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Product Environmental Footprint in the construction sector – Proposal and assessment of a representative product for carbon-reinforced concrete

Pamela Haverkamp *, Laura Schmidt, Jana Gerta Backes, Marzia Traverso

Institute of Sustainability in Civil Engineering, Faculty of Civil Engineering, RWTH Aachen University, Mies-van-der-Rohe-Str. 1, Aachen 52074, Germany

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ABSTRACT

In this study, a representative product for carbon-reinforced concrete (CRC) in Germany is proposed according to the Product Environmental Footprint (PEF) method by the European Commission. Following the objectives of the PEF method, the main goal is to enhance comparability with other studies and promote transparency regarding the environmental performance of products. A CRC façade panel was chosen as the representative product based on insights from German market statistics and sectorial stakeholders. Furthermore, a PEF study was conducted for the defined product. Based on this study, the main environmental hotspots according to PEF are identified – most relevant impact categories, life cycle stages, processes and elementary flows. For instance, the most relevant impact categories were found to be Human Toxicity, cancer, Climate Change, and Resource Use, fossils. For each of these impact categories the most relevant processes and elementary flows were determined. Moreover, the most relevant life cycle was found to be the raw material extraction and pre-processing. An innovative aspect of this study is related to the calculation of the environmental impacts at the end of life. For the first time, the Circular Footprint Formula introduced in the PEF method is applied in the context of CRC. In this regard, a baseline and an alternative scenario are explored. In general, the outcomes of this study are a first step towards the application of the PEF methodology in the context of CRC and create a basis that fosters comparability and transparency in environmental assessments for CRC.

1. Introduction

Carbon-reinforced concrete (CRC) is a promising construction material that combines concrete with a carbon fiber reinforcement [1]. In comparison to its conventional counterpart, steel-reinforced concrete (SRC), CRC can potentially reduce the amount of resources needed in certain construction elements. Depending on the context it is applied, CRC can save up a considerable amount of concrete in building components while providing the same function as in an SRC element [2]. This material savings is mostly due to the fact that CRC does not corrode. Material can be then saved since the part of the concrete cover needed to avoid the corrosion of the reinforcement is no longer required [3].

Concrete is composed of aggregates, water, and cement. The latter is a very critical component, not only in terms of functionality, but also in terms of environmental performance. The global cement consumption is estimated at 4.65 billion tons per year [4], while the carbon dioxide (CO_2) emissions for the production of cement are estimated in around 1600 Gt in 2022 [5]. With its material savings, CRC has the potential of reducing some of the environmental impacts related to the cement industry. To achieve this, the adequate quantification and communication of the sustainability performance of CRC plays a central role. Life Cycle Assessment (LCA) has been recognized as a relevant and nowadays well-known method to measure the environmental performance of materials and products; standardized by ISO 14040/44 [6,7]. This

Abbreviations: CFF, Circular Footprint Formula; CO_2, Carbon dioxide; CPA, Classification of Products by Activity; CRC, Carbon-reinforced concrete; EC, European Commission; EF, Environmental Footprint; EoL, End of life; EP, Epoxy resin; EPD, Environmental Product Declaration; EU, European Union; FU, Functional unit; LCA, Life Cycle Assessment; LCI, Life cycle inventory; LCIA, Life cycle impact assessment; NACE, Nomenclature statistique des activités économiques dans la Communauté Européenne; PAN, Polyacrylonitrile; PCDD/Fs, Polychlorinated Dibenzo-p-Dioxins and Furans; PEF, Product Environmental Footprint; PEFCRs, Product Environmental Footprint Category Rules; RP, Representative Product; RSL, Reference service life; SBR, Styrene-butadiene rubber; SRS, Steel-reinforced concrete; TCDD, 2,3,7,8-Tetrachlorodibenzo-p-dioxin.

* Corresponding author.

E-mail addresses: pamela.haverkamp@inab.rwth-aachen.de (P. Haverkamp), laura.schmidt@rwth-aachen.de (L. Schmidt), jana.backes@inab.rwth-aachen.de (J.G. Backes), marzia.traverso@inab.rwth-aachen.de (M. Traverso).

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method has been used in the construction industry in multiple occasions [8]. LCA enables the assessment of the environmental performance of building materials and production chains as well as the identification of environmentally critical process steps and materials [6,7]. In particular, there are norms focused on the application of LCA in construction, such as EN 15804 and ISO 21930 at product level as well as EN 15978 at building level [9–12].

Despite the standardization of the method, LCA offers such a degree of freedom and flexibility, that many studies are neither reproducible nor comparable due to assumptions and value judgements incorporated in the assessment [13,14]. Additionally, consumers may be confused due to the numerous amounts of existing methods to measure and communicate the environmental performance of products [15]. Furthermore, the interpretation and communication of LCA results to a broader, non-expert audience is still one of the issues faced by the method [16–18]. In this regard, the European Commission (EC) developed the Product Environmental Footprint (PEF) method, an LCA-based approach to improve the comparability of environmental assessments and the communication of the environmental performance of products to consumers [14,19]. Based on the premises of improved comparability, harmonization and communication, PEF is a promising method to assess the environmental performance of disruptive innovations such as CRC. Moreover, PEF offers a great opportunity to improve and communicate the environmental footprint (EF) of CRC.

Given these considerations, a harmonized framework is essential to ensure the robustness and comparability of CRC elements. The PEF method addresses these challenges; however, few studies have explored its application in the construction sector, most of which primarily focus on specific elements of the method, such as the Circular Footprint Formula (CFF). Notably, no studies have examined one of the key components for ensuring comparability in PEF – the definition of representative products (RP). The RP is a core element of Product Environmental Footprint Category Rules (PEFCR), which provide instructions for the application of the PEF method for a certain product category. To bridge this gap, we propose a RP for CRC-based products in Germany. The RP defined in this study can support the development of PEFCR for the product category of CRC.

In Sections 2 and 3 of this paper, CRC and PEF are presented more in detail, including a description of the application of PEF in the construction industry. A proposal for the RP is made for the German market in Section 4. In Section 5, the methodology for the RP is presented, while the results are shown in Section 6 and the main hotspots and trade-offs are discussed in Section 7. Finally, the conclusions of the study are presented in Section 8.

2. Carbon-reinforced concrete

CRC is a composite material containing carbon fiber reinforcement and concrete. In terms of functionality, CRC can perform as well as SRC, while in terms of durability, CRC could even last longer than SRC [20]. The main difference between CRC and SRC is related to the possible effects of corrosion on the reinforcement [3]. The steel reinforcement of SRC is vulnerable to corrosion [21]. To avoid this issue, SRC elements are usually provided an additional concrete cover with the sole objective of protecting the steel rebars or mesh [22]. Since the reinforcement of CRC does not corrode, it is possible to forgo the protective concrete cover against corrosion (a thickness for fire protection and to ensure the bond between reinforcement and concrete matrix remains), which leads to potential environmental benefits due to reduced material consumption and emissions [23]. Due to the possibility of creating thinner elements, CRC is especially suitable to be used in façade elements, walls, slabs, and many other construction elements [24]. However, other uses are possible, e.g., for the reinforcement of existing structures [25].

As aforementioned, carbon fiber reinforcement and concrete are needed for CRC. The production process of carbon fibers typically begins with the use of polyacrylonitrile (PAN), derived from petroleum. PAN is combined with solvents to create PAN fibers, wound onto spools. This process is followed by oxidation, carbonization, potential graphitization, surface treatment, and sizing of the PAN fibers to obtain carbon fibers [24]. The fibers are then further processed in textile machines to form fabrics or rods, coated with a plastic matrix that ensures appropriate mechanical resistance. Depending on the required mechanical properties, epoxy resin (EP) or styrene-butadiene rubber (SBR) can be used as impregnation substances. The impregnated carbon fibers are then formed into rebars or mats used to reinforce concrete elements. In general, the same types of concrete used in SRC can be used in CRC.

Regarding its use stage, it is estimated that CRC has a service life of 100 years, longer than the usual service life of SRC (usually estimated with an average of 60 years) [20,26]. As for the end of life (EoL) of the CRC, not much information is available due to the fact that the material has not been used in practice for a long time [26]. Nevertheless, several options are available, provided that a separation of the material fractions (concrete and carbon fibers) takes place. The method for the fraction separation as well as different EoL routes has already been discussed by Backes et al. [26]. The concrete fraction can be used as a filling material for road construction (downcycling) or as secondary raw material in the concrete production (recycling). For the carbon fiber fraction, the current EoL disposal in Germany is landfilling [27]. Other than that, the most feasible option currently is the mechanical recycling. However, the resulting “recycled” fibers do not have the same mechanical properties as primary fibers. In this regard, thermal recycling (pyrolysis) offers a recycled fiber with better properties. However, this recycling process is more energy-intensive than mechanical recycling and the fibers can still not be re-used in its original field of application [27].

3. Product Environmental Footprint

The PEF method was launched by the EC with the goal to develop a harmonized European approach for environmental assessment studies [28]. The method builds on already existing methods, standards and guidance documents, such as LCA, Ecological Footprint and Greenhouse Gas Protocol [13,19,29,30]. In general, PEF is an LCA-based measure of the environmental performance of a good or service throughout its life cycle, considering the supply chain activities [30].

The PEF method provides clear instructions for modeling the environmental impacts of material and energy flows as well as comprehensive technical guidance [30,31]. The main aim of PEF is an increased comparability of the environmental performance of products by reducing the flexibility in methodological choices provided, for instance, in ISO 14040 and ISO 14044 [28,32]. Furthermore, this method is mainly intended for the communication of the assessment results [33]. In this regard, PEF defines the requirements for each decision point and provides guidance to enable consistent, robust, and reproducible studies [28]. Two guidance documents are available for conducting PEF studies – the PEF Guide and the suggestions for updating the PEF method [30,34].

PEF foresees the development of PEFCR [34,35]. The PEFCR provide consistent and specific rules for considering relevant environmental information of products in a particular product category [19,28,30,32]. Some aspects covered by PEFCR are goal and scope of the study, relevant or irrelevant impact categories, appropriate system boundaries, key parameters, life cycle stages, data source guidance, among others. PEFCR ensure a relevant and consistent application of the PEF method for the selected product category [29–31]. These rules can also potentially produce savings in time, workload, and costs to create a PEF study of a product from a product category with defined PEFCR [35]. PEF studies with the goal of performing comparisons and comparative statements must be made in accordance to an existing PEFCR [30,36,37]. If PEFCR are not available for the required product category, as it is the case for CRC, they must be developed according to the requirements in the suggestions for updating the PEF method [30].

For the development of PEFCR, a classification of the product with the CPA/NACE (Classification of Products by Activity/Nomenclature statistique des activités économiques dans la Communauté européenne) code is foreseen to ensure comparability within product categories [30,38]. Furthermore, a RP must be defined in the scope of the PEFCR, which reflects the average product – virtual or real – sold in the market of the European Union [30,32]. A virtual RP may be chosen if several technologies or materials are available for the product category under consideration and enough market and technical data is available. In turn, a real product can be selected if market information is missing [39]. For each RP, an initial PEF study (PEF-RP) must be conducted to identify key impact categories, life cycle stages, processes, and elemental flows, and to record data needs, data collection, and data quality requirements [30,37,39]. Since the RP serves as a benchmark for the product category, performance classes can be calculated based on the RP profile [39].

Although the main goals of the method are the implementation of life cycle thinking in European policy and the improvement of the environmental performance of all products throughout their life cycle [40], PEF has faced some criticism. Several studies have focused on the weaknesses of the methodology in different aspects [41]. According to Finkbeiner [42], it is not clear if the PEF approach effectively supports its targets (e.g. harmonization of methods, comparability, credible communication, etc.) in a substantial way. Instead, the author concludes that the PEF method rather contributes to confusion and proliferation of assessment methods [42]. Furthermore, the definition of the product categories and representative product, as well as the EoL allocation and impact assessment have also been criticized [15,19,35,36,38,41,43]. The EC has addressed this criticism in different ways. On the one hand, the EC has clarified the main objective of the PEF method – developed a harmonized European approach to be used in policies of the European Union (EU), instead of harmonizing existing approaches and standards [13]. On the other hand, several changes were introduced in the methodology at the end of the EF pilot phase [30], a 5-year period (2013–2018) in which the participants were encouraged to apply the proposed approaches and further methods that were seen as more suitable in the corresponding cases [13]. In general, it can be said that PEF is an evolving method that represents a major opportunity to not only assess and communicate, but also improve the environmental impacts of products from a policy perspective.

3.1. Phases of a PEF study

To conduct a PEF-RP, four phases must be completed. These phases are in accordance to the LCA method [6,7]. The phases are as follows: 1) definition of the goal and scope of the PEF study, 2) collection and analysis of the life cycle inventory (LCI), 3) conduction of the life cycle impact assessment (LCIA) with pre-defined impact categories, and 4) interpretation and reporting of the EF [30,40].

In the first step, the main reasons for the study as well as the intended application and audience are defined [39]. Furthermore, the main methodological choices are fixed [30]. A crucial methodological question at this point is the exact definition of the functional unit (FU), for which four main aspects must be described: 1) function "What", 2) quantity "How much" 3) quality "How good", 4) lifespan "How long" [30,39]. In addition, the reference flow is defined. This reflects the quantity of a product needed to meet the defined FU [30,39]. Moreover, the system boundaries must be defined.

The second phase of a PEF study is the compilation and analysis of the LCI. All material and energy resource inputs, outputs, and emissions to air, water, and soil are collected and presented [30,40]. A screening step in this phase helps to focus on the data quality requirements and iteratively refine the product lifecycle model [30]. The quality of the data is assessed in terms of technological, geographical and time-related representativeness as well as precision [40].

In the LCIA, the third phase of the PEF study, the environmental performance of the (representative) product is evaluated using the environmental impact categories and models already defined by the method [28]. Similar to the LCA method, the LCI data is classified and characterized in this phase, in accordance to the PEF impact categories and models. Furthermore, the results must be normalized and weighted, which in comparison to ISO 14040/44 is mandatory. In the normalization step, the contributions of the results to a relative reference unit are calculated; i.e. in PEF, the normalized results are expressed based on statistical data on emissions and resources used globally in one year per capita [40,44]. The normalized results can then be multiplied by weighting factors reflecting the relative importance of the assessed impact categories [30,45]. The weighting set developed for the PEF method is a hybrid evidence- and judgement-based approach [45].

The interpretation phase aims to draw conclusions and recommendations from the assessment. In this regard, main hotspots in terms of most relevant impact categories, life cycle stages, processes and elementary flows are identified. Furthermore, uncertainty and data quality issues must be addressed in this phase. Finally, the report of a PEF study summarizes it in terms of relevance, completeness, consistency, accuracy, and transparency [30].

3.2. PEF in the construction sector

A review of relevant, available literature showed that PEF applications in the construction sector are not widespread. During the EF pilot phase, PEFCR for four products from the construction sector were developed: metal sheets [46], decorative paints [47], pipelines [48], and thermal insulation [49]. A regional PEFCR for wooden windows based on the Italian market context was proposed under the framework of the LIFE MAGIS project, funded by the European Union [50].

The PEF4Building project, initiated by the EC, tested the applicability of the PEF methodology for two office buildings in which the focus of the study was not on PEF results, but on insights into methodological challenges in applying PEF [51]. The PEF study on buildings (without existing PEFCR for buildings) considered EN 15978, the PCR for buildings, and national methodologies, noting that they use different types of benchmarks (i.e., limit values, reference values, target values). The authors recommend a common EU methodology for calculating the environmental impact of buildings and defining environmental benchmarks, i.e., PEFCR for buildings. Energy benchmarks for buildings already exist in the EU, but there are no material benchmarks. PEFCR for buildings could serve as the basis for new PEFCR for construction products and be aligned with existing PEFCR. [51]

Lechón et al. [52] applied the PEF method in combination with Life Cycle Costing to a single-family house in Cross Laminated Timber construction, analyzing hotspots and improvement measures. On another note, Durão et al. [29], Eberhardt et al. [53], Obrecht et al. [54], Mirzaie et al. [55], and Rajagopalan et al. [56] used the CFF of the PEF method, comparing it to other EoL approaches.

After its original launch, several impact categories of the PEF method were not in agreement with those of EN 15804. Following demands for harmonization of these two approaches e.g., Spirinckx et al. [51] and Lechón et al. [52] resulted in the adaptation of EN 15804 in 2021 [11].

Regarding EoL modeling, the PEF method does not specify how to estimate changed material qualities after multiple life cycles, so the user must make a reasonable assumption [53]. Thus, an information gap is created for materials that remain in the building after re-development and no uniform application of the CFF is guaranteed [53,56]. Due to the quality correction of environmental impacts, the CFF does not match the mass balance. Furthermore, given the long Reference Service Life (RSL) of certain components (e.g., concrete columns), allocating emissions that occur today to life cycles of 80, 160, or 240 years is highly uncertain and could lead to greenwashing [57]. The results are difficult to compare because different RSL databases are used. Consequently, it is important that data on RSL and maintenance of different materials are included in future studies [56]. According to Finkbeiner et al. [35], it is generally questionable whether one formula applies to all products for EoL assessment.

Furthermore, Durão et al. [29] made a comparison between PEF and Environmental Product Declaration (EPD) schemes compliant with EN 15804 – the set of core rules EPD of construction products. It was found that with the updated PEF method and the revision of the norm, some harmonization happened with regards to system boundaries, EoL allocation and the considered impact categories and characterization methods [29]. Nevertheless, EPDs and PEF studies cannot be compared for the same material [29]. This lack of comparison is in part due to the fact that the EN 15804 is the only standard that considers some special characteristics of the construction sector, e.g. construction products are not final products [11,29].

Based on this literature overview, no studies have adopted the PEF method as the basis for a harmonized framework to assess and communicate the environmental performance of a construction material or product. In particular, none of the studies explored the topic of the definition of a RP as one of the foundations for harmonization and comparability, which is the aim of the current contribution.

4. Proposal for a representative product of carbon reinforced concrete: Façade element

CRC is an innovative, but not new, construction material in Germany, which is currently still in development and finding its way into the market. To assess the environmental potentials of this material, several LCA studies have already been carried out [26,27,58–60]. Although many of these studies follow existing LCA standards (e.g., 14040/44, EN 15804, etc.), they present different methodological choices and assumptions that affect the results and do not allow a robust comparison of the outcomes, e.g., consideration of different FUs and system boundaries, or use of varied impact assessment methods. An approach that addresses these issues can be found in the PEF methodology.

As a first step towards the application of PEF in the context of this disruptive material, we propose a RP for a CRC element. The definition of this RP applies only in Germany due to the fact that only German data has been considered. The RP has been defined following the approach of the PEFCR Guidance [39].

To define the RP, it is necessary to assess the corresponding market to determine which applications of the material are relevant. An assessment of the German market, determined that the use of CRC is not yet very widespread. Statistic records and consultation with relevant market stakeholders showed that, at the time of the current study, the most popular application of CRC is in the form of façade elements [61]. Due to this fact, the RP for the German context was defined as a façade element.

It is important to highlight that the component thickness for CRC is determined by the load-bearing capacity and manufacturing-related boundary conditions. This fact, the novelty of CRC (i.e., limited widespread) as well as the heterogeneity in the technical and aesthetical requirements of buildings do not allow the definition of a real nor a market-based virtual RP per se (entirely based on market values). Thus, the characteristics of the RP were defined in cooperation with the consulted German CRC producer based on a static preliminary design of a filigree façade panel. This element is the basis for an initial RP and provides helpful characteristic values for the FU. The main characteristics of the RP are presented in Table 1 and its schematic depiction is presented in Fig. 1.

Table 1
Characteristics of selected RP.

Parameter	Value / Description
Dimensions	4000 mm * 3600 mm * 40 mm
Concrete compressive strength class	C50/60 (according to EN 206–1)
Average compressive strength	58 N/mm^2
Impregnation of reinforcement	EP
Yarn cross-section	3.62^2
Tensile strength	> 2800 N/mm2
Modulus of elasticity	> 230,000 N/mm2
Mass of reinforcement	9.5 kg
Anchorage	Stainless steel diagonal anchors with accompanying compression and suction anchors (estimated weight 6 kg)

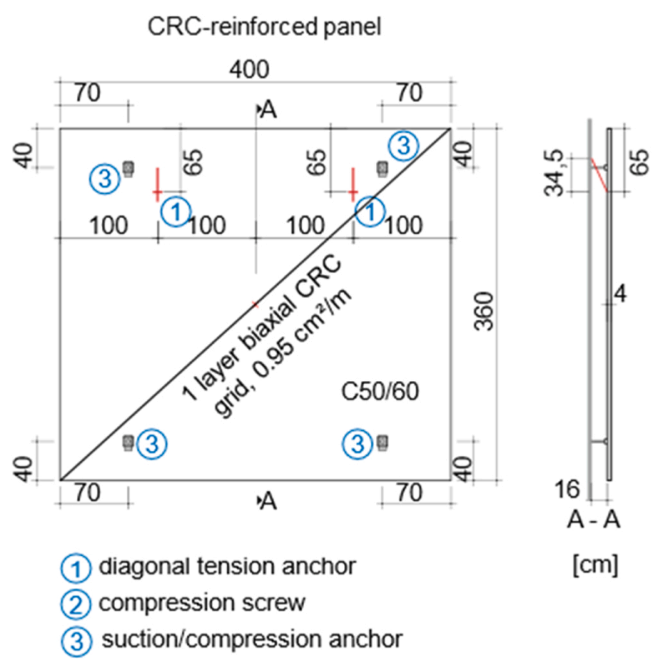

Fig. 1. Schematic depiction of RP [60].

5. PEF-RP of carbon reinforced concrete façade panel

5.1. Goal and Scope of PEF study

This study aims to assess the environmental impacts of the defined RP of a CRC façade panel with a cradle-to-grave approach. The defined RP can serve as a basis for comparison, as well as for the identification of environmental hotspots and optimization opportunities. Furthermore, this case study will provide a further reference in the application, benefits and challenges of the PEF method for construction products and materials. All information of the PEF-RP is given in detail; thus, modification and optimization of the models is possible for interested parties.

The system boundaries cradle-to-grave include raw material acquisition and pre-processing, transport to manufacturing site, manufacturing processes, use and in this study seen as relevant, the EoL (using the CFF) [30]. For the sake of harmonization, these system boundaries are aligned with the life cycle modules specified in EN 15804 [11]. The processes evaluated in this study are shown in Fig. 2. The processes with dashed lines were not included (see Fig. 2: A5 and B1-B7).

As aforementioned, the structure of the system boundaries is based on the information modules of the EN 15804, which is commonly accepted in the construction industry [11]. The system boundaries include the extraction and pre-processing of the raw materials (module A1), as well as their transport to the production site (module A2). Furthermore, the production of the façade panel and its transport to the construction site are included in modules A3 and A4, respectively. The installation of the panels can vary depending on the configuration of the building where they are being installed. Therefore, module A5 was not

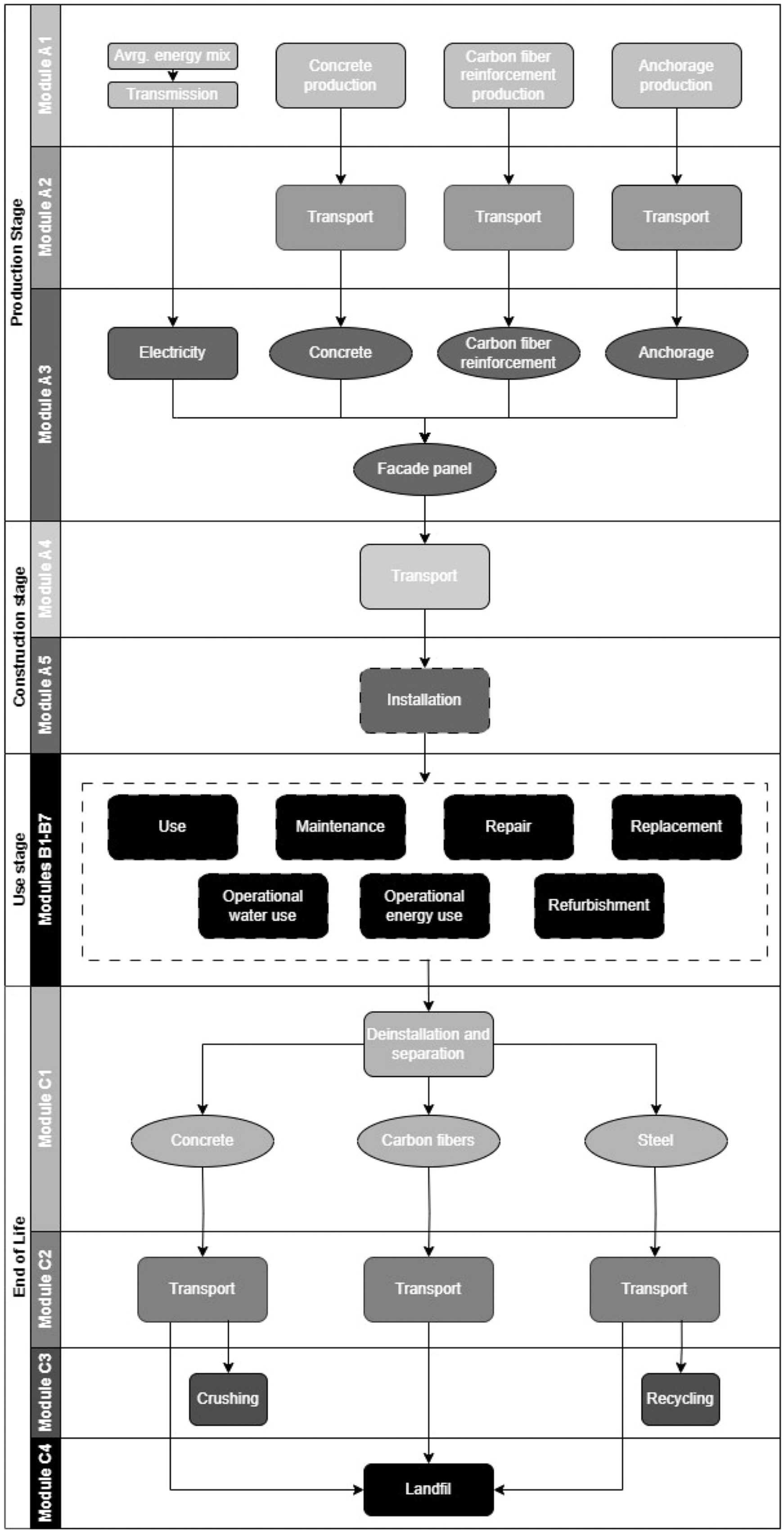

Fig. 2. System boundaries.

included in the system boundaries. Furthermore, it is assumed that panels have a service life of 100 years. For this study, the authors work with the assumption that no environmental impacts arise from the use of the façade (module B1). Based on consultations with experts from the industry, it is further assumed that no measures for maintenance (module B2), repair (module B3), replacement (module B4) or refurbishment (module B5) are needed. Due to the nature of the façade element, no energy (module B6) or water (module B7) is needed for its functioning. Regarding the EoL, a baseline scenario is defined in which the carbon fibers and a small part of the concrete are landfilled. The façade anchorage and around 95 % of the concrete are recycled. The EoL scenario comprises the selective demolition of the façade panel (module C1), the transport of its material fractions for their treatment (module C2), the treatment of the recovered material (module C3) and final disposal (module C4). The assumptions for the different life cycle stages are addressed more in detail in Section 5.2.

The impact assessment is carried out using the impact categories and characterization models defined for the PEF method [30]. The normalization and weighting are conducted using the factors proposed by the EC. The chosen impact assessment method is EF 3.0.

The FU for this case study is defined following the approach of the PEF method (Table 2).

The reference flow, i.e. the amount of outputs from processes needed to fulfil the function expressed by the defined FU, is presented in Table 3.

The RP-model is made based on both primary and secondary data for Germany. Primary data was obtained from research groups of the RWTH Aachen University and industry stakeholders. Secondary data was obtained from scientific literature and database datasets. The LCA software GaBi ts 10.6 © was used with the environmental databases XIV Construction materials, XV Textile finishing, XXII Carbon composites, and Ecoinvent 3.6 (2020.2). The selected datasets do not consider infrastructure processes.

5.2. Life Cycle Inventory

The LCI presented in this Section is based on the system boundaries presented above Fig. 2. For those materials or processes, for which there were several dataset options, the worst-case scenario in terms of Climate Change was selected.

For the stage of raw material extraction (module A1), the concrete and carbon fiber reinforcement production are modelled. To model the concrete, the dataset "DE: Concrete C50/60 (A1-A3)" of the *Verein Deutscher Zementwerke e.V.* from the GaBi© database was used. In turn, the steel anchor was modelled using the dataset "EU-28: Stainless steel sheet (EN15804 A1-A3) Sphera".

The LCI for the carbon reinforcement is presented in Table 4. It was assumed that the reinforcement is produced in Germany. The reinforcement is produced from uncoated fibers made of PAN. These fibers are then woven and impregnated with EP. The impregnated fibers were modeled with a dataset of the GaBi© database XXII Carbon composites. Furthermore, the fibers to produce the reinforcement were transported in a distance of 100 km. The energy needed to produce the reinforcement is included in the model. [60]

Table 2
Definition of FU.

Element	Description
What?	A façade panel of carbon-reinforced concrete to protect the building structure from the effects of weather and to serve as a design element for the individual design of the building
How much?	4000 mm* 3600 mm* 40 mm
How good?	Achievement of the compressive strength class C50/60 (for the concrete) (DIN EN 206–1) as well as a tensile strength of at least 2800 N/mm² and a modulus of elasticity of at least 230,000 N/mm² (ISO 10406–1:2008 and DIN EN 1990, respectively)
How long?	100 years

Table 3
Reference flow.

Material	Unit	Amount
Concrete C50/60	kg	1370
Carbon fibers	kg	8.5
Steel	kg	9.5

Table 4
Carbon fiber inventory.

Material	Unit	Input	Dataset
Impregnated fiber (PAN bases, EP)	kg/ m^2	0.42	DE: Carbon fiber reinforced plastic part - 63 - (CFRP. CF: GLO, P: DE)
Truck	km	100	GLO: Truck, euro4, 28-32t gross weight/ 22 t payload capacity
Production of carbon scrim	kWh	0.05	DE: Electricity grid mix (2020)

The concrete and the carbon fiber for the façade panel must be transported to the factory (module A2). In this regard, the dataset "GLO: Truck, euro4, 28–32t gross weight/ 22 t payload capacity" was used for a distance of 100 km.

For the production of the façade panel, it is assumed that the concrete is compacted using vibration compaction [62]. Precise data on the duration of vibration and the associated energy demand is difficult to find in literature, partly because the machines are individually adjusted to the respective application and the settings are very user dependent [63]. Therefore, the assumptions and calculations of a previously conducted LCA study on the RP are used, in which the vibration compaction of concrete has a power consumption of 0.4 kWh per façade panel, modelled in GaBi with the process "DE: Electricity grid mix (2020)".

The transport of the finished panel to the construction site (module A4) is modeled with a distance of 250 km [4]. The installation of the façade panel and its use stage are not considered in the model, as explained in Section 5.1.

At the EoL of the façade panel, it is assumed that it is deinstalled from the building envelope and separated into its different constituent parts (i.e., carbon fibers, concrete, and steel (anchorage)). For the EoL route, a baseline scenario is defined. Although there are recycling alternatives for the carbon fibers, the current practice at the EoL in Germany is landfilling, as stated in Section 2. Therefore, it is assumed that 100 % of the carbon fibers are landfilled. As for the concrete fraction, it was found that in Germany 78.8 % of the concrete is recycled, 15.7 % is used in the backfilling of excavations or landfills, and 5.5 % is landfilled [64]. Based on these figures, it is assumed that 78.8 % of the concrete fraction is recycled as aggregates for the concrete production, 15.7 % is used as filling material in the frost protection layer of roads, and 5.5 % is landfilled. Finally, 100 % of the steel anchorage is assumed to be recycled.

To evaluate the environmental impacts at the EoL, the CFF is applied. The CFF enables the quantification of the inventory at the EoL under consideration of material, energy, and disposal. In particular, this formula considers recycled materials entering the product system, materials for recycling exiting the system, avoided primary materials, energy recovery processes, and material disposal. [30] The formula is presented in the following:

5.2.1. Material

$$(1-R_1)E_v + R_1 * \left(AE_{recycled} + (1-A)E_v * \frac{Q_{Sin}}{Q_P}\right) * (1-A)R_2 * \left(E_{recyclingEoL} - E_v^* * \frac{Q_{Sout}}{Q_P}\right)$$

5.2.2. Energy

$$(1-B)R_3 * \left(E_{ER} - LHV * X_{ER,heat} * E_{SE,heat} - LHV * X_{ER,elec} * E_{SE,elec}\right)$$

5.2.3. Disposal

$$(1-R_2-R_3) * E_D$$

Where:

A is the allocation factor of burdens and credits between two product systems
B is the allocation factor of energy recovery processes
$Q_{S,in}$ is the quality of the incoming secondary material (i.e., of the recycled material)
$Q_{S,out}$ is the quality of the outgoing secondary material (i.e., of the material for recycling)
Q_P is the quality of the primary material (i.e., of the virgin material)
R_1 is the recycled content of the incoming material
R_2 is the percentage of the product's material that will undergo recycling within the subsequent product system
R_3 is the percentage of the product's material that will undergo energy recovery at EoL
$X_{ER,heat}$ is the efficiency of the energy recovery process for heat
$X_{ER,elec}$ is the efficiency of the energy recovery process for electricity
LHV is the lower heat value of the material used in the energy recovery process
E_V are the emissions and resources from the extraction of virgin material
$E_{recycled}$ are the emissions and resources from the processing of incoming recycled materials
$E_{recycling,EoL}$ are the emissions and resources from the recycling of outgoing materials at the EoL
E^*_V are the emissions and resources from the extraction of virgin materials assumed to be substituted by secondary materials (i.e., by $E_{recycling,EoL}$)
E_{ER} are the emissions and resources from energy recovery processes
$E_{SE,heat}$ are the emissions and resources from the heat source assumed to be substituted by the recovered heat
$E_{SE,elec}$ are the emissions and resources from the electricity source assumed to be substituted by the recovered electricity
E_D are the emissions and resources from the waste disposal (without energy recovery)

The parameters A, B, R_1, R_2, and R_3, as well as the quality ratios $Q_{S,in}/Q_P$ and $Q_{S,out}/Q_P$, are material dependent. The EC has defined their values for certain material groups (metals, paper, plastics, glass, wood, batteries, chemicals, thermal insulation, olive oil, rubbers, textiles, resins, aramid and glass fibers, and fillers) [65]. Furthermore, default values have also be drawn. Both the material-specific and the default values of the parameters can be found in Annex C of the PEFCR Guidance document.

For the case study in this paper, the parameters for the carbon fibers and the concrete were defined based on assumptions and the guidance in Zampori and Pant [30]. For the steel, the needed values were extracted from Annex C. The selected parameters are presented in Table 5.

For both the carbon fibers and the concrete, since no material-specific value was available, the A-factor was defined as 0.5. This value signifies that the environmental loads and credits are shared equally among two product systems. Furthermore, Zampori and Pant [30] specify that the B-Factor is to be set to zero in PEF studies. It was assumed that all materials of the façade element are of primary nature (i.e., $R_1 = 0$), with the exception of the steel that, according to Annex C, contains some secondary material (hence, $R_1 = 0.107$).

Regarding the material proportion to be recycled at EoL, different scenarios were established for each material to define R_2. For the carbon fibers and the concrete, the definition of R_2 was made based on secondary data from literature, specifically from a German report on the generation and fate of mineral construction waste [64]. In the case of the concrete, there were several recycling possibilities. For this reason, a R_2-value was defined for each possibility: 0.394 to describe the recycling of the concrete as coarse aggregate to be used in the concrete production, 0.394 for the recycling as fine aggregate also in the concrete production, and 0.157 to depict the recycling of the concrete for aggregate in the frost protection layer of roads. For steel (anchorage), the value for R_2 was extracted from Annex C.

The value of R_3 is country-specific. Hence, it was taken from the Annex C for Germany, where the landfill and incineration share of waste in different European countries are presented. Therefore, the cases in which a landfill scenario was depicted, the corresponding incineration share for Germany was also considered. Regarding the quality ratios, none was applied for the carbon fibers, since it was assumed that the incoming materials are primary, and no recycling takes place at the EoL. For the concrete, three different quality ratios for the outgoing materials were defined. For the definition of the ratios, economic aspects were considered as recommended by Zampori and Pant [30]. In particular, the value of the primary and secondary materials in each case was determined.

Finally, the selected parameters were multiplied with the inventory values and assigned to the corresponding datasets. The final LCI for the EoL is presented in Table 6.

Since the baseline scenario is entirely based on secondary data, an alternative worst-case scenario was defined, in which the concrete is assumed to be landfilled completely. The CFF parameters and the resulting LCI for the EoL are presented in Table 7 and Table 8, respectively.

5.3. Life Cycle Impact Assessment

The impacts are assessed using the method EF 3.0. In total, the 16 listed impact categories are assessed: Climate Change (fossil, biogenic, land use and land use change, total), Ozone Depletion, Human Toxicity (cancer and non-cancer), Particulate Matter, Ionizing Radiation (human health), Photochemical Ozone Formation (human health), Acidification, Eutrophication (terrestrial, freshwater, marine), Ecotoxicity

Table 5
CFF parameters.

Material	EoL route	A	B	R_1	R_2	R_3	$Q_{s,in}/Q_p$	$Q_{s,out}/Q_p$
Carbon fibers	100 % landfill / incineration	0.5	0	0	0	0.99	N/A	N/A
Concrete	78.8 % recycling as coarse and fine aggregate in concrete production	0.5	0	0	0.394*	0.99	N/A	0.71*
	15.7 % recycling as aggregate in the frost protection layer of roads				0.394**			0.64**
	5.5 % landfill / incineration				0.157***			0.46***
Steel	95 % recycling	0.2	0	0.107	0.95	0.99	1	1
	5 % landfill / incineration							

N/A = does not apply
* recycling as coarse aggregate in the concrete production
** recycling as fine aggregate in the concrete production
*** recycling as aggregate in the frost protection layer of roads

Table 6
EoL LCI.

Material / Process	Amount	Unit	Dataset	Comment
Demolition				
Selective demolition	1.09	kg	DE: Diesel mix at refinery Sphera	[66]
Carbon fibers				
Transport to landfill	0.426	tkm	DE: Diesel mix at refinery Sphera	A distance of 50 km was assumed
Landfilling treatment for carbon fibers	0.0852	kg	EU−28: Construction waste dumping (EN15804 C4) Sphera	
Incineration of carbon fibers	8.4348	kg	EU−28: Waste incineration of municipal solid waste (MSW) ELCD/CEWEP	Incineration takes place in landfill facility
Concrete				
Landfilling treatment for concrete	0.7535	kg	EU−28: Construction waste dumping (EN15804 C4) Sphera	Country: Germany Share incineration in Germany = 99 %
Incineration of concrete	74.5965	kg	EU−28: Waste incineration of municipal solid waste (MSW) ELCD/CEWEP	Incineration takes place in landfill facility
Concrete transport to landfill	3.7675	tkm	DE: Diesel mix at refinery Sphera	A distance of 50 km was assumed
Concrete recycling process	647.325	kg	DE: Diesel mix at refinery Sphera (0141 kg) DE: Electricity grid mix Sphera (5,37 MJ)	[66]
Concrete transport to recycling plant	32.36625	tkm	DE: Diesel mix at refinery Sphera GLO: Truck, Euro 4, 26–28 t gross weight / 18.4 t payload capacity Sphera	A distance of 50 km was assumed
Credit for saved primary coarse aggregates for concrete production	−190.501	kg	DE: Gravel (Grain size 2/32) (EN15804 A1-A3) Sphera	
Credit for saved primary fine aggregates for concrete production	−173.870	kg	EU−28: Crushed sand grain 0–2 mm (EN15804 A1-A3) Sphera	
Credit for saved primary coarse aggregates for road frost protection layer	−24.588	kg	DE: Gravel (Grain size 2/32) (EN15804 A1-A3) Sphera	It was assumed that 50 % of the 15.7 % was used recycled coarse aggregates
Credit for saved primary fine aggregates for road frost protection layer	−24.588	kg	EU−28: Crushed sand grain 0–2 mm (EN15804 A1-A3) Sphera	It was assumed that 50 % of the 15.7 % was used recycled coarse aggregates
Steel				
Steel transport to recycling plant	0.361	tkm	DE: Diesel mix at refinery Sphera	A distance of 50 km was assumed
Steel recycling process	7.22	kg	GLO: Credit for recycling of stainless steel scrap Sphera <Mfg>	Considers also credits for avoided primary material production
Steel transport to landfill	0.02375	tkm	DE: Diesel mix at refinery Sphera	A distance of 50 km was assumed
Landfilling treatment for steel	0.00475	kg	DE: Landfill for inert matter (Steel) PE	
Incineration of steel	0.47025	kg	EU−28: Waste incineration of municipal solid waste (MSW) ELCD/CEWEP	Incineration takes place in landfill facility

Table 7
CFF parameters alternative scenario.

Material	EoL route	A	B	R_1	R_2	R_3	$Q_{s,in}/Q_p$	$Q_{s,out}/Q_p$
Carbon fibers	100 % landfill / incineration	0.5	0	0	0	0.99	N/A	N/A
Concrete	100 % landfill / incineration	0.5	0	0	0	0.99	N/A	N/A
Steel	95 % recycling 5 % landfill / incineration	0.2	0	0.107	0.95	0.99	1	1

(freshwater), Land Use, Water use and Resource Use (minerals and metals and fossils). The characterized results of the RP are presented in Table 9.

6. Interpretation

The LCIA were analyzed and hotspots are defined in accordance to the procedure defined in Zampori and Pant [30]. In particular, hotspots regarding impact categories, life cycle stages, processes and elementary flows are identified. The first two (impact categories and life cycle stages), are mainly relevant with regards to awareness creation and the (external and internal) communication of results [30]. In turn, through the definition of the most relevant processes and elementary flows, concrete actions can be identified to improve the environmental impact of the assessed product system.

The hotspot analysis is based on the environmental contributions of the RP's normalized and weighted results. The EF normalization and weighting sets were used for this purpose [44,45,67]. First, the most relevant impact categories were determined – the impact categories contributing to at least 80 % of the total environmental impact, from the largest to the smallest contribution. The contribution of the different environmental impact categories to the total environmental impact is presented in Table 10.

Considering the definition given above, the most relevant impact categories are Human Toxicity, cancer, Climate Change, and Resource Use, fossils, with a total contribution of 84 %.

Next, the most relevant life cycle stages were identified for the most relevant impact categories. Those stages comprise the portions of the life cycle stages amounting to at least 80 % of the total environmental impact in the corresponding impact categories. Table 11 shows the contribution of each life cycle stage for the most relevant impact categories. The most relevant life cycle stage for all impact categories is raw material extraction and pre-processing (module A1).

The most relevant processes were determined by identifying the processes of the most relevant impact category collectively contributing to at least 80 % of the environmental impacts. Table 12 presents the contribution of the considered processes to the overall environmental impacts. The contribution of the processes less than 1 % was aggregated.

Table 8
EoL LCI alternative EoL scenario (difference in Concrete).

Material / Process	Amount	Unit	Dataset	Comment
Demolition				
Selective demolition	1.09	kg	DE: Diesel mix at refinery Sphera	[66]
Carbon fibers				
Transport to landfill	0.426	tkm	DE: Diesel mix at refinery Sphera	A distance of 50 km was assumed
Landfilling treatment for carbon fibers	0.0852	kg	EU−28: Construction waste dumping (EN15804 C4) Sphera	
Incineration of carbon fibers	8.4348	kg	EU−28: Waste incineration of municipal solid waste (MSW) ELCD/ CEWEP	Incineration takes place in landfill facility
Concrete				
Landfilling treatment for concrete	13.7	kg	EU−28: Construction waste dumping (EN15804 C4) Sphera	Country: Germany Share incineration in Germany = 99 %
Incineration of concrete	1356.3	kg	EU−28: Waste incineration of municipal solid waste (MSW) ELCD/ CEWEP	Incineration takes place in landfill facility
Concrete transport to landfill	68.5	tkm	DE: Diesel mix at refinery Sphera	A distance of 50 km was assumed
Steel				
Steel transport to recycling plant	0.361	tkm	DE: Diesel mix at refinery Sphera	A distance of 50 km was assumed
Steel recycling process	7.22	kg	GLO: Credit for recycling of stainless steel scrap Sphera <Mfg>	Considers also credits for avoided primary material production
Steel transport to landfill	0.02375	tkm	DE: Diesel mix at refinery Sphera	A distance of 50 km was assumed
Landfilling treatment for steel	0.00475	kg	EU−28: Waste incineration of municipal solid waste (MSW) ELCD/ CEWEP	
Incineration of steel	0.47025	kg	EU−28: Waste incineration of municipal solid waste (MSW) ELCD/ CEWEP	Incineration takes place in landfill facility

The most relevant processes in the impact category Climate Change are concrete and carbon fiber production, as well as the steel production and the credit for steel recycling. For Human Toxicity, cancer, the most relevant process was identified as the steel production. Finally, in the case of Resource Use, fossils, the most relevant processes are the production of carbon fiber and concrete, credit for steel recycling, concrete incineration, and steel production, in that order.

The most relevant elementary flows are determined for both: the most relevant impact categories and the most relevant processes (all flows contributing to at least 80 % of the environmental impacts). These are listed in Table 13.

6.1. EoL alternative scenario: 100 % landfill

As stated in Section 5.2, an alternative scenario was calculated by assuming that the recovered concrete and carbon fibers are sent to a landfill at the EoL (Table 8). The steel is still considered to be recycled since this is a practice that is widespread in the industry. For the described alternative scenario, a hotspot analysis regarding the impact categories, life cycle stages, and processes was carried out to determine how the new scenario affected the study outcomes (Tables 14–16). All other parameters were kept the same.

Table 9
Characterized LCIA results for the RP.

Impact Category	Unit	Total life cycle
Acidification	Mole of H+ eq.	9.31E−01
Climate change - total	kg CO_2 eq.	4.56E+ 02
Climate Change - biogenic		6.33E−01
Climate change - fossil		4.55E+ 02
Climate change - land use and land use change		1.68E−01
Ecotoxicity, freshwater – total	CTUe	1.82E+ 03
Eutrophication, freshwater	kg P eq.	3.66E−04
Eutrophication, marine	kg N eq.	3.69E−01
Eutrophication, terrestrial	Mole of N eq.	4.26E+ 00
Human toxicity, cancer - total	CTUh	1.36E−05
Human toxicity, non-cancer - total		4.38E−06
Ionising radiation, human health	kBq U235 eq.	2.05E+ 01
Land use	Pt	4.78E+ 02
Ozone depletion	kg CFC−11 eq.	−2.00E−06
Particulate matter	Disease incidences	3.75E−06
Photochemical ozone formation, human health	kg NMVOC eq.	9.28E−01
Resource use, fossils	MJ	4.94E+ 03
Resource use, mineral and metals	kg Sb eq.	−7.74E−04
Water use	m^3 world equiv.	2.34E+ 01

Table 10
Contribution of environmental impact categories to overall results.

Impact Category	Contribution
Acidification	2 %
Climate Change	28 %
Ecotoxicity, freshwater	2 %
Eutrophication, freshwater	< 1 %
Eutrophication, marine	1 %
Eutrophication, terrestrial	2 %
Human toxicity, cancer	41 %
Human toxicity, non-cancer	< 1 %
Ionising radiation, human health	< 1 %
Land Use	< 1 %
Ozone Depletion	< 1 %
Particulate Matter	1 %
Photochemical Ozone Formation, human health	3 %
Resource Use, fossils	15 %
Resource Use, mineral and metals	2 %
Water Use	< 1 %

The shares of the impact categories are distributed differently in the alternative scenario, with the relevance of Climate Change increasing significantly (from 28 % to 39 %) and that of Human Toxicity, cancer decreasing significantly (from 41 % to 29 %). Furthermore, module A1 (raw material extraction and pre-processing) is still the life cycle stage with the greatest environmental impact, although the shares in the individual three impact categories vary slightly. The relevance of the processes per impact category corresponds to that of the previous scenario, only the contribution of the individual processes varies slightly.

7. Discussion

The LCA study of a proposed RP for CRC was carried out. In the next sub-sections, the outcomes of the assessment are addressed. In particular, the hotspots in connection to impact categories, life cycle stages, processes and elementary flows are discussed. In this regard, the most relevant impact categories and life cycle stages point out major areas in which the stakeholders involved of the CRC industry can focus their attention. Moreover, the most relevant processes and elementary flows provide insights that can lead to the optimization of specific processes.

Table 11
Contribution of life cycle stages in the most relevant impact categories to overall results.

Impact category	A1	A2	A3	A4	C1	C2	C3	C4
Climate Change	91 %	2 %	< 1 %	6 %	< 1 %	1 %	< 1 %	< 1 %
Human toxicity, cancer	100 %	< 1 %	< 1 %	< 1 %	< 1 %	< 1 %	< 1 %	< 1 %
Resource use, fossils	89 %	3 %	< 1 %	7 %	1 %	1 %	< 1 %	< 1 %

Table 12
Process contribution to the most relevant impact categories.

Most relevant impact category	Process	Contribution
Climate Change – total	Concrete production	34 %
	Carbon fiber production	42 %
	Credit for steel recycling	7 %
	Steel production	6 %
	Transport waste steel	5 %
	Transport concrete	2 %
	Processes with contribution < 1 % each	2 %
	Concrete incineration	1 %
	Transport waste concrete	1 %
Human Toxicity, cancer	Steel production	95 %
	Credit for steel recycling	4 %
	Processes with contribution < 1 % each	1 %
Resource Use, fossils	Carbon fiber production	57 %
	Concrete production	11 %
	Credit for steel recycling	7 %
	Concrete incineration	6 %
	Steel production	6 %
	Transport waste concrete	5 %
	Transport concrete	2 %
	Credit for concrete recycling	1 %
	Transport waste steel	1 %
	Processes with contribution < 1 % each	4 %

Table 13
Most relevant elementary flows (added contribution is at least 80 %).

Most relevant impact category	Most relevant elementary flow	Contribution
Human toxicity, cancer - total	Polychlorinated dibenzo-p-furans (2,3,7,8 - TCDD)*	82 %
	Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD)*	18 %
Climate Change - total	Carbon dioxide	91 %
Resource use - fossils	Natural gas	52 %
	Crude oil	21 %
	Hard coal	15 %

* part of the steel production

Table 14
Most relevant impact categories for the 100 % landfill scenario.

Impact Category	Contribution
Climate Change	39 %
Human toxicity, cancer	29 %
Resource use - fossils	17 %

Table 15
Most relevant life cycle stages for the 100 % landfill scenario LF.

Most relevant impact category	Most relevant life cycle stage	Contribution
Climate Change	A1	87 %
Human toxicity, cancer	A1	99 %
Resource use - fossils	A1	84 %

Table 16
Most relevant processes for the 100 % landfill scenario.

Most relevant impact category	Most relevant processes	Contribution	Total contribution
Climate change	Concrete production	34 %	82 %
	Carbon fiber production	41 %	
	Credit for steel recycling	7 %	
Human toxicity, cancer	Steel production	95 %	95 %
Resource use - fossils	Carbon fiber production	70 %	93 %
	Concrete production	16 %	
	Credit for steel recycling	7 %	

7.1. Most relevant impact categories

The results in Table 10 show that the impact categories of Human Toxicity, cancer, Climate Change, and Resource Use, fossils are the most relevant, amounting to 84 % of the total results. The weighting set of the EF method, assigns the highest weight to the impact category Climate Change (given in kg CO_2 eq., also known as carbon footprint). Thus, this fact combined with the high impacts of concrete and carbon fiber production on Climate Change make this impact category one of the most relevant. This impact category is often used by policymakers and companies to set environmental targets. Therefore, the result obtained in this study confirms the need of further considering this impact category.

The impact categories Human Toxicity, cancer and Resource Use, fossils were determined to be the most relevant with a contribution to the total environmental impacts of more than 41 % and 15 %, respectively. The high relevance of Human Toxicity, cancer is primarily attributed to the use of steel for the anchor of the façade panel, which strongly influences this category (as further discussed in Section 7.4). In turn, the significant impact of Resource Use, fossils is mainly linked to concrete and carbon fiber production. For the purposes of consideration for setting environmental targets, however, the results of these impact categories should be considered carefully due to the limited robustness of the impact assessment methods applied [30].

7.2. Most relevant life cycle stages

The hotspot analysis (Table 11) pointed out that for all relevant impact categories, the most relevant life cycle stage corresponds to module A1 (raw material extraction and pre-processing), particularly in the production of the carbon fibers, concrete, and steel (as discussed in Sections 7.3 and 7.4). In the case of Human Toxicity, cancer, the contribution of module A1 resulted in almost 100 % of the impacts. Overall, the obtained outcomes go in line with several previous studies conducted in the context of CRC, where the extraction and pre-processing of the raw materials were a major hotspot [60,68].

These results highlight the central role of the selection of the raw materials in CRC. To improve the environmental impacts connected to raw material extraction and pre-processing, the development and use of alternative materials could have a favorable effect. For instance, the implementation of cements with a reduced proportion of clinker (e.g., limestone calcined clay cement) may be advantageous due to the reduced energy consumption. Indeed, these have been proven to have a better environmental performance than ordinary Portland cement [58, 69]. Furthermore, the integration of secondary raw materials (e.g., recycled carbon fibers and steel) may as well help improve the environmental performance in module A1. Other strategies could include service life extension and recycling methods that produce high quality secondary materials.

According to the hotspot analysis, transport processes (modules A2 and A4) have a much lower relevance than module A1. However, for the impact categories Climate Change and Resource Use, fossils their combined contribution amounts to 9 % and 11 %, respectively. Although it would not be as impactful as changes done in module A1, the use of regional materials or the adoption of alternative vehicles and fuels may have a positive impact in the environmental performance of the proposed RP. In particular the latter (alternative vehicles and fuels) demonstrates great potential for improvement in terms of environmental performance [70], which, in turn, could positively affect the performance of the RP.

7.3. Most relevant processes

When examining the contribution of the different processes to the most relevant impact categories, it was noticed that different processes where considered the most relevant depending on the category that was analyzed.

For Climate Change (Table 12), it was evident that the production of the carbon fibers and the concrete, and the credit for steel recycling are the most impactful. The starting materials for the carbon fibers is a petroleum derivate and the production process of the fibers comprises oxidation, carbonization, graphitization and surface treatment [58]. All these steps make the carbon reinforcement a highly energy- and resource-intensive material [71]. Therefore, it is not surprising that the fiber production makes up the greatest share of the aforementioned impact category. It is also important to highlight that the carbon fibers makeup only 0.6 % of the total mass of the RP. Nevertheless, in terms of Climate Change, the fibers are the most important material to consider and optimize. In this regard, studies have shown that the use of fibers with a SBR impregnation (in contrast to the epoxy impregnation considered in the RP as worst-case scenario) could be beneficial in the environmental impact of CRC elements, but at the same time also changing the stiffness of fibers [58]. The concrete production was the second most contributing process. Concrete is one of the most impactful materials worldwide [72] and has a considerable footprint in terms of Climate Change [73]. Moreover, concrete comprises around 98 % of the RP's mass making it a central lever for improving the environmental performance of the RP. As mentioned in Section 7.2, CRC elements could benefit from the use of concrete made out of cements with a reduced amount of clinker. Finally, it was observed that the recycling of the steel from the anchors has a positive influence on the results for Climate Change. This positive impact in the results emphasizes not only the importance of an accurate modelling of the EoL of the RP, but also highlights the positive impact of in the use of secondary raw material (and savings in primary raw material) under the framework of circular economy.

In the case of Human Toxicity, cancer (Table 12), more than 95 % of the impacts were due to the steel production. A more detailed discussion of this outcome is provided in Section 7.4. Within the category Resource Use, fossils (Table 12), the impacts are disaggregated among more processes: carbon fiber production (57 %), concrete production (11 %), credit for steel recycling (7 %), incineration of concrete (6 %), and steel production (6 %). As abovementioned, the carbon fiber and concrete production are highly resource- and energy-intensive processes. In these cases, the use of alternative energy source in the production could improve the environmental performance in this impact category. In the case of the carbon fibers, improvements in technology and economic feasibility would be required to be able to successfully recycle and use secondary fibers for the same purpose as primary fibers [27]. Moreover, due to the possibility of high recycling rates for steel, a considerable positive impact can be observed for this environmental category.

7.4. Most relevant elementary flows

The most relevant elementary flow for the impact category of Climate Change was CO_2 (Table 13). Although this impact category is made up of far more chemical compounds than just CO_2 and methane, for example, has a far greater impact (x28), CO_2 is primarily decisive for the CO_2 footprint in the considered processes.

For Human Toxicity, cancer, the most relevant elementary flows are Polychlorinated Dibenzo-p-Dioxins and Furans (PCDD/Fs). These flows are most likely to be linked to the steel production, since this was the most relevant process for this impact category. According to Yang et al., steel scrap usually contains various chlorinated compounds in the form of paint, oils, and other substances that promote the formation of PCDD/Fs during electric arc furnace operation [74,75], which was the technology used to model the steel production for the RP. Therefore, particular attention should be set on the quality of the steel scrap and sintering technologies used in the steel plant [75].

In the impact category Resource Use, fossils, the most relevant elementary flows are natural gas, crude oil, hard coal, and uranium. These flows are mainly linked to the energy consumption in the different production processes, as well as the raw materials of the carbon fibers. The use of renewable energy sources in the different processes involved in the life cycle of the RP, but specially the carbon fiber, concrete, and steel production, as well as concrete incineration, could help improve the performance in this impact category. This is similar to the results in Backes et al. [58]

7.5. EoL alternative scenario: 100 % landfill

The results of this scenario analysis show that the consideration of the worst-case scenario for the EoL for the concrete and carbon fibers does not have a great impact in the results of the hotspot analysis (Table 15). In regard of the most relevant impact categories and life cycle stages, the same results are obtained in the alternative 100 % landfill scenario. Furthermore, it can be seen that carbon fiber production is still the most impactful process. However, the contribution of this process in the landfilling scenario is now greater, as seen in Table 16. It is theorized that the reason for this change is connected to the landfilling of the concrete and carbon fibers. Since no (fossil) energy is required for the recycling of these materials, the relevance of the carbon fiber production increases. Moreover, in this scenario the steel production is no longer relevant.

7.6. Limitations of the study

The current study aimed to define a RP for the German market of CRC, a disruptive innovation in the construction sector. Although great effort was invested in the definition of a product that best represents the aforementioned market, CRC is a new material for which limited data is available. This lack of market data can significantly affect the definition and environmental performance of the RP. For example, CRC has multiple applications, and the choice of the representative construction element could vary if more data were available. Additionally, different types of concrete and carbon fibers have varying environmental profiles as demonstrated by Backes et al. [58]. Since these materials significantly contribute to the environmental impacts of CRC elements, the environmental profile of the RP can differ depending on the considered materials. Moreover, CRC could be considered as an intermediate material that can be used in different forms and for different purposes, similar to steel. Nevertheless, to create a RP that is comparable based on its performance, a function had to be defined (façade element). This function was identified for Germany with the support of German stakeholders.

Another point that has to be considered is the materials used to model the RP. Since the authors did not have the possibility to receive specific information regarding the type of concrete and carbon fibers used to build the panel, the worst-case scenario was chosen for these materials. This scenario was defined by choosing the concrete type and the carbon fibers with the worst performance in terms of Climate Change. In this regard, studies have already shown the central role of dataset selection for the concrete and the carbon fibers [58]. Although it is theorized that the modelling of other types of concrete and carbon fibers would still have as a result that these materials and their associated processes are the most impactful, future studies involving the RP of CRC could demonstrate the actual influence of these parameters in the results. Furthermore, the study heavily relied on secondary data for the modelling.

While the highest-quality data was preferred, the authors recognize that relying on secondary data might introduce uncertainties. For instance, to model reinforcement production, several options were available in the GaBi© databases covering different production techniques and energy consumptions. A conservative approach was adopted by selecting the dataset with the worst-case scenario for Climate Change. If the environmental performance of this material differs greatly from reality, this might lead to unrealistic benchmarks, that either cannot be met at all or are met by all market participants, regardless of their efforts to improve the environmental performance of their products. Similarly, the most conservative estimates were used for transport distances and energy consumption for the production of the RP. However, their influence on the overall results was minimal. Finally, a certain degree of uncertainty is associated to the selected EoL scenario. Since no information is currently available about the EoL route of the material fractions from CRC, the baseline EoL scenario was based purely on secondary data. Furthermore, the data reflects current EoL practices and technologies, which may evolve over time, particularly given the long lifespans of CRC. For example, pyrolysis could emerge as a relevant method for recycling carbon fibers from CRC. This technology has the potential to preserve the quality of the fibers, enabling reuse for their original purpose and preventing downcycling. However, this method requires significantly more energy than the conventional alternative of mechanical recycling, affecting the overall environmental profile of the RP [26].

8. Conclusion

This study aimed to establish a first approach of a PEF study for CRC by proposing a RP for this material. Of particular relevance was the PEF-RP, which included the modelling of the EoL scenario with the CFF. To apply the CFF in the context of concrete and the carbon fiber reinforcement, the authors had to rely on literature as well as standard values proposed by the PEF method to define the required parameters. In general, the definition of the RP for a PEF study represents an important step in the assessment of the environmental performance of CRC, as current (PEF) standards and guidelines do not consider this building material explicitly. As there is an increasing need for comparable information about the environmental performance of CRC construction products, PEF represents a suitable methodology that ensures both comparability and transparency.

This contribution presents the first-ever application of the CFF to CRC. While many other EoL allocation approaches exist, the CFF is stands out for its comprehensiveness and flexibility. This approach accounts not only for different EoL fates (recycling, reuse, landfill, etc.), but also considers possible loss of quality, as well as the market situation of the material (i.e., offer and demand of secondary materials). These attributes are particularly relevant for CRC, as they can encourage the use of secondary materials and incentive recyclability at the EoL, both of which could enhance the environmental profile of CRC applications.

A CRC façade panel measuring 4000 * 3600 * 40 mm built with concrete of the strength class C50/60 and with a carbon fiber reinforcement impregnated with EP was defined as an RP. The PEF study of the RP was conducted and various hotspots were identified. For instance, it was found that the most relevant impact categories are Human Toxicity, cancer, Climate Change, and Resource Use, fossils. Regarding the life cycle stages, the most relevant was found to be the raw material extraction and pre-processing (module A1). As the most relevant processes, the carbon fiber and concrete production, as well as the credit for steel recycling were identified as the most impactful for Climate Change. For Human Toxicity, cancer, the most relevant process was steel production, while for Resource Use, fossils, the most relevant processes were production of carbon fiber, concrete, and steel, credit for steel recycling and concrete incineration. Finally, the most relevant elementary flows were identified as CO_2 (Climate Change), PCDD/Fs (Human Toxicity, cancer), natural gas, crude oil, hard coal, and uranium (Resource Use, fossils).

The outcomes of this study provided a deeper understanding of the potential environmental impacts connected to CRC elements. By analyzing the outcomes considering all impact categories and identifying hotspots at different levels, detailed insight could be gained of the most relevant parameters connected to the environmental impacts of CRC for the selected RP. Moreover, the results can serve as a benchmark for the environmental impacts of CRC elements, enhancing comparability. This benchmark can support industry improvements in several ways. On the one side, it can encourage the collection of more detailed data on the application of CRC across different regions, enabling the optimization of the RP model or the creation of new ones. On the other side, the concrete industry can use the hotspots identified to improve the performance of their products. Additionally, policymakers can use these findings to promote the implementation of CRC applications that prioritize not only technical, but also environmental performance Similar studies could be done in the future in which more accurate data is used, given the data limitations encountered in this work. Finally, the use stage could be considered in future studies to quantify the actual contribution of this portion of the life cycle on the overall results.

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CRediT authorship contribution statement

Pamela Haverkamp: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Laura Schmidt:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation. **Jana Gerta Backes:** Writing – review & editing, Project administration, Investigation, Data curation, Conceptualization. **Marzia Traverso:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

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