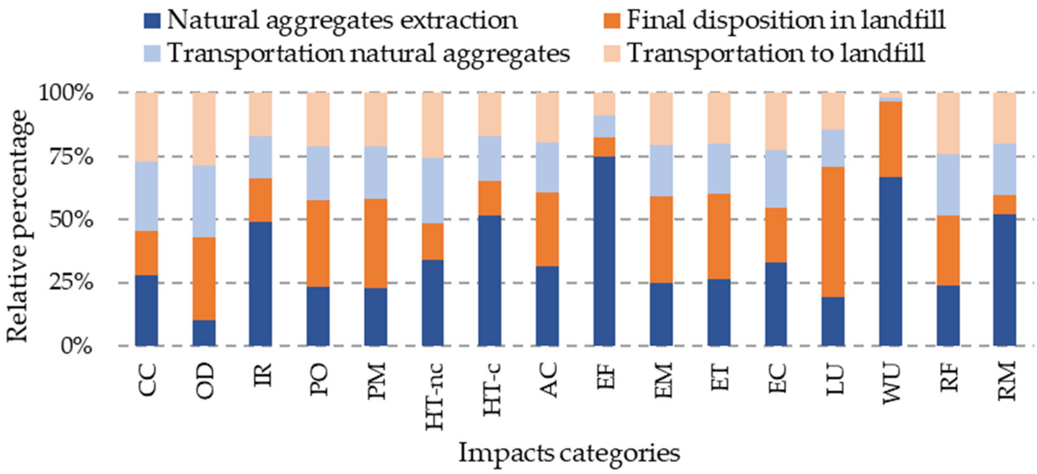


Figure 4. Cumulative percentage of the potential environmental impacts of processes related to the avoided impacts. CC—Climate change; OD—Ozone depletion; IR—Ionizing radiation; PO—Photochemical ozone formation; PM—Particulate matter; HT-nc—Human toxicity, non-carcinogenic; HT-c—Human toxicity, carcinogenic; AC—Acidification; EF—Eutrophication, freshwater; EM—Eutrophication, marine; ET—Eutrophication, terrestrial; EC—Ecotoxicity, freshwater; LU—Land use; WU—Water use; RF—Resource use, fossils; RM—Resource use, minerals and metals.

Figure 5 compares the potential environmental impacts generated by DRB normalized with respect to the ORB results. This comparison points out that the potential impacts of DRB are higher than ORB for all 16 categories—11 present values up to 30% higher than the ordinary beam, 4 are in the range of 30 to 50%, and only HT-nc shows values higher than 100%. As presented in Table 1, the composition of both beams is very similar (the only differences are in the amount of post-tensioning steel used in DRB, which is almost three times greater than the amount of prestressing steel used in ORB, and in the use of natural gravel in ORB and recycled aggregate in DRB), but with very close quantities. The joint observation of the information provided in Table 1 and the results gathered in Figures 3 and 5 clearly indicates that the greater consumption of steel for post-tensioning in DRB is responsible for the greater potential impacts for this beam when compared to ORB since, as already attested, steel was an important contributor to all impact categories.

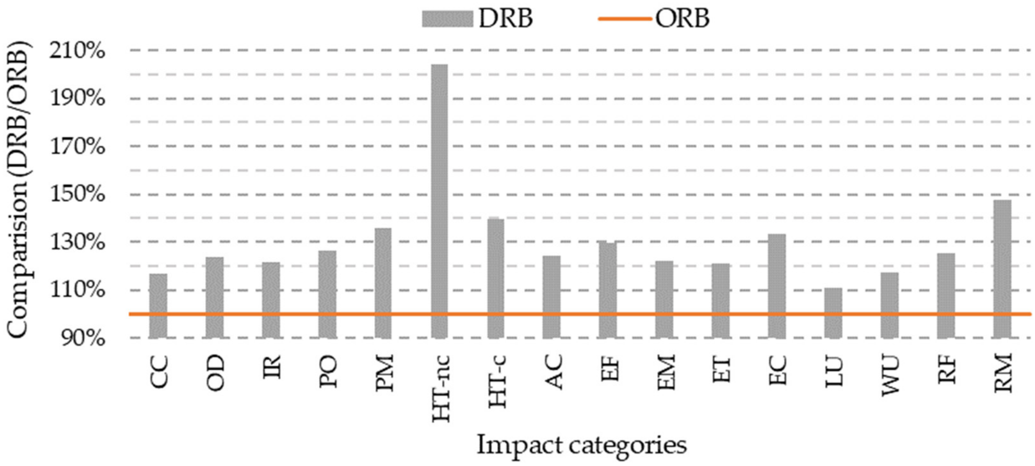


Figure 5. Normalized comparison between DRB and ORB (reference) potential environmental impacts. CC—Climate change; OD—Ozone depletion; IR—Ionizing radiation; PO—Photochemical ozone formation; PM—Particulate matter; HT-nc—Human toxicity, non-carcinogenic; HT-c—Human toxicity, carcinogenic; AC—Acidification; EF—Eutrophication, freshwater; EM—Eutrophication, marine; ET—Eutrophication, terrestrial; EC—Ecotoxicity, freshwater; LU—Land use; WU—Water use; RF—Resource use, fossils; RM—Resource use, minerals and metals.

3.2. Sensitivity Analysis

In this section, the comparison between the two beams is evaluated in terms of the chosen items for the sensitivity analysis. Figure 6 shows the life cycle modeling results of DRB, considering the data extracted from the EPD and Ecoinvent for steel, which were normalized in relation to the ORB results obtained considering, respectively, the data from the EPD and Ecoinvent. Thus, it is possible to display both results in a single graph, even if the normalizations have been completed individually for each case. As can be seen, when some environmental impacts of steel have a reduction, the difference between the two beams also reduces since the amount of steel is the main difference between the beams' compositions. For example, for RM, the decrease is 28%, and for HT-nc, it is 76%. This is expected for other types of steel, different from the ordinary one used in the construction sector, with higher mechanical performance, produced on a smaller scale (e.g., the case of prestressing steel strands/re-fer re-bars), which tends to have higher environmental impacts. When steel manufacturers start making more EPDs or similar LCA-based documents and studies for their specific products, it will be possible to use better quality data.

It is known that the production of steel is normally performed via two routes: an integrated route, which is highly emissions-intensive, with average emissions of 1.85 $kgCO_2$/kg steel, and a route that employs recycled steel with average emissions of around 0.4 $kgCO_2$/kg steel [65]. Steel production is normally associated with the intensive amount of energy consumption and Greenhouse Gas (GHG) emissions; however, toxicity impacts are worth analyzing, and trade-offs can occur between these impacts [66].

Therefore, for the LCA modeling of reusable concrete structures, the data quality of steel is a very important issue, especially if special types of steel are used in the product composition.

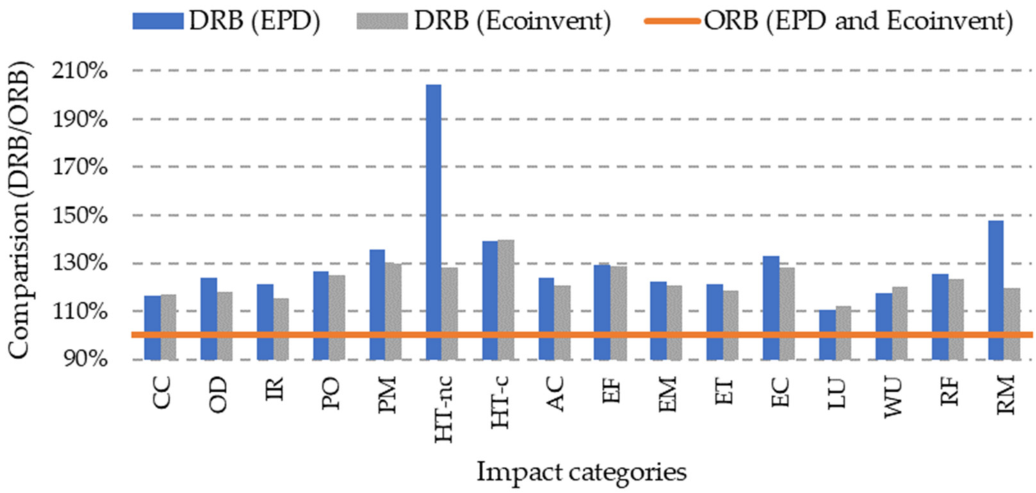


Figure 6. Normalized comparison between DRB and ORB (reference) potential environmental impacts, considering different data of steel. CC—Climate change; OD—Ozone depletion; IR—Ionizing radiation; PO—Photochemical ozone formation; PM—Particulate matter; HT-nc—Human toxicity, non-carcinogenic; HT-c—Human toxicity, carcinogenic; AC—Acidification; EF—Eutrophication, freshwater; EM—Eutrophication, marine; ET—Eutrophication, terrestrial; EC—Ecotoxicity, freshwater; LU—Land use; WU—Water use; RF—Resource use, fossils; RM—Resource use, minerals and metals.

Figure 7 makes it possible to compare the results of life cycle modeling for ORB and DRB, taking into account the different activities of obtaining sand, namely quarry operation and extraction from the riverbed. Thus, the results of life cycle modeling considering quarry operation for ORB and DRB were normalized regarding their respective results considering sand extracted from the riverbed, exposing both results in a single graph, even though the normalizations were individual, as in the previous figure. Note that only LU and WU potential impact categories exhibited significant differences. For ORB, using sand obtained by quarry operation instead of extracted from the riverbed generated a decrease of 44% for LU and an increase of 20% for WU. Similarly, for DRB, the decrease was 40% for LU, and the increase was 17% for WU.

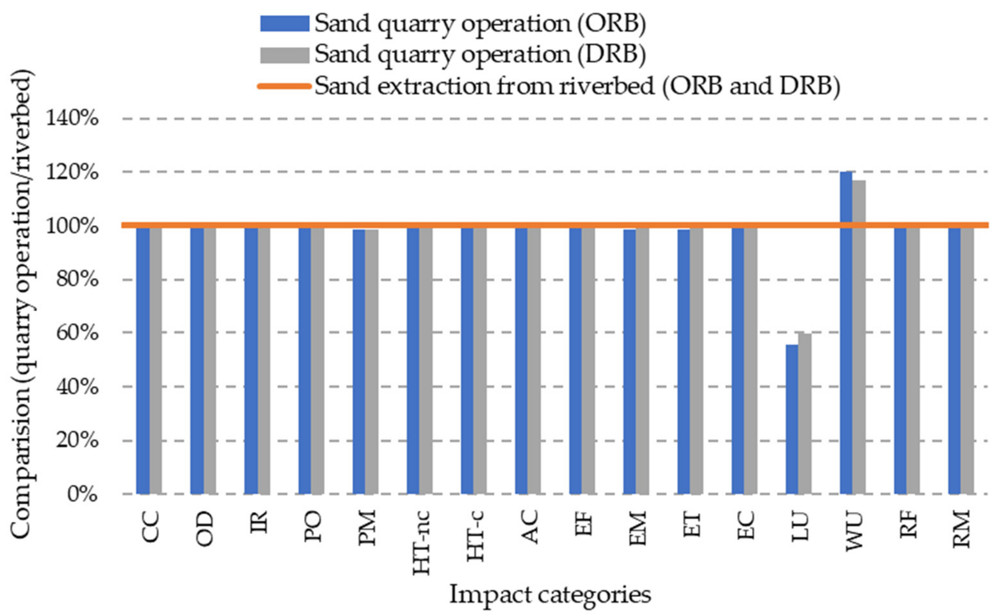


Figure 7. Sensitivity analysis of potential environmental impacts related to sand extraction processes for ORB (reference) and DRB normalized in relation to the riverbed extraction process. CC—Climate change; OD—Ozone depletion; IR—Ionizing radiation; PO—Photochemical ozone formation; PM—

Particulate matter; HT-nc—Human toxicity, non-carcinogenic; HT-c—Human toxicity, carcinogenic; AC—Acidification; EF—Eutrophication, freshwater; EM—Eutrophication, marine; ET—Eutrophication, terrestrial; EC—Ecotoxicity, freshwater; LU—Land use; WU—Water use; RF—Resource use, fossils; RM—Resource use, minerals and metals.

The influence of energy sources (electrical grids or diesel generators) on the activities of processing recycled aggregates for DRB is assessed in Figure 8. In this sense, the results of life cycle modeling with energy supplied by electrical grids were normalized concerning the results obtained considering diesel generators. Thus, it is evident in Figure 8 that the small differences resulting from the change of these energy sources are negligible in the potential impacts—in fact, the maximum increase was 0.3% in the IR category, and the maximum decrease was 0.6% in the PM category. EU-27 countries have already implemented radical policies to decarbonize the national energy grids and achieve the carbon-free objective targeted by 2050 for the energy sector [67]. A large reduction of fossil-driven energy production is expected by 2030, with a cut of 80% of coal, oil and natural gas and a consequential massive implementation of renewable sources, particularly wind and solar sources. Therefore, the sensitivity of the results shown in Figure 8, particularly the CC impact category, during the energy transition period, is expected to be strictly dependent on temporal factors and current geo-political structural changes.

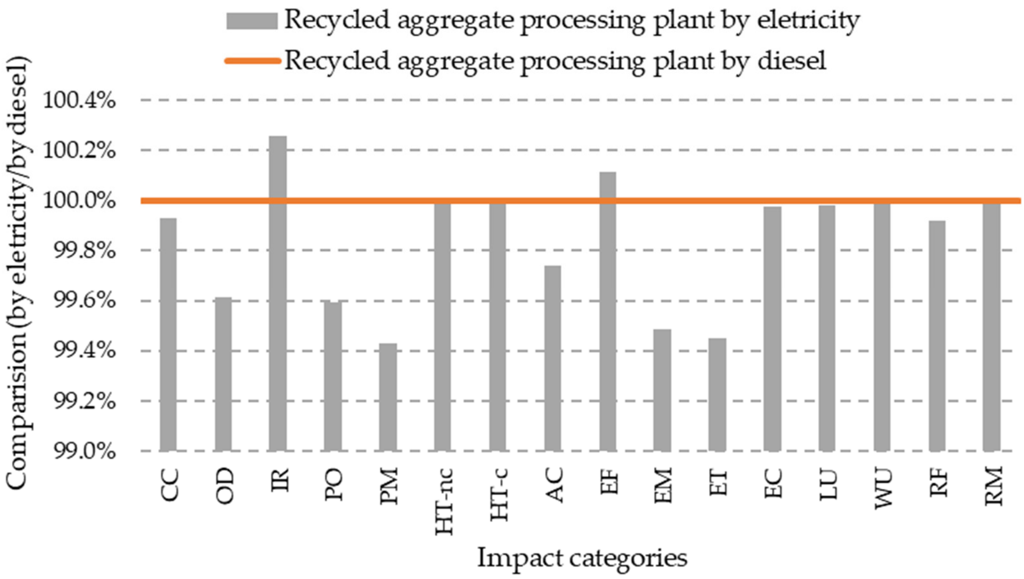


Figure 8. Sensitivity analysis of potential environmental impacts related to the recycled aggregate processing plant, normalized in relation to the plant by diesel. CC—Climate change; OD—Ozone depletion; IR—Ionizing radiation; PO—Photochemical ozone formation; PM—Particulate matter; HT-nc—Human toxicity, non-carcinogenic; HT-c—Human toxicity, carcinogenic; AC—Acidification; EF—Eutrophication, freshwater; EM—Eutrophication, marine; ET—Eutrophication, terrestrial; EC—Ecotoxicity, freshwater; LU—Land use; WU—Water use; RF—Resource use, fossils; RM—Resource use, minerals and metals.

3.3. Avoided Impacts Evaluation by Reuse

Finally, life cycle modeling was also performed considering the single score for ORB and DRB, allowing easier comparison of environmental impacts for DRB reuse scenarios. Thus, in Figure 9, the results of this modeling are presented, considering three allocation scenarios: 100-0 (cut-off), 50:50 (equal share) and 0-100 (end-of-life recycling). Making an initial analysis of the generated impacts (positive values), it is possible to strengthen the results already observed up to this point, where the cement and different types of steel were the main contributors to the impacts of the two beams. Specifically, for the DRB, the avoided impacts related to recycled aggregates and the different reuse scenarios are represented. In this comparison, the contribution from material production and the avoided impact was assumed without including demolition and reconstruction from ORB. A larger deviation of the results might be observed if multiple life cycles of the beam were assumed.

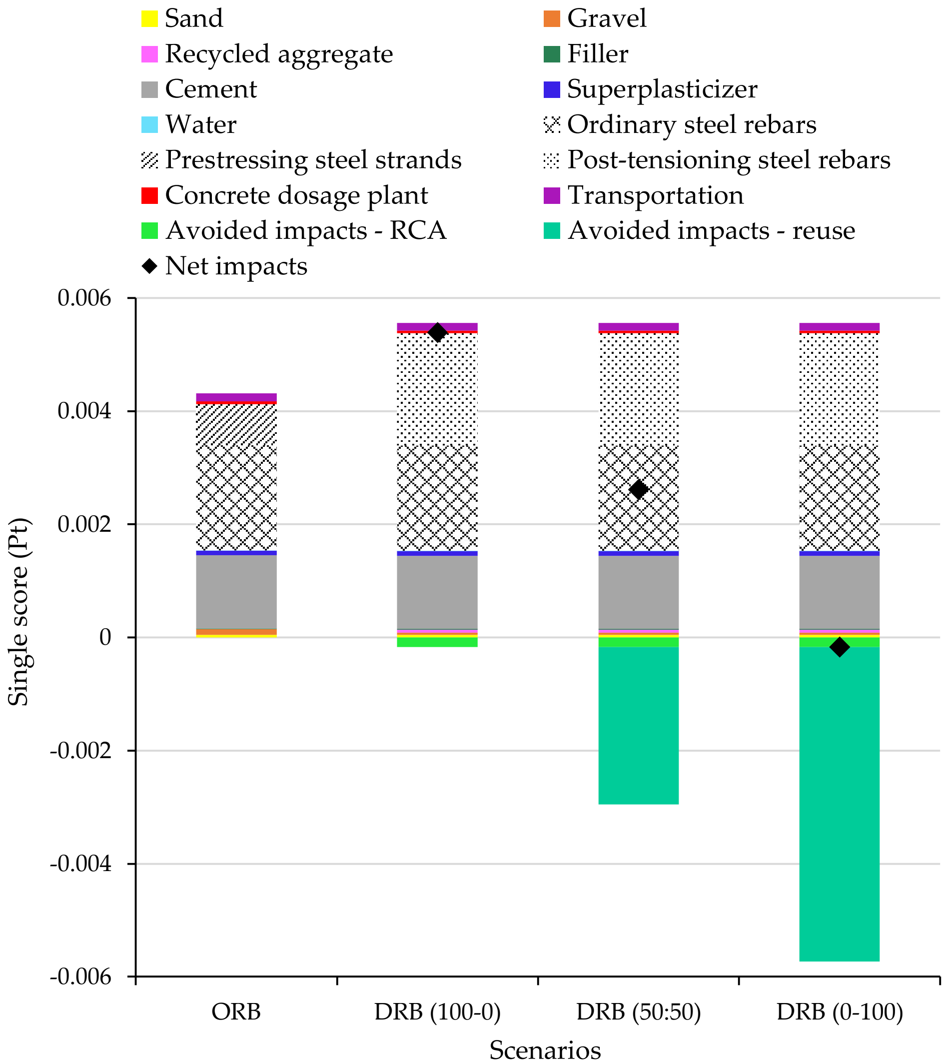


Figure 9. Single score (Pt) of the life cycle of ORB and three different scenarios of reuse of DBR: 100-0 (cut-off), 50:50 (equal share) and 0-100 (end-of-life recycling).

Regarding reuse scenarios, it is clear that when more benefits are allocated in the second life (0-100 case) of the beam, it will have fewer environmental impacts. However, it is important to state that this is a kind of artificial quantification that, beyond technical aspects, has political interests. It is already known that accounting for avoided impacts by LCA of reused elements or recycled materials is not well established in the scientific literature since there are difficulties in terms of methodological choices and the risk of double accounting [68–70]. On the other hand, in terms of CE, it is very important to quantify the benefits in order to incentivize reuse, recycling and DfD strategies and for this, it will be essential to have clear rules.

Most of the existing literature regarding the application of DfD in buildings is focused on steel and timber solutions [34,71]. There are few examples, such as the study of Xia et al. [40] on concrete structures, and this makes the comparison between our finds with previous works difficult. Thus, the present study serves as an important source of data for reusable concrete structures. The environmental benefits due to the reuse strategy are much greater than those from recycling, in agreement with the Xia et al. [40] findings.

Finally, it is important to highlight the main limitations of this study: the considered life cycle stages, the degradation process of reusable products (in case of concrete structures, especially due to carbonation and corrosion processes) and the reusable rate.

In terms of life cycle stages, the construction process of DfD structures is normally higher than conventional ones; Xia et al. [40] found an increase of around 20%. However, it is already known that the construction impacts are normally much smaller than the impacts of the materials production stage, normally corresponding to values below 5% of total impacts [54] for concrete structures, and this will result in insignificant differences.

Even if the end-of-life stage is not included within the system boundaries of the analysis, it can play a fundamental role in the life cycle carbon footprint due to waste treatment, which can increase the natural carbonation process [72]. Carbon uptake by portlandite (CH) and calcium silicate hydrate (CSH) is a chemical reaction that depends on: (i) type of concrete (air permeability and available CH and CSH); (ii) environmental conditions (relative humidity and CO_2 content); (iii) geometry of the cement-based element; (iv) exposition to the air (fully exposed, sheltered or protected); and (v) duration of the exposition. When included in carbon footprint assessment, carbonation can contribute to reducing the CC impact category if a long service life is planned for the structure [73]. Generally, only a minimal share of the carbon emissions through calcination is reabsorbed in the structure due to the slow carbonation front evolution [74]. However, when a structure is demolished, the kinetics change completely, as concrete is crushed, and the higher exposed surface to the air of particles increases the speed of CO_2 uptake [75].

Durability and degradation in the first life of the product are very difficult to predict, and depending on where the product is located and on the building layer composition (e.g., coverings and protection layers), the degradation process might be very slow [76]. Specifically, in this case study, in which the beam is made of a purely cement-based (without pozzolans that can reduce concrete pH) concrete with high compressive strength (60 MPa), the adopted solution tends to contribute positively to carbonation and corrosion processes.

4. Conclusions

In this study, a Deconstructable and Reusable Beam (DRB) with recycled aggregates (RACs) was compared with an ordinary (ORB) one in terms of environmental performance using the Life Cycle Assessment (LCA) methodology. Based on our research and the premises adopted in LCA modeling, we want to highlight the main findings:

- The simple comparison (without considering reuse scenarios) between DRB and ORB showed that the first option achieved higher rates of environmental impacts than the second, mainly regarding human toxicity (non-carcinogenic), in which the potential environmental impacts were 104% higher for DRB. For other impact categories, this increase was up to 50%.
- DRB presented higher environmental impacts than ORB due to the higher amount of post-tensioning steel, which is almost three times greater than that used in ORB.
- New deconstructable and reusable beams should pay attention to the design process, especially in terms of the use of special steel reinforcements. Therefore, the data quality of steel is a very important issue in LCA modeling.
- When steel data are compared, there are big differences for some impact categories (more than 50%), such as human toxicity (non-carcinogenic) and resource use (minerals and metals).
- When the avoided impacts of recycling are accounted for as benefits, a 9% reduction in impacts was observed for the Land Use and Ozone depletion categories.

- The sensitivity analysis in terms of steel data, sand extraction process (quarry operation or riverbed) and type of process for recycled aggregate production showed that the overall conclusions do not change, strengthening our findings.
- The benefits due to reuse scenarios can drastically reduce the impacts of DRB. When impacts were equally divided between all cycles (50:50 approach), DRB presented a net impact value 39% lower than the ordinary beam. This reduction was even greater (104%) when the impacts were fully directed to the second life cycle (0-100 approach). However, allocation approaches and methodological issues must be well defined.

Our study highlights the importance of accounting for the benefits when reuse and recycling strategies are introduced for the development of circular building products in order to incentivize this kind of development. Although it is already known that there is no consensus in terms of the methodology that should be used to account for benefits (especially for reuse of elements), it is important to evaluate different scenarios or approaches, to see how methodological choices affect the decision-making process.

For future works, other life cycle stages should be considered, including the potential of degradation of the element and the carbonation in end-of-life of concrete structures and improvements of the data used in modeling. For further research, the authors also recommend performing finite element modeling (FEM) of the Deconstructable and Reusable Beam and then performing a parametric study using the proposed FEM to fully understand the behavior of this innovative structural element.

Author Contributions: Conceptualization, L.C.M., L.I.C.F., L.R.C., M.P., F.P., R.D.T.F. and E.M.; methodology, L.C.M., L.I.C.F., L.R.C., M.P. and F.P.; software, L.I.C.F.; validation, L.C.M., L.I.C.F., L.R.C., M.P. and F.P.; formal analysis, L.C.M., L.I.C.F., L.R.C., M.P., F.P., R.D.T.F. and E.M.; investigation, L.C.M., L.I.C.F., L.R.C., M.P., F.P., R.D.T.F. and E.M.; resources, M.P., G.Z., M.C.R., J.M. and E.M.; data curation, L.I.C.F., M.P., G.Z., M.C.R., J.M.; writing—original draft preparation, L.C.M., L.I.C.F., L.R.C., M.P., F.P., R.D.T.F. and E.M.; writing—review and editing, L.C.M., L.I.C.F., L.R.C., M.P., F.P., R.D.T.F. and E.M.; visualization, L.R.C., M.P., F.P., G.Z., M.C.R., J.M. and R.D.T.F.; supervision, L.R.C., M.P., F.P., G.Z., M.C.R., J.M. and R.D.T.F.; project administration, L.R.C., M.P., R.D.T.F. and E.M.; funding acquisition, M.P., J.M., F.P. and E.M. All authors have read and agreed to the published version of the manuscript.

Funding: This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 873964 (METABUILDING project). The research was also funded by NEST Project from Architecture, Built environment and Construction Engineering (ABC) department of Politecnico de Milano.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Environmental impact factors.

	Environmental Impact Categories	CC kg CO_2 eq	OD 10^{-8} kg CFC11 eq	IR kBq U-235 eq	PO 10^{-3} kg NMVOC eq
Concrete	Sand-riverbed (kg)	0.0047	0.0995	0.0003	0.0640
	Sand-quarry operation (kg)	0.0042	0.0398	0.0004	0.0274
	Gravel (kg)	0.0085	0.0665	0.0019	0.0377
	Recycled aggregate-diesel (kg)	0.0022	0.0467	0.0001	0.0303
	Recycled aggregate-electricity (kg)	0.0014	0.0206	0.0003	0.0131
	Filler (kg)	0.0028	0.0458	0.0002	0.0603
	Cement (kg)	0.8726	2.5771	0.0334	1.5164

	Superplasticizer (kg)	1.3324	21.2954	0.0935	5.1678
	Water (kg)	0.0004	0.0023	0.0001	0.0011
Steel	Ordinary steel rebars (kg)	1.8905	10.1704	0.1074	8.6492
	Prestressing steel strands (kg)	1.8660	13.6000	0.1450	9.3100
	Post-tensioning steel rebars (kg)	1.8660	13.6000	0.1450	9.3100
	Concrete dosage plant (m³)	5.6279	88.2950	1.2308	35.9557
	Transportation (t.km)	0.1664	3.7687	0.0131	0.6785
	Final disposition in landfill (kg)	0.0053	0.2163	0.0007	0.0549
	Environmental Impact Categories	**PM Disease inc. (10^{-8})**	**HT-nc 10^{-8} CTUh**	**HT-c 10^{-8} CTUh**	**AC 10^{-3} mol H+ eq**
Concrete	Sand-riverbed (kg)	0.1272	0.0028	0.0002	0.0485
	Sand-quarry operation (kg)	0.0515	0.0065	0.0004	0.0291
	Gravel (kg)	0.0622	0.0128	0.0010	0.0525
	Recycled aggregate-diesel (kg)	0.0601	0.0013	0.0006	0.0230
	Recycled aggregate-electricity (kg)	0.0243	0.0010	0.0005	0.0117
	Filler (kg)	0.0841	0.0043	0.0002	0.0573
	Cement (kg)	0.9202	0.5662	0.0132	1.9537
	Superplasticizer (kg)	6.5637	1.5355	0.1673	8.4819
	Water (kg)	0.0016	0.0019	0.0001	0.0019
Steel	Ordinary steel rebars (kg)	13.6944	4.2443	1.6700	7.6478
	Prestressing steel strands (kg)	17.1000	32.3000	1.6600	8.9700
	Post-tensioning steel rebars (kg)	17.1000	32.3000	1.6600	8.9700
	Concrete dosage plant (m³)	64.0154	3.2438	0.1849	37.3637
	Transportation (t.km)	1.1492	0.1948	0.0068	0.6645
	Final disposition in landfill (kg)	0.0969	0.0057	0.0003	0.0496
	Environmental Impact Categories	**EF 10^{-3} kg P eq**	**EM 10^{-3} kg N eq**	**ET 10^{3} mol N eq**	**EC CTUe**
Concrete	Sand-riverbed (kg)	0.0002	0.0213	0.00023	0.039
	Sand-quarry operation (kg)	0.0013	0.0089	0.00010	0.078
	Gravel (kg)	0.0048	0.0125	0.00015	0.138
	Recycled aggregate-diesel (kg)	0.0001	0.0101	0.00011	0.020
	Recycled aggregate-electricity (kg)	0.0005	0.0044	0.00005	0.014
	Filler (kg)	0.0004	0.0201	0.00028	2.231
	Cement (kg)	0.0867	0.5328	0.00604	5.333
	Superplasticizer (kg)	0.4350	1.1935	0.01259	27.099
	Water (kg)	0.0002	0.0004	0.00000	0.006
Steel	Ordinary steel rebars (kg)	0.8922	1.9463	0.01842	47.002
	Prestressing steel strands (kg)	0.9100	2.1000	0.02110	56.700
	Post-tensioning steel rebars (kg)	0.9100	2.1000	0.02110	56.700
	Concrete dosage plant (m³)	1.8936	12.1599	0.12940	47.909
	Transportation (t.km)	0.0111	0.2035	0.00222	1.918
	Final disposition in landfill (kg)	0.0005	0.0173	0.00019	0.092
	Environmental Impact Categories	**LU Pt**	**WU m³ depriv.**	**RF MJ**	**RM 10^{-6} kg Sb eq**
Concrete	Sand-riverbed (kg)	2.4496	0.0087	0.0649	0.0032
	Sand-quarry operation (kg)	0.0676	0.0602	0.0517	0.0336
	Gravel (kg)	0.1130	0.0147	0.1226	0.0776

	Recycled aggregate-diesel (kg)	0.0042	0.0001	0.0302	0.0011
	Recycled aggregate-electricity (kg)	0.0032	0.0001	0.0218	0.0016
	Filler (kg)	0.0163	0.0035	0.0348	0.0109
	Cement (kg)	0.7638	0.0562	3.3137	1.3281
	Superplasticizer (kg)	3.1868	0.9356	30.4979	17.6673
	Water (kg)	0.0014	0.0431	0.0058	0.0016
Steel	Ordinary steel rebars (kg)	7.7564	0.6897	20.1647	6.4287
	Prestressing steel strands (kg)	7.1000	0.6120	22.3000	17.6000
	Post-tensioning steel rebars (kg)	7.1000	0.6120	22.3000	17.6000
	Concrete dosage plant (m^3)	11.5360	0.4675	88.3039	5.5456
	Transportation (t.km)	1.7284	0.0071	2.5103	0.5978
	Final disposition in landfill (kg)	0.3090	0.0066	0.1470	0.0117

Table A2. Potential environmental impacts of the life cycle of 1 m of the Ordinary Beam (ORB).

	Environmental Impact Categories	**CC** kg CO_2 eq	**OD** 10^{-8} kg CFC11 eq	**IR** kBq U-235 eq	**PO** kg NMVOC eq
Concrete	Sand	0.241	5.078	0.016	0.003
	Gravel	0.805	6.289	0.180	0.004
	Recycled aggregate	0.000	0.000	0.000	0.000
	Filler	0.023	0.377	0.002	0.000
	Cement	27.288	80.588	1.043	0.047
	Superplasticizer	0.713	11.391	0.050	0.003
	Water	0.005	0.034	0.002	0.000
Steel	Ordinary steel rebars	17.844	95.994	1.014	0.082
	Prestressing steel strands	5.456	39.765	0.424	0.027
	Post-tensioning steel rebars	0.000	0.000	0.000	0.000
	Concrete dosage plant	0.473	7.417	0.103	0.003
	Transportation	1.648	37.320	0.130	0.007
	Avoided impacts	0.000	0.000	0.000	0.000
	Total	54.496	284.254	2.964	0.176
	Environmental Impact Categories	**PM** Disease inc. (10^{-8})	**HT-nc** 10^{-8} CTUh	**HT-c** 10^{-8} CTUh	**AC** mol H+ eq
Concrete	Sand	6.488	0.141	0.012	0.002
	Gravel	5.883	1.215	0.097	0.005
	Recycled aggregate	0.000	0.000	0.000	0.000
	Filler	0.692	0.035	0.001	0.000
	Cement	28.775	17.705	0.412	0.061
	Superplasticizer	3.511	0.821	0.089	0.005
	Water	0.024	0.028	0.002	0.000
Steel	Ordinary steel rebars	129.255	40.060	15.762	0.072
	Prestressing steel strands	49.999	94.443	4.854	0.026
	Post-tensioning steel rebars	0.000	0.000	0.000	0.000
	Concrete dosage plant	5.377	0.272	0.016	0.003
	Transportation	11.380	1.929	0.068	0.007
	Avoided impacts	0.000	0.000	0.000	0.000
	Total	241.384	156.649	21.313	0.182
	Environmental Impact Categories	**EF** 10^{-3} kg P eq	**EM** 10^{-3} kg N eq	**ET** 10^{-3} mol N eq	**EC** CTUe

Concrete	Sand	0.011	1.086	11.922	1.972
	Gravel	0.457	1.178	14.057	13.049
	Recycled aggregate	0.000	0.000	0.000	0.000
	Filler	0.003	0.165	2.287	18.360
	Cement	2.711	16.661	188.843	166.783
	Superplasticizer	0.233	0.638	6.732	14.495
	Water	0.004	0.005	0.051	0.085
Steel	Ordinary steel rebars	8.421	18.370	173.829	443.633
	Prestressing steel strands	2.661	6.140	61.695	165.786
	Post-tensioning steel rebars	0.000	0.000	0.000	0.000
	Concrete dosage plant	0.159	1.021	10.870	4.024
	Transportation	0.110	2.015	21.985	18.996
	Avoided impacts	0.000	0.000	0.000	0.000
	Total	14.769	47.281	492.271	847.185
	Environmental Impact Categories	**LU Pt**	**WU m^3 depriv.**	**RF MJ**	**RM 10^{-6} kg Sb eq**
Concrete	Sand	124.984	0.445	3.313	0.164
	Gravel	10.694	1.387	11.603	7.345
	Recycled aggregate	0.000	0.000	0.000	0.000
	Filler	0.134	0.029	0.286	0.090
	Cement	23.884	1.757	103.623	41.531
	Superplasticizer	1.705	0.500	16.313	9.450
	Water	0.021	0.638	0.087	0.024
Steel	Ordinary steel rebars	73.209	6.510	190.325	60.678
	Prestressing steel strands	20.760	1.789	65.203	51.461
	Post-tensioning steel rebars	0.000	0.000	0.000	0.000
	Concrete dosage plant	0.969	0.039	7.418	0.466
	Transportation	17.116	0.071	24.859	5.919
	Avoided impacts	0.000	0.000	0.000	0.000
	Total	273.474	13.166	423.029	177.128

Table A3. Potential environmental impacts of the life cycle of 1 m of the Deconstructable and Reusable Beam (DRB) with Ecoinvent and steel EPD data.

	Environmental Impact Categories	**CC kg CO_2 eq**	**OD 10^{-8} kg CFC11 eq**	**IR kBq U-235 eq**	**PO kg NMVOC eq**
Concrete	Sand	0.241	5.078	0.016	0.003
	Gravel	0.308	2.406	0.069	0.001
	Recycled aggregate	0.552	12.326	0.042	0.003
	Filler	0.023	0.377	0.002	0.000
	Cement	27.288	80.588	1.043	0.047
	Superplasticizer	0.713	11.391	0.050	0.003
	Water	0.006	0.036	0.002	0.000
Steel	Ordinary steel rebars	17.844	95.994	1.014	0.082
	Prestressing steel strands	0.000	0.000	0.000	0.000
	Post-tensioning steel rebars	14.929	108.807	1.160	0.074
	Concrete dosage plant	0.473	7.417	0.103	0.003
	Transportation	1.640	37.145	0.129	0.007

Avoided impacts	Natural aggregates extraction	0.446	3.484	0.100	0.002
	Transportation natural aggregates	0.436	9.878	0.034	0.002
	Final disposition in landfill	0.276	11.336	0.034	0.003
	Transportation to landfill	0.436	9.878	0.034	0.002
	Total	63.580	351.688	3.595	0.223
	Environmental Impact Categories	**PM Disease inc. (10^{-8})**	**HT-nc 10^{-8} CTUh**	**HT-c 10^{-8} CTUh**	**AC mol H+ eq**
Concrete	Sand	6.488	0.141	0.012	0.002
	Gravel	2.251	0.465	0.037	0.002
	Recycled aggregate	6.160	0.578	0.049	0.003
	Filler	0.692	0.035	0.001	0.000
	Cement	28.775	17.705	0.412	0.061
	Superplasticizer	3.511	0.821	0.089	0.005
	Water	0.026	0.030	0.002	0.000
Steel	Ordinary steel rebars	129.255	40.060	15.762	0.072
	Prestressing steel strands	0.000	0.000	0.000	0.000
	Post-tensioning steel rebars	136.809	258.416	13.281	0.072
	Concrete dosage plant	5.377	0.272	0.016	0.003
	Transportation	11.326	1.920	0.067	0.007
Avoided impacts	Natural aggregates extraction	3.259	0.673	0.054	0.003
	Transportation natural aggregates	3.012	0.511	0.018	0.002
	Final disposition in landfill	5.082	0.301	0.014	0.003
	Transportation to landfill	3.012	0.511	0.018	0.002
	Total	327.658	319.934	29.711	0.225
	Environmental Impact Categories	**EF 10^{-3} kg P eq**	**EM 10^{-3} kg N eq**	**ET 10^{-3} mol N eq**	**EC CTUe**
Concrete	Sand	0.011	1.086	11.922	1.972
	Gravel	0.175	0.451	5.378	4.993
	Recycled aggregate	0.034	1.062	11.607	6.058
	Filler	0.003	0.165	2.287	18.360
	Cement	2.711	16.661	188.843	166.783
	Superplasticizer	0.233	0.638	6.732	14.495
	Water	0.004	0.006	0.055	0.092
Steel	Ordinary steel rebars	8.421	18.370	173.829	443.633
	Prestressing steel strands	0.000	0.000	0.000	0.000
	Post-tensioning steel rebars	7.280	16.801	168.811	453.629
	Concrete dosage plant	0.159	1.021	10.870	4.024
	Transportation	0.110	2.005	21.882	18.907
Avoided impacts	Natural aggregates extraction	0.253	0.653	7.786	7.228
	Transportation natural aggregates	0.029	0.533	5.819	5.028
	Final disposition in landfill	0.026	0.906	9.925	4.846
	Transportation to landfill	0.029	0.533	5.819	5.028
	Total	19.111	57.734	596.397	1127.918
	Environmental Impact Categories	**LU Pt**	**WU m^3 depriv.**	**RF MJ**	**RM 10^{-6} kg Sb eq**
Concrete	Sand	124.984	0.445	3.313	0.164
	Gravel	4.091	0.531	4.439	2.810
	Recycled aggregate	4.751	0.025	8.161	1.624

	Filler	0.134	0.029	0.286	0.090
	Cement	23.884	1.757	103.623	41.531
	Superplasticizer	1.705	0.500	16.313	9.450
	Water	0.022	0.684	0.093	0.026
Steel	Ordinary steel rebars	73.209	6.510	190.325	60.678
	Prestressing steel strands	0.000	0.000	0.000	0.000
	Post-tensioning steel rebars	56.804	4.896	178.411	140.809
	Concrete dosage plant	0.969	0.039	7.418	0.466
	Transportation	17.036	0.070	24.742	5.892
Avoided impacts	Natural aggregates extraction	5.923	0.768	6.427	4.069
	Transportation natural aggregates	4.530	0.019	6.579	1.567
	Final disposition in landfill	16.197	0.346	7.704	0.615
	Transportation to landfill	4.530	0.019	6.579	1.567
	Total	303.058	15.468	530.544	261.973

Table A4. Potential environmental impacts of the life cycle of 1 m of the Deconstructable and Reusable Beam (DRB) with just Ecoinvent data.

	Environmental Impact Categories	**CC kg CO_2 eq**	**OD 10^{-8} kg CFC11 eq**	**IR kBq U-235 eq**	**PO kg NMVOC eq**
Concrete	Sand	0.241	5.078	0.016	0.003
	Gravel	0.308	2.406	0.069	0.001
	Recycled aggregate	0.552	12.326	0.042	0.003
	Filler	0.023	0.377	0.002	0.000
	Cement	27.288	80.588	1.043	0.047
	Superplasticizer	0.713	11.391	0.050	0.003
	Water	0.006	0.036	0.002	0.000
Steel	Ordinary steel rebars	17.844	95.994	1.014	0.082
	Prestressing steel strands	0.000	0.000	0.000	0.000
	Post-tensioning steel rebars	15.125	81.369	0.859	0.069
	Concrete dosage plant	0.473	7.417	0.103	0.003
	Transportation	1.640	37.145	0.129	0.007
Avoided impacts	Natural aggregates extraction	0.446	3.484	0.100	0.002
	Transportation natural aggregates	0.436	9.878	0.034	0.002
	Final disposition in landfill	0.276	11.336	0.034	0.003
	Transportation to landfill	0.436	9.878	0.034	0.002
	Total	63.776	324.249	3.295	0.217
	Environmental Impact Categories	**PM Disease inc. (10^{-8})**	**HT-nc 10^{-8} CTUh**	**HT-c 10^{-8} CTUh**	**AC mol H+ eq**
Concrete	Sand	6.488	0.141	0.012	0.002
	Gravel	2.251	0.465	0.037	0.002
	Recycled aggregate	6.160	0.578	0.049	0.003
	Filler	0.692	0.035	0.001	0.000
	Cement	28.775	17.705	0.412	0.061
	Superplasticizer	3.511	0.821	0.089	0.005
	Water	0.026	0.030	0.002	0.000
Steel	Ordinary steel rebars	129.255	40.060	15.762	0.072
	Prestressing steel strands	0.000	0.000	0.000	0.000

	Post-tensioning steel rebars	109.562	33.956	13.361	0.061
	Concrete dosage plant	5.377	0.272	0.016	0.003
	Transportation	11.326	1.920	0.067	0.007
Avoided impacts	Natural aggregates extraction	3.259	0.673	0.054	0.003
	Transportation natural aggregates	3.012	0.511	0.018	0.002
	Final disposition in landfill	5.082	0.301	0.014	0.003
	Transportation to landfill	3.012	0.511	0.018	0.002
	Total	300.412	95.474	29.791	0.215
	Environmental Impact Categories	**EF 10^{-3} kg P eq**	**EM 10^{-3} kg N eq**	**ET 10^{-3} mol N eq**	**EC CTUe**
Concrete	Sand	0.011	1.086	11.922	1.972
	Gravel	0.175	0.451	5.378	4.993
	Recycled aggregate	0.034	1.062	11.607	6.058
	Filler	0.003	0.165	2.287	18.360
	Cement	2.711	16.661	188.843	166.783
	Superplasticizer	0.233	0.638	6.732	14.495
	Water	0.004	0.006	0.055	0.092
Steel	Ordinary steel rebars	8.421	18.370	173.829	443.633
	Prestressing steel strands	0.000	0.000	0.000	0.000
	Post-tensioning steel rebars	7.138	15.571	147.345	376.042
	Concrete dosage plant	0.159	1.021	10.870	4.024
	Transportation	0.110	2.005	21.882	18.907
Avoided impacts	Natural aggregates extraction	0.253	0.653	7.786	7.228
	Transportation natural aggregates	0.029	0.533	5.819	5.028
	Final disposition in landfill	0.026	0.906	9.925	4.846
	Transportation to landfill	0.029	0.533	5.819	5.028
	Total	18.969	56.504	574.931	1,050.331
	Environmental Impact Categories	**LU Pt**	**WU m^3 depriv.**	**RF MJ**	**RM 10^{-6} kg Sb eq**
Concrete	Sand	124.984	0.445	3.313	0.164
	Gravel	4.091	0.531	4.439	2.810
	Recycled aggregate	4.751	0.025	8.161	1.624
	Filler	0.134	0.029	0.286	0.090
	Cement	23.884	1.757	103.623	41.531
	Superplasticizer	1.705	0.500	16.313	9.450
	Water	0.022	0.684	0.093	0.026
Steel	Ordinary steel rebars	73.209	6.510	190.325	60.678
	Prestressing steel strands	0.000	0.000	0.000	0.000
	Post-tensioning steel rebars	62.055	5.518	161.328	51.433
	Concrete dosage plant	0.969	0.039	7.418	0.466
	Transportation	17.036	0.070	24.742	5.892
Avoided impacts	Natural aggregates extraction	5.923	0.768	6.427	4.069
	Transportation natural aggregates	4.530	0.019	6.579	1.567
	Final disposition in landfill	16.197	0.346	7.704	0.615
	Transportation to landfill	4.530	0.019	6.579	1.567
	Total	308.310	16.090	513.461	172.597

Table A5. Single score (Pt) of the life cycle of ORB and three different scenarios of reuse of DBR.

	Environmental Impact Categories Single Score (Pt) (10^{-3})	ORB	DRB (100-0)	DRB (50:50)	DRB (0-100)
Concrete	Sand	0.048	0.048	0.048	0.048
	Gravel	0.097	0.037	0.037	0.037
	Recycled aggregate	0.000	0.053	0.053	0.053
	Filler	0.013	0.013	0.013	0.013
	Cement	1.294	1.294	1.294	1.294
	Superplasticizer	0.084	0.084	0.084	0.084
	Water	0.005	0.006	0.006	0.006
Steel	Ordinary steel rebars	1.861	1.861	1.861	1.861
	Prestressing steel strands	0.724	0.000	0.000	0.000
	Post-tensioning steel rebars	0.000	1.980	1.980	1.980
	Concrete dosage plant	0.048	0.048	0.048	0.048
	Transportation	0.139	0.138	0.138	0.138
	Avoided impacts-RCA	0.000	0.170	0.170	0.170
	Avoided impacts-Reuse	0.000	0.000	2.781	5.562
	Net impacts	4.313	5.391	2.611	-0.170

References

1. IEA—International Energy Agency. Technology Roadmap—Low-Carbon Transition in the Cement Industry, Paris, April 2018. Available online: https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry (accessed on 9 July 2022).
2. Fiol, F.; Thomas, C.; Manso, J.M.; López, I. Influence of Recycled Precast Concrete Aggregate on Durability of Concrete's Physical Processes. *Appl. Sci.* **2020**, *10*, 7348. https://doi.org/10.3390/app10207348.
3. Imtiaz, L.; Kashif-Ur-Rehman, S.; Alaloul, W.S.; Nazir, K.; Javed, M.F.; Aslam, F.; Musarat, M.A. Life Cycle Impact Assessment of Recycled Aggregate Concrete, Geopolymer Concrete, and Recycled Aggregate-Based Geopolymer Concrete. *Sustainability* **2021**, *13*, 13515. https://doi.org/10.3390/su132413515.
4. Caldas, L.R.; Saraiva, A.B.; Lucena, A.F.; Da Gloria, M.Y.; Santos, A.S.; Filho, R.D.T. Building materials in a circular economy: The case of wood waste as CO2-sink in bio concrete. *Resour. Conserv. Recycl.* **2020**, *166*, 105346. https://doi.org/10.1016/j.resconrec.2020.105346.
5. Caldas, L.R.; Saraiva, A.B.; Andreola, V.M.; Filho, R.D.T. Bamboo bio-concrete as an alternative for buildings' climate change mitigation and adaptation. *Constr. Build. Mater.* **2020**, *263*, 120652. https://doi.org/10.1016/j.conbuildmat.2020.120652.
6. Da Gloria, M.Y.R.; Andreola, V.M.; dos Santos, D.O.J.; Pepe, M.; Filho, R.D.T. A comprehensive approach for designing workable bio-based cementitious composites. *J. Build. Eng.* **2020**, *34*, 101696. https://doi.org/10.1016/j.jobe.2020.101696.
7. Jamaludin, N.F.A.; Muthusamy, K.; Jaafar, M.F.; Yahaya, F.M. Use of Palm Oil Clinker in Concrete Research: A Review. *Construction* **2021**, *1*, 35–43. https://doi.org/10.15282/construction.v1i1.6436.
8. Minunno, R.; O'Grady, T.; Morrison, G.M.; Gruner, R.L. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. *Resour. Conserv. Recycl.* **2020**, *160*, 104855. https://doi.org/10.1016/j.resconrec.2020.104855.
9. Verian, K.P.; Ashraf, W.; Cao, Y. Properties of recycled concrete aggregate and their influence in new concrete production. *Resour. Conserv. Recycl.* **2018**, *133*, 30–49. https://doi.org/10.1016/j.resconrec.2018.02.005.
10. Pani, L.; Francesconi, L.; Rombi, J.; Mistretta, F.; Sassu, M.; Stochino, F. Effect of Parent Concrete on the Performance of Recycled Aggregate Concrete. *Sustainability* **2020**, *12*, 9399. https://doi.org/10.3390/su12229399.
11. Ouyang, K.; Shi, C.; Chu, H.; Guo, H.; Song, B.; Ding, Y.; Guan, X.; Zhu, J.; Zhang, H.; Wang, Y.; et al. An overview on the efficiency of different pretreatment techniques for recycled concrete aggregate. *J. Clean. Prod.* **2020**, *263*, 121264. https://doi.org/10.1016/j.jclepro.2020.121264.
12. Rangel, C.S.; Pepe, M.; Amario, M.; Menegatti, L.C.; Martinelli, E.; Filho, R.D.T. Effects of Freeze-Thaw and Wet-Dry Cycles on Tension Stiffening Behavior of Reinforced RAC Elements. *Appl. Sci.* **2021**, *11*, 10063. https://doi.org/10.3390/app112110063.
13. Bu, C.; Liu, L.; Lu, X.; Zhu, D.; Sun, Y.; Yu, L.; OuYang, Y.; Cao, X.; Wei, Q. The Durability of Recycled Fine Aggregate Concrete: A Review. *Materials* **2022**, *15*, 1110. https://doi.org/10.3390/ma15031110.
14. Amario, M.; Rangel, C.S.; Pepe, M.; Filho, R.D.T. Optimization of normal and high strength recycled aggregate concrete mixtures by using packing model. *Cem. Concr. Compos.* **2017**, *84*, 83–92. https://doi.org/10.1016/j.cemconcomp.2017.08.016.
15. Alqarni, A.S.; Abbas, H.; Al-Shwikh, K.M.; Al-Salloum, Y.A. Influence of Treatment Methods of Recycled Concrete Aggregate on Behavior of High Strength Concrete. *Buildings* **2022**, *12*, 494. https://doi.org/10.3390/buildings12040494.

16. Xing, W.; Tam, V.W.; Le, K.N.; Hao, J.L.; Wang, J. Life cycle assessment of recycled aggregate concrete on its environmental impacts: A critical review. *Constr. Build. Mater.* **2021**, *317*, 125950. https://doi.org/10.1016/j.conbuildmat.2021.125950.
17. Zhang, Y.; Luo, W.; Wang, J.; Wang, Y.; Xu, Y.; Xiao, J. A review of life cycle assessment of recycled aggregate concrete. *Constr. Build. Mater.* **2019**, *209*, 115–125. https://doi.org/10.1016/j.conbuildmat.2019.03.078.
18. Grabois, T.; Caldas, L.; Julião, N.; Filho, R.T. An Experimental and Environmental Evaluation of Mortars with Recycled Demolition Waste from a Hospital Implosion in Rio de Janeiro. *Sustainability* **2020**, *12*, 8945. https://doi.org/10.3390/su12218945.
19. Dias, A.; Nezami, S.; Silvestre, J.; Kurda, R.; Silva, R.; Martins, I.; de Brito, J. Environmental and Economic Comparison of Natural and Recycled Aggregates Using LCA. *Recycling* **2022**, *7*, 43. https://doi.org/10.3390/recycling7040043.
20. Bennett, B.; Visintin, P.; Xie, T. Global warming potential of recycled aggregate concrete with supplementary cementitious materials. *J. Build. Eng.* **2022**, *52*, 104394. https://doi.org/10.1016/j.jobe.2022.104394.
21. O'Grady, T.M.; Minunno, R.; Chong, H.-Y.; Morrison, G.M. Interconnections: An Analysis of Disassemblable Building Connection Systems towards a Circular Economy. *Buildings* **2021**, *11*, 535. https://doi.org/10.3390/buildings11110535.
22. Toniolo, S.; Camana, D.; Guidolin, A.; Aguiari, F.; Scipioni, A. Are design for disassembly principles advantageous for the environment when applied to temporary exhibition installations? *Sustain. Prod. Consum.* **2021**, *28*, 1262–1274. https://doi.org/10.1016/j.spc.2021.07.016.
23. Tleuken, A.; Torgautov, B.; Zhanabayev, A.; Turkyilmaz, A.; Mustafa, M.; Karaca, F. Design for Deconstruction and Disassembly: Barriers, Opportunities, and Practices in Developing Economies of Central Asia. *Procedia CIRP* **2022**, *106*, 15–20. https://doi.org/10.1016/j.procir.2022.02.148.
24. Kanters, J. Design for Deconstruction in the Design Process: State of the Art. *Buildings* **2018**, *8*, 150. https://doi.org/10.3390/buildings8110150.
25. Crowther, P. Re-Valuing Construction Materials and Components Through Design for Disassembly. In *Unmaking Waste in Production and Consumption: Towards the Circular Economy*; Emerald Publishing Limited: Bingley, UK, 2018; Chapter 18, pp. 309–321. https://doi.org/10.1108/978-1-78714-619-820181024.
26. Xiao, J.; Ding, T.; Zhang, Q. Structural behavior of a new moment-resisting DfD concrete connection. *Eng. Struct.* **2017**, *132*, 1–13. https://doi.org/10.1016/j.engstruct.2016.11.019.
27. Ding, T.; Xiao, J.; Zhang, Q.; Nezhad, A.A. Experimental and numerical studies on design for deconstruction concrete connections: An overview. *Adv. Struct. Eng.* **2018**, *21*, 2198–2214. https://doi.org/10.1177/1369433218768000.
28. Bertin, I.; Saadé, M.; Le Roy, R.; Jaeger, J.-M.; Feraille, A. Environmental impacts of Design for Reuse practices in the building sector. *J. Clean. Prod.* **2022**, *349*, 131228. https://doi.org/10.1016/j.jclepro.2022.131228.
29. Figueira, D.; Ashour, A.; Yıldırım, G.; Aldemir, A.; Şahmaran, M. Demountable connections of reinforced concrete structures: Review and future developments. *Structures* **2021**, *34*, 3028–3039. https://doi.org/10.1016/j.istruc.2021.09.053.
30. Vandervaeren, C.; Galle, W.; Stephan, A.; De Temmerman, N. More than the sum of its parts: Considering interdependencies in the life cycle material flow and environmental assessment of demountable buildings. *Resour. Conserv. Recycl.* **2021**, *177*, 106001. https://doi.org/10.1016/j.resconrec.2021.106001.
31. British Standards Institution. *EN 15978—Sustainability of Construction Works: Assessment of Environmental Performance of Buildings: Calculation Method*; BSI: London, UK, 2012.
32. British Standards Institution. *EN 15804—Sustainability of Construction Works: Environmental Product Declarations*; Core Rules for the Product Category of Construction Products; BSI: London, UK, 2011.
33. Joensuu, T.; Leino, R.; Heinonen, J.; Saari, A. Developing Buildings' Life Cycle Assessment in Circular Economy-Comparing methods for assessing carbon footprint of reusable components. *Sustain. Cities Soc.* **2021**, *77*, 103499. https://doi.org/10.1016/j.scs.2021.103499.
34. Eckelman, M.J.; Brown, C.; Troup, L.N.; Wang, L.; Webster, M.D.; Hajjar, J.F. Life cycle energy and environmental benefits of novel design-for-deconstruction structural systems in steel buildings. *Build. Environ.* **2018**, *143*, 421–430. https://doi.org/10.1016/j.buildenv.2018.07.017.
35. Eberhardt, L.M.; Van Stijn, A.; Rasmussen, F.N.; Birkved, M.; Birgisdottir, H. Development of a Life Cycle Assessment Allocation Approach for Circular Economy in the Built Environment. *Sustainability* **2020**, *12*, 9579. https://doi.org/10.3390/su12229579.
36. Xiao, J.; Chen, Z.; Ding, T.; Xia, B. Effect of recycled aggregate concrete on the seismic behavior of DfD beam-column joints under cyclic loading. *Adv. Struct. Eng.* **2020**, *24*, 1709–1723. https://doi.org/10.1177/1369433220982729.
37. Cai, G.; Xiong, F.; Xu, Y.; Larbi, A.S.; Lu, Y.; Yoshizawa, M. A Demountable Connection for Low-Rise Precast Concrete Structures with DfD for Construction Sustainability-A Preliminary Test under Cyclic Loads. *Sustainability* **2019**, *11*, 3696. https://doi.org/10.3390/su11133696.
38. Eberhardt, L.C.M.; Birgisdóttir, H.; Birkved, M. Life cycle assessment of a Danish office building designed for disassembly. *Build. Res. Inf.* **2018**, *47*, 666–680. https://doi.org/10.1080/09613218.2018.1517458.
39. Rasmussen, F.; Birkved, M.; Birgisdóttir, H. Upcycling and Design for Disassembly—LCA of buildings employing circular design strategies. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *225*, 012040. https://doi.org/10.1088/1755-1315/225/1/012040.
40. Xia, B.; Ding, T.; Xiao, J. Life cycle assessment of concrete structures with reuse and recycling strategies: A novel framework and case study. *Waste Manag.* **2020**, *105*, 268–278. https://doi.org/10.1016/j.wasman.2020.02.015.
41. Arrigoni, A.; Zucchinelli, M.; Collatina, D.; Dotelli, G. Life cycle environmental benefits of a forward-thinking design phase for buildings: the case study of a temporary pavilion built for an international exhibition. *J. Clean. Prod.* **2018**, *187*, 974–983. https://doi.org/10.1016/j.jclepro.2018.03.230.

42. Pepe, M.; Toledo Filho, R.D.; Koenders, E.A.B.; Martinelli, E. A novel mix design methodology for Recycled Aggregate Concrete. *Constr. Build. Mater.* **2016**, *122*, 362–372. https://doi.org/10.1016/j.conbuildmat.2016.06.061.
43. de Andrade, G.P.; Polisseni, G.D.C.; Pepe, M.; Filho, R.D.T. Design of structural concrete mixtures containing fine recycled concrete aggregate using packing model. *Constr. Build. Mater.* **2020**, *252*, 119091. https://doi.org/10.1016/j.conbuildmat.2020.119091.
44. British Standards Institute Staff. *ISO 14044—Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; BSI: London, UK, 2006.
45. British Standards Institute Staff. *ISO 14040—Environmental Management—Life Cycle Assessment—Principles and Framework*; BSI: London, UK, 2006.
46. Guardigli, L.; Monari, F.; Bragadin, M.A. Assessing Environmental Impact of Green Buildings through LCA Methods: Acomparison between Reinforced Concrete and Wood Structures in the European Context. *Procedia Eng.* **2011**, *21*, 1199–1206. https://doi.org/10.1016/j.proeng.2011.11.2131.
47. Borghi, G.; Pantini, S.; Rigamonti, L. Life cycle assessment of non-hazardous Construction and Demolition Waste (CDW) management in Lombardy Region (Italy). *J. Clean. Prod.* **2018**, *184*, 815–825. https://doi.org/10.1016/j.jclepro.2018.02.287.
48. Hjulsbro Steel AB. Environmental Product Declaration. 2020. Available online: https://hjulsbrosteel.com (accessed on 21 July 2022).
49. de Souza, D.M.; Lafontaine, M.; Charron-Doucet, F.; Chappert, B.; Kicak, K.; Duarte, F.; Lima, L. Comparative life cycle assessment of ceramic brick, concrete brick and cast-in-place reinforced concrete exterior walls. *J. Clean. Prod.* **2016**, *137*, 70–82. https://doi.org/10.1016/j.jclepro.2016.07.069.
50. Allacker, K.; Mathieux, F.; Manfredi, S.; Pelletier, N.; De Camillis, C.; Ardente, F.; Pant, R. Allocation solutions for secondary material production and end of life recovery: Proposals for product policy initiatives. *Resour. Conserv. Recycl.* **2014**, *88*, 1–12. https://doi.org/10.1016/j.resconrec.2014.03.016.
51. Coelho, A.; de Brito, J. Environmental analysis of a construction and demolition waste recycling plant in Portugal – Part I: Energy consumption and CO2 emissions. *Waste Manag.* **2013**, *33*, 1258–1267. https://doi.org/10.1016/j.wasman.2013.01.025.
52. Turk, J.; Cotič, Z.; Mladenovič, A.; Šajna, A. Environmental evaluation of green concretes versus conventional concrete by means of LCA. *Waste Manag.* **2015**, *45*, 194–205. https://doi.org/10.1016/j.wasman.2015.06.035.
53. Monteiro, N.B.R.; Neto, J.M.M.; da Silva, E.A. Environmental assessment in concrete industries. *J. Clean. Prod.* **2021**, *327*, 129516. https://doi.org/10.1016/j.jclepro.2021.129516.
54. Habert, G.; Miller, S.A.; John, V.M.; Provis, J.L.; Favier, A.; Horvath, A.; Scrivener, K.L. Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nat. Rev. Earth Environ.* **2020**, *1*, 559–573. https://doi.org/10.1038/s43017-020-0093-3.
55. Gomes, F.; Brière, R.; Feraille, A.; Habert, G.; Lasvaux, S.; Tessier, C. Adaptation of environmental data to national and sectorial context: application for reinforcing steel sold on the French market. *Int. J. Life Cycle Assess.* **2013**, *18*, 926–938. https://doi.org/10.1007/s11367-013-0558-4.
56. De Sousa, C.J.F. *Viabilidade Econômico-Ambiental da Substituição do Coque Utilizado em Alto-Forno para Obtenção do Ferro Gusa: Estudo de Caso*; Universidade Federal de Santa Catarina: Florianópolis, Brazil, 2015. Available online: https://repositorio.ufsc.br/handle/123456789/171995 (accessed on 8 September 2022).
57. Silva, A.C.G. *Avaliação Estrutural da Influência do Pó Pré-Ligado Fe65Nb na Produção de Matrizes Metálicas via Metalurgia do Pó*; Universidade Federal de Ouro Preto: Ouro Preto, Brazil, 2019. Available online: www.sisbin.ufop.br (accessed on 1 July 2022).
58. Goulouti, K.; Padey, P.; Galimshina, A.; Habert, G.; Lasvaux, S. Uncertainty of building elements' service lives in building LCA & LCC: What matters? *Build. Environ.* **2020**, *183*, 106904. https://doi.org/10.1016/j.buildenv.2020.106904.
59. Rentier, E.; Cammeraat, L. The environmental impacts of river sand mining. *Sci. Total Environ.* **2022**, *838*, 155877. https://doi.org/10.1016/j.scitotenv.2022.155877.
60. dos Santos, G.Z.B.; Caldas, L.R.; Filho, J.D.A.M.; Monteiro, N.B.R.; Rafael, S.I.M.; da Silva, N.M. Circular alternatives in the construction industry: An environmental performance assessment of sisal fiber-reinforced composites. *J. Build. Eng.* **2022**, *54*, 104603. https://doi.org/10.1016/j.jobe.2022.104603.
61. Hossein, A.H.; AzariJafari, H.; Khoshnazar, R. The role of performance metrics in comparative LCA of concrete mixtures incorporating solid wastes: A critical review and guideline proposal. *Waste Manag.* **2022**, *140*, 40–54. https://doi.org/10.1016/j.wasman.2022.01.010.
62. Likes, L.; Markandeya, A.; Haider, M.; Bollinger, D.; McCloy, J.S.; Nassiri, S. Recycled concrete and brick powders as supplements to Portland cement for more sustainable concrete. *J. Clean. Prod.* **2022**, *364*, 132651. https://doi.org/10.1016/j.jclepro.2022.132651.
63. Filho, R.T.; Gonçalves, J.; Americano, B.; Fairbairn, E. Potential for use of crushed waste calcined-clay brick as a supplementary cementitious material in Brazil. *Cem. Concr. Res.* **2007**, *37*, 1357–1365. https://doi.org/10.1016/j.cemconres.2007.06.005.
64. Gupta, S.; Chaudhary, S. State of the art review on supplementary cementitious materials in India – II: Characteristics of SCMs, effect on concrete and environmental impact. *J. Clean. Prod.* **2022**, *357*, 131945. https://doi.org/10.1016/j.jclepro.2022.131945.
65. Muslemani, H.; Liang, X.; Kaesehage, K.; Ascui, F.; Wilson, J. Opportunities and challenges for decarbonizing steel production by creating markets for 'green steel' products. *J. Clean. Prod.* **2021**, *315*, 128127. https://doi.org/10.1016/j.jclepro.2021.128127.

66. Liu, Y.; Li, H.; Huang, S.; An, H.; Santagata, R.; Ulgiati, S. Environmental and economic-related impact assessment of iron and steel production. A call for shared responsibility in global trade. *J. Clean. Prod.* **2020**, *269*, 122239. https://doi.org/10.1016/j.jclepro.2020.122239.
67. Zachmann, G. Decarbonisation of Energy Determining a Robust Mix of Energy Carriers for a Carbon-Neutral EU STUDY Requested by the ITRE Committee. 2022. Available online: https://www.europarl.europa.eu/RegData/etudes/STUD/2021/695469/IPOL_STU%282021%29695469_EN.pdf (accessed on 23 July 2022).
68. Andersen, R.; Ravn, A.S.; Ryberg, M.W. Environmental benefits of applying selective demolition to buildings: A case study of the reuse of façade steel cladding. *Resour. Conserv. Recycl.* **2022**, *184*, 106430. https://doi.org/10.1016/j.resconrec.2022.106430.
69. Eberhardt, L.C.M.; van Stijn, A.; Rasmussen, F.N.; Birkved, M.; Birgisdottir, H. Towards circular life cycle assessment for the built environment: A comparison of allocation approaches. *IOP Conf. Series: Earth Environ. Sci.* **2020**, *588*, 032026. https://doi.org/10.1088/1755-1315/588/3/032026.
70. van der Harst, E.; Potting, J.; Kroeze, C. Comparison of different methods to include recycling in LCAs of aluminium cans and disposable polystyrene cups. *Waste Manag.* **2016**, *48*, 565–583. https://doi.org/10.1016/j.wasman.2015.09.027.
71. Lei, H.; Li, L.; Yang, W.; Bian, Y.; Li, C.-Q. An analytical review on application of life cycle assessment in circular economy for built environment. *J. Build. Eng.* **2021**, *44*, 103374. https://doi.org/10.1016/j.jobe.2021.103374.
72. Andersson, R.; Stripple, H.; Gustafsson, T.; Ljungkrantz, C. Carbonation as a method to improve climate performance for cement based material. *Cem. Concr. Res.* **2019**, *124*, 105819. https://doi.org/10.1016/j.cemconres.2019.105819.
73. Torres, H.; Correa, E.; Castaño, J.G.; Echeverría, F. Simplified Mathematical Model for Concrete Carbonation. *J. Mater. Civ. Eng.* **2017**, *29*, 04017150. https://doi.org/10.1061/(asce)mt.1943-5533.0002001.
74. Villain, G.; Thiery, M. Gammadensimetry: A method to determine drying and carbonation profiles in concrete. *NDT E Int.* **2006**, *39*, 328–337. https://doi.org/10.1016/j.ndteint.2005.10.002.
75. Thiery, M.; Dangla, P.; Belin, P.; Habert, G.; Roussel, N. Carbonation kinetics of a bed of recycled concrete aggregates: A laboratory study on model materials. *Cem. Concr. Res.* **2013**, *46*, 50–65. https://doi.org/10.1016/j.cemconres.2013.01.005.
76. Janjua, S.Y.; Sarker, P.K.; Biswas, W.K. Sustainability implications of service life on residential buildings—An application of life cycle sustainability assessment framework. *Environ. Sustain. Indic.* **2021**, *10*, 100109. https://doi.org/10.1016/j.indic.2021.100109.