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# Assessing the Ability of the Cradle to Cradle Certified™ Products Program to Reliably Determine the Environmental Performance of Products

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**Abstract:** Concepts and tools supporting the design of environmentally friendly products (including materials, goods or services) have increased over the last years. The Cradle to Cradle Certified™ Products Program (C2CP) is one of these approaches. In this work, the ability of C2CP to reliably determine the environmental performance of products was analyzed through the application of a criteria-based assessment scheme. Additionally, to compare C2CP with three other already established tools (life cycle assessment, product environmental footprint and material flow analysis), the same criteria-based scheme was applied. Results show that C2CP is not scientifically reliable enough to assure that certified products actually have a good environmental performance. The most relevant shortcoming of C2CP relates to its limited assessment scope, due to the fact that neither the entire life cycle of the product nor all relevant environmental impacts are covered. Based on already established tools and their practical implementation recommendations for increasing the reliability of C2CP are provided.

**Keywords:** cradle to cradle; life cycle assessment; product environmental footprint; material flow analysis

## 1. Introduction

Environmental issues have become more and more important in recent years, which led to consumers as well as producers paying more attention to the products they purchase. As a result, companies now have a greater incentive to design more environmentally friendly products (intermediate as well as final) and market them to consumers and other businesses has been increasing over the last years. For both producers and consumers, this comes along with the challenge to determine the environmental performance of materials/products in a scientifically reliable way.

In recent years, several methods and approaches have been specifically developed to support companies—in varying degrees of detail—to assess their products' environmental performance [1]. Examples include carbon [2] and water footprinting [3], life cycle assessment (LCA) [4] or more recently the product environmental footprint (PEF) approach of the European Commission (EC) [5,6]. Many of these methods are accepted by a broad set of international stakeholders as documented by the respective international standards [7,8]

In addition to such tools and methods which are primarily used to conduct environmental assessments, in the last few years, there has been a surge in approaches and tools intended to serve other purposes such as eco-design (e.g., European Ecodesign Directive [9]), eco-efficiency strategies [10,11] and environmental labels and declarations [12–15]. Additionally, other tools such as environmental ABC analysis, Environmental Failure Mode and Effects Analysis [16] have also found their way into the practices of companies. They do not represent environmental assessment methods per se, but either use some of the existing assessment approaches discussed above or they contain their own environmental assessment schemes. These environmental assessment schemes often contain a set of predefined quantitative and qualitative environmental criteria, which have to be fulfilled for a product to be classified as environmentally friendly.

The ability of these implicit assessment schemes to reliably determine environmental performance of products—especially the comprehensiveness and relevance of the criteria they define—is crucial to guarantee that the product actually performs well with regard to environmental impacts and benefits. While there is ample literature on some of these emerging methods (e.g., eco-design, type I and type III ecolabels), other methods such as the Cradle to Cradle Certified™ Product Program [17] (in the following referred to as Cradle-to-Cradle Program (C2CP)) have so far not been put under sufficient scientific examination. Existing literature on the C2CP (e.g., [18–21]; see also Section 2) provides basic insight into some of its weaknesses and drawbacks, but have a rather narrow scope (e.g., Bakker et al. [18] analyzed strength and weaknesses of C2CP with regard to applicability for student design projects). However, its underlying environmental assessment criteria as well as the scientific reliability of its awarding criteria have not yet been comprehensively analyzed reliably.

Thus, the goal of this paper is to analyze the ability of the C2CP to reliably determine the environmental performance of products and to assure that certified products are actually beneficial for the environment, as is the intention of C2CP. A systematic and broad criteria-based assessment analysis of the C2CP is carried out and its shortcomings are identified. To better judge the assessment results, in this study, C2CP was compared against other established methods (LCA [22] and PEF [23]) and the end-of-life phase of products (Material Flow Analysis (MFA) [24]) (Section 2), which are evaluated using the same criteria-based assessment scheme.

LCA and PEF are selected for the comparison because their goal is to assess environmental impacts of products/materials. MFA on the other hand is chosen because the method quantifies resource flows and stocks of (primary and secondary) materials or substances and therefore focuses next to other life cycle stages, predominantly on the end-of-life (EoL) of materials. In Section 2, all analyzed methods (C2CP, LCA, PEF and MFA) are first introduced. A short overview of existing literature on the C2CP is also presented, summarizing available critiques of the method. In Section 3, the applied criteria-based assessment approach is described in detail. Identified shortcomings of the C2CP as well as recommendations on how to address these shortcomings are explained and discussed in detail (Section 4). Finally, conclusions are drawn (Section 5). This work is a continuation of the work by Minkov et al. [25], which also analyzed C2CP, but only in terms of its robustness as a communication tool.

## 2. Background

In this section, the Cradle to Cradle® design approach as well as the C2CP are introduced in more detail, alongside LCA, PEF and MFA. Cradle to Cradle® is a registered trademark that is owned and licensed by McDonough Braungart Design Chemistry, LLC (MBDC).

The Cradle to Cradle® design approach envisions a future of absolute environmental sustainability based on the following three principles [17]:

- Waste equals food: All materials and emissions (if not specified otherwise) are seen as beneficial for the environment or the technosphere (i.e., the biological or the technical cycle, respectively). Products shall be designed in a way that they pose no danger to human health and can be recycled continuously. By complying to this principle, no waste is generated, and all outputs are inputs for (an)other system(s). Based on these cycles, closed-looped systems can be defined and established.
- Strengthen renewable energy: Using renewable energy is defined as being of crucial importance to effective design. Their use should be increased as much as possible.
- Celebrate diversity: The key to innovation is to design products that are technically diverse (i.e., avoiding "one-size-fits-all designs").

The C2CP was introduced in 2005 and is managed by the private Cradle to Cradle Products Innovation Institute since 2010 [17]. It provides rules to certify materials, sub-assemblies and finished products. However, certain products such as food, beverages, pharmaceuticals or fuels as well as buildings (but not building and construction related materials) are excluded. As stated by Kausch et al. (2016) [26], these products are excluded because they do not fit the scope of the C2CP. They further state that the evaluation criteria need to be revised to include additional products such as buildings. Currently, almost 500 products have been certified, with the majority being in the "Building Supply and Materials" sector [25,27].

For a product to be certified, it has to fulfill the requirements of five "quality categories": material health, material reutilization, renewable energy and carbon management, water stewardship and social fairness. To each of these five quality categories, an achievement level is assigned, "basic" being the lowest and "platinum" being the highest. The lowest achieved level, assigned to one of the five quality categories, defines the overall achievement level of the product.

In the last few years, several publications evaluated the suitability of C2CP for measuring the environmental impacts of products. An overview of these publications is shown in Table 1. They were identified using the search engines Google scholar (https://scholar.google.com/) and Web of Science (https://webofknowledge.com/) searching for terms such as "cradle to cradle" and "C2C". Furthermore, the reference lists of the selected publications were examined with regard to additional publications not identified at the first round of online search. Lastly, the C2CP website (www.C2CPcertified.org/) was searched for published reports and program's guidance documents by the Cradle to Cradle Products Innovation Institute. Next, all publications were screened for further analysis with regard to their content and publications addressing the ability of C2CP to measure environmental impacts (see Table 1).

**Table 1.** Overview of publications focusing on the reliability of C2CP to determine the environmental performance of products.

| Title and Author(s) | Short Summary |
|---|---|
| Impacts of the Cradle to Cradle certified products program, published by Vercoulen (2014) [28] | Analysis of existing methods addressing impacts relevant to the C2CP and introducing a developed framework as a solution |
| Characterization of the Cradle to Cradle Certified™ Products Program in the Context of Eco-labels and Environmental Declarations, published by Minkov et al. (2018) [25] | Analysis with regard to maturity of C2CP as a tool for external communication |
| Are Cradle to Cradle certified products environmentally preferable? Analysis from an LCA approach, published by Llorach-Massana et al. (2015) [29] | Analysis of C2CP certification with regard to distinguishing environmentally more preferable products as well as informing consumers correctly about the environmental performance |
| Usability of Life Cycle Assessment for Cradle to Cradle purposes—Position paper of Netherlands Ministry of Infrastructure and the Environment, published by Bor et al. (2011) [30] | Exploration of the usability of LCA for C2CP purposes |
| Designing Cradle to Cradle products: a reality check, published by Bakker et al. (2010) [18] | Analysis of the applicability of the C2CP concept in day-to-day product development in a business setting |
| Exploring the Feasibility of Cradle to Cradle (Product) Design: Perspectives from New Zealand Scientists, published by Reay et al. (2011) [31] | Feasibility of using the C2CP for sustainable product design in New Zealand is examined by asking a sample of New Zealand scientists to explore the underlying science and reliability of the C2C framework |
| Are emissions or wastes consisting of biological nutrients good or healthy? —Letter to the editor, published by Reijnders (2008) [32] | Statement that no wastes or emissions derived from biological materials are ecologically irrelevant and intrinsically good or healthy |
| Cradle to Cradle and LCA, published by Bjørn and Hauschild (2018) [20]<br>Absolute versus Relative Environmental Sustainability—What can the Cradle-to-Cradle and Eco-efficiency Concepts Learn from Each Other? published by Bjørn and Hauschild (2013) [33] | Introduction in C2CP framework and certification scheme Comparison of LCA and eco-efficiency with C2CP |

Following, the shortcomings identified in the above-mentioned studies (see Table 1) are briefly listed. Several methodological shortcomings undermine the ability of the C2CP to deliver reliable assessments of the environmental performance of products. The most common ones are:

- Biological nutrients are always considered as beneficial independent of their occurrence. However, too much emissions, e.g., sulfur dioxide emissions, within the ecosystem can lead to environmental pollution, e.g., acidification [20,29,31,32].
- Quality loss of recycled products and materials, which often occurs during recycling is not considered in the awarding criteria. However, the reuse ability of products/materials depends on their quality [18,21,33].
- Energy efficiency (referring to using as little energy as possible) is not considered in C2CP, because the long-term goal is to only use renewable energy, which is assumed to have no emissions. However, to reduce environmental impacts, the absolute as well as relative (per product unit) energy consumed has to be considered. Furthermore, even renewable energy cannot be produced without discharging any emissions [18,20,29,31,33].
- Further, C2CP does not consider the scarcity of bio-based resources, however, e.g., productive land to grow biomass is limited [20,29].
- C2CP does not consider all relevant substances/emissions over the entire life cycle of the analyzed product [28], e.g., acidifying and eutrophying emissions (impacting the quality of water bodies and soils) as well as particulate matter emissions (impacting human health) are not taken into account. The awarding criteria of C2CP are not product-specific, but generic and equal for all products [25].
- C2CP does not cover the complete life cycle of a product at all certification levels, which can lead to burden shifting between life cycle phases [25,28–30].

These identified shortcomings are described in detail and illustrated by examples (where possible) in Section 4.

The LCA method assesses and addresses potential environmental impacts associated with a product or service throughout its life cycle. It is a worldwide accepted standard, harmonized in the ISO standards 14040 [4] and 14044 [22]. LCA help identify options to improve the environmental performance of products or processes over their full life cycle, providing information for decision-makers in industry, governmental and non-government organizations as well as information for marketing/reporting purposes, e.g., implementing an ecolabeling schemes [22,34]. Currently, several labels are based on LCA, e.g., EU Ecolabel of the European union [35] or Germany's Blue Angel [36].

The PEF method—a life cycle-based multi-criteria measure of the environmental performance of products and services—was published in 2013 by the EC [23]. PEF is largely based on LCA principles, but provides further specifications for selected aspects (e.g., end-of-life modeling or determining the relevance of impact assessment categories). The PEF method therefore decreases the flexibility provided by the ISO standards regarding methodological choices [23,37]. PEF has been tested in practice in a 3.5-year pilot phase, which was completed in April 2018. At this point, several goals and applications of the PEF method are possible, including in-house product improvement, business-to-business or business-to-consumer green claims (with or without comparisons or comparative assertions) of products within one product category. However, the establishment of a label to enhance comparative assertions of products is pushed by the EC as several parallel studies with regard to communicating PEF results via label are carried out [6,38,39].

MFA is based on the Austrian standard ÖNORM S 2096 (Material flow analysis—Application in waste management) [40] but was picked up and implemented by several stakeholders around the world (e.g., [41–45]). MFA is a method to analyze quantitative flows and stocks of materials including extraction, manufacturing, consumption, recycling and disposal [46]. Thus, the methods can help quantify flows and stocks of materials or substances in a defined system. It is often used to study material or product flows across different industrial sectors or within ecosystems and therefore it can support the analysis of policy strategies such as the circular economy and end-of-life aspects. Beside its use in policy, MFA has become a widely used tool in other fields as well, e.g., environmental management, product design, and life cycle assessment [24,46].

## 3. Methodological Approach

In this section, the criteria-based assessment scheme to determine the shortcoming of C2CP as well as possible solutions for improvement is presented. C2CP is analyzed through its Cradle to Cradle Certified$^{TM}$ Product Standard v3.1 [17] (hereinafter referred to as Product Standard) applying a criteria-based assessment scheme to systematically determine further shortcomings in addition to the ones highlighted by the literature overview. Shortcomings are identified with regard to the overall principles of C2CP as well as with regard to the awarding criteria of four out of five quality categories (social fairness is not included, because this analysis focuses on environmental performance only). Shortcomings are described in detail and (where possible) demonstrated in an example together with the shortcomings determined. Further, the criteria-based assessment scheme is applied to other methods with focus on environmental aspects (LCA [22] and PEF [5]) or on the end-of-life phase of products (MFA [24]). Based on the methodological frameworks and practical implementations of these existing methods, recommendations on how to improve C2CP are provided for all identified shortcomings.

The criteria-based assessment scheme is developed by carrying out six steps:

(1) Definition of the goal of the assessment scheme: the goal of the assessment scheme is to determine the reliability of mainly the C2CP method [17], but also that of the LCA [4,22], PEF [5] and MFA [24] methods.
(2) Identification of existing assessment schemes for methods addressing environmental impacts: the following assessment schemes exist for evaluating methods determining environmental impacts: Reimann et al. [47]; European Commission-Joint Research Centre [48]; Lehmann et al. [39]; and Forin et al. [49].
(3) Analysis whether existing criteria of the above schemes (Step 2) can contribute to the goal of the herein applied assessment scheme: Not all of the criteria can be used to fit the goal of the assessment scheme (Step 1); e.g., availability of characterization factors in LCA software tools is included in the schemes used by the European Commission-Joint Research Centre [48], Lehmann et al. [39] and Forin et al. [49] but is not relevant to the goal of this assessment. Several criteria can be directly used in the herein developed assessment scheme, e.g., stakeholder acceptance as addressed by Reimann et al. [47], European Commission-Joint Research Centre [48], Lehmann et al. [39] and Forin et al. [49]. For further explanations regarding why certain criteria are relevant, please see information in Section S1 of the Supplementary Materials.
(4) Determination whether certain aspects (for which criteria are needed) are missing to reach the goal of the respective assessment scheme: due to the comprehensiveness of the criteria in the identified publications, there was no need to define additional criteria.
(5) Development of additional criteria for the identified aspects (in Step 4): Not necessary, because missing aspects could not be identified.
(6) Compilation of existing and newly developed criteria into a criteria-based assessment scheme: Criteria identified in (Step 3) are compiled to an overall assessment scheme (see Table 1).

The criteria-based assessment scheme consists of five criteria: *stakeholder acceptance, documentation and review, environmental relevance, scientific soundness* and *applicability* (see Table 2). The criteria are explained in more detail in the Supplementary Materials (Section S1).

With two exceptions all sub-criteria can be evaluated with *yes, partly* and *no*. *Yes,* means that all requirements of the criterion are fulfilled. *No* means that none of the requirements are fulfilled and *partly* means that only some of the requirements are fulfilled. The criterion *effort to collect data* (sub-criterion 5b) cannot be answered with *yes, partly* or *not*. Thus, possible answers for this criterion are *low, medium* and *high*. For the criterion *authoritative body endorses the method* (sub-criterion of criterion 1), the answer is specified into *one*, *several* and *multiple*, because the number of authoritative bodies endorsing the method differs.

**Table 2.** Overview of criteria and sub-criteria to analyze C2CP as well as the existing methods focusing on environmental assessment (LCA and PEF) and on end-of-life of products and materials (MFA).

| Criterion | Sub-Criterion |
|---|---|
| (1) Stakeholder acceptance | a. Used in policy<br>b. Authoritative body supports method<br>c. Stakeholder participation |
| (2) Documentation and review | a. Method is documented<br>b. Uncertainties are addressed |
| (3) Environmental relevance | a. Broad coverage of environmental emissions<br>b. Relevant environmental impacts are addressed<br>c. Entire life cycle is addressed |
| (4) Scientific soundness | a. Method has undergone scientific review<br>b. Method is object to scientific work<br>c. Method allows for reproducibility |
| (5) Applicability | a. Globally valid<br>b. Effort to collect data<br>c. Tool to support application |

## 4. Results and Discussion

In this section, the results of the criteria-based analysis are presented as they appear in Table 1 (Section 4.1–Section 4.5), followed by an overview of the results and recommendations (Section 4.6 and Table 3). Identified shortcomings and benefits of C2CP as well as recommendations on how to improve C2CP are explained in more detail and illustrated by examples. The criteria-based assessment scheme has also been applied to LCA, PEF and MFA and compared to the C2CP.

**Table 3.** Results of the criteria-based assessment for C2CP, LCA, PEF and MFA.

| Methods/Criteria | | C2CP | LCA | PEF | MFA |
|---|---|---|---|---|---|
| Stakeholder acceptance | Used in policies | No | Yes | No [1] | Partly |
| | Authoritative body supports method | One | Multiple | One | One |
| | Stakeholder participation | Partly | Yes | Partly | Partly |
| Documentation and review | Method is documented | Yes | Yes | Yes | Yes |
| | Uncertainties are addressed | No | Yes | Partly | Partly |
| Environmental relevance | Broad coverage of relevant emissions | Partly | Yes | Yes | Partly |
| | Relevant environmental impacts are addressed | No | Yes | Partly | No |
| | Entire life cycle is considered | No | Yes | Yes | Yes |
| Scientific soundness | Method has undergone scientific review | Partly | Yes | Yes | Partly |
| | Method is object of scientific work | Partly | Yes | Partly | Yes |
| | Allows for reproducibility | Yes | Yes | Yes | Yes |
| Applicability | Globally valid | Yes | Partly | Partly | Yes |
| | Effort of data collection | High | High | High | High |
| | Tool to support application | No | Yes | Yes | Yes |

[1] The PEF project is in its pilot phase. After the pilot phase is completed (probably April 2018), strategies for policy implementation will be developed. However, even though it is likely that (some) principles of PEF will be implemented into existing/new regulations, it cannot be guaranteed.

### 4.1. Stakeholder Acceptance

Within criterion 1 stakeholder acceptance, three sub-criteria are analyzed. With regard to the first sub-criterion a, being *used in policy*, proponents of C2CP argue that the circular economy concept is based on or was inspired by the C2CP [50,51]. However, the EU Action Plan for the Circular Economy [52] does not refer to C2CP as one of its underlying principles. Thus, as no clear policy use can currently be identified for C2CP, the sub-criterion is answered with a *no*. However, as C2CP pursues a long-term vision of a desirable sustainable future, where all products will be designed in a way that they cause no harm to the environment or human health, its overall framework is advantageous for policy (where long-term strategies are implemented). LCA, on the other hand, is used in policy as it represents the basis for several ecolabels such as the EU flower [35] and therefore, in the case of LCA, this sub-criterion is answered with a *yes*. With regard to the PEF, it is currently not used in policy and the sub-criterion is therefore answered with *no*. However, the use of PEF in policy is stated as the main goal of the PEF project [38] leading to the assumption that this evaluation is likely to change soon. The MFA method supports the resource efficiency approach of the EU [53]. The sub-criterion is therefore answered with *partly*.

The sub-criterion *authoritative body supports the method* (sub-criterion 1b of criterion *stakeholder acceptance*) is answered with *one* for C2CP, because since January 2017, the US Environmental Protection Agency uses C2CP in their public procurement recommendations for seven construction product categories in the building and construction sector [54]. For the LCA method, which is supported by the EU [35], ISO [14] and UNEP [55], this sub-criterion is evaluated with *multiple*. PEF is reinforced by the EU [5]. Thus, the sub-criterion is answered with *one*. For MFA, which is supported by UNEP [56], the criterion is answered with *one* as well.

Next, the sub-criterion *stakeholder participation* during method development (sub-criterion 1c of criterion *stakeholder acceptance*) is analyzed. According to the C2CP policy for revision [57], when revising the Product Standard, two public comment periods are foreseen, during which external stakeholders can provide inputs [57]. However, at the time of writing this paper, public stakeholder consultation had not yet started for the current revision of the C2C method, which began in June 2014 and is expected to finish by the end of 2018 [25]. Nevertheless, as listed on their homepage, five advisory groups with experts selected by C2CP have been formed to provide expert guidance in the update. Based on this information it seems that a versatile group of stakeholders is included, but it is unclear how other external stakeholders can take part. Thus, the sub-criterion is answered with *partly*. As the LCA method is standardized by ISO, diverse stakeholder groups from science, policy, companies and the non-governmental sector contributed to method development. If changes are to be made to the standards, a committee of experts is established, which decides over all changes of the norm. Additionally, a public stakeholder consultation is carried out, where everyone can comment on the standard's draft. Thus, this sub-criterion is answered with *yes* for LCA. In the case of PEF, some documents, e.g., PEF guide and Product Environmental Footprint Category Rules (PEFCR) guidance, are accessible through an Internet platform, which is open for comments to all stakeholders [58]. However, the majority of the documents (e.g., Technical Advisory Board issue papers, trainings and webinars as well as position papers and replies) are not provided for all stakeholders. Thus, this sub-criterion is answered with *partly*. The basic principle of the MFA method are not updated, but several stakeholders use and thereby improve the method (e.g., [45,59,60]). Consequently, the sub-criterion is answered with *partly* as well.

### 4.2. Documentation and Review

For criterion 2 *documentation and review* the sub-criterion a *method is documented* is answered with *yes* for all analyzed methods. C2CP is documented in the Product Standard [17], and several books addressing C2CP have been published (e.g., [61,62]). The ISO 14040/44 standards [4,22] are the two main documents establishing standardized requirements for the LCA method. Additionally, several books (e.g., [63,64]) and journal articles (e.g., [65,66]) discuss the method and its specifics. Given that the PEF method was developed only recently, next to the method documentation [5] and PEFCR guidance [38], so far only few publications are available discussing its applicability (e.g., [37,39,67]). However, with the end of the pilot phase and the publication of the final PEFCRs in the near future, more information will be available soon. MFA is documented by the Austrian standard ÖNORM S 2096 [40] and was picked up and is implemented by several stakeholders around the world for which multiple publications exist (e.g., [41–45]).

Sub-criterion 2b, *uncertainties are addressed* (of criterion *documentation and review*), has to be answered with *no* for C2CP, because only other scientists (e.g., [19,20,25,31]) address uncertainties of C2CP, but not the Product Standard or the authors of the method. For the LCA and MFA methods, the sub-criterion is answered with *yes*. Uncertainties of these methods as well as of case studies using the methods are addressed in multiple ways. For example, according to the ISO 14040/44 LCA studies are required to carry out a sensitivity analysis, an uncertainty analysis as well as a gravity analysis. Moreover, gaps and limitation of LCA are addressed within several publications (e.g., [37,68,69]). Similarly, uncertainties of MFA have frequently been discussed in literature (e.g., [59,60,70]). With regard to the PEF method, as it is based on LCA, it inherited some of the identified uncertainties and limitations. However, unlike LCA, the PEF method itself does not stipulate carrying out an uncertainty analysis or a gravity analysis in case studies. Further, uncertainties related to the PEF method alone, e.g., uncertainties in its suggested circular footprint formula or weighting scheme, are not addressed in the respective documents [38]. A few publications address some of these challenges (e.g., [6,37,71]), but not sufficiently to understand all possible limitations and consequences. Therefore, the sub-criterion is answered with *partly*.

### 4.3. Environmental Relevance

Criterion 3 *environmental relevance* of the assessment scheme consists of three sub-criteria. Sub-criterion a, *broad coverage of substance*, is analyzed first. C2CP requires that all chemicals above 1000 ppm within one product be determined and analyzed with regard to their toxicity [57]. Further, it has to be determined if volatile organic compound emissions with Chronic Reference Exposure Levels are emitted from products, which affect the indoor environment. The last group of substances considered are greenhouse gas (GHG) emissions. Other substances/emissions (e.g., phosphorus or ammonium emissions in water leading to eutrophication; sulfur oxide emissions into air leading to acidification; abd particulates leading to fine dust pollution) are not considered. Thus, the sub-criterion is answered with *partly*.

All other substances/emissions not covered by C2CP are seen as beneficial for the ecosystem [32,33]. The C2CP concept assumes that the more nutrients are introduced into a system, the higher the benefits for this system are [17,20]. This might be true for the technosphere, where technical nutrients can be stored and used at the desired time. However, when too much nutrients are introduced into the ecosphere, negative impacts can arise. Acidification and eutrophication are classical examples of nutrient overloads in the environment [20,29,32]. This assumption is also in contradiction with the currently ongoing planetary boundary discussion, where the introduction of additional nutrients (e.g., atmospheric aerosols, nitrogen and phosphorus) is seen as a challenge for the ecosystem [72,73]. Similarly, when alien species (which are also classified as a biological nutrient) are introduced into the environment, they can become invasive species harming the local environment [74]. Biological nutrients are defined by the Product Standard [17] as nutrients, which are usable for living organisms. However, by this definition and considering the logic of C2CP, polyethylene terephthalate (PET) could also be considered a biological nutrient and therefore beneficial for the environment, as scientists just recently discovered that the bacterium *Ideonella sakaiensis* is able to degrade PET [75]. However, reality shows that the opposite is true: PET and other plastics are currently a severe threat for the ecosystem and measures to avoid littering of plastic (including PET) and polluting the ocean are high on the political agenda [76–78].

LCA and PEF comply with the requirements of ISO 14040/44, which state that all relevant substances over the product's life cycle must be considered in the analysis, because "comprehensiveness" this is one of the underlying principles of LCA. Thus, the sub-criterion is answered with *yes* for both methods. The MFA method determines the material flows of abiotic and biotic resources and raw materials (metals, fossils, agricultural products, etc.) only. Consequently, it does not account for all relevant substances from an environmental perspective. However, given that the goal of the method is to track resource/raw material flows throughout the economy, it does cover all relevant resources. Thus, the sub-criterion is answered with *partly*.

The next sub-criterion refers to the *consideration of relevant environmental impacts* (sub-criterion 3b of criterion *environmental relevance*). For C2CP, several relevant impacts are not accounted for and thus trade-offs that occur between impacts cannot be identified. This can be demonstrated with the use of bio-based materials which is promoted by C2CP. When compared with, e.g., fossil-based materials, bio-plastics perform better with regard to some impact categories such as climate change, acidification and resource depletion. However, the consideration of, e.g., land use aspects including soil degradation, is crucial when assessing bio-based materials [79–81]. However, it is not considered in C2CP. When such missing aspects are included in the analysis, the comparison of bio-based and fossil-based materials/products is not that straight forward anymore [82–84]. This trade-off is further demonstrated in the example of biomass production (see Figure 1).

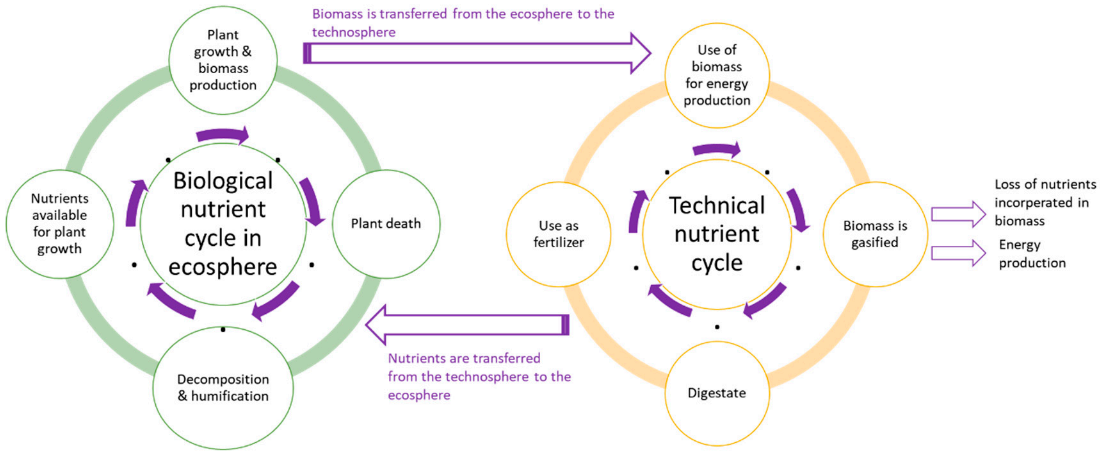


**Figure 1.** Overview of the biomass circulation in the biological and technical nutrient cycle.

Within the ecosphere, biomass is produced when plants grow. After a certain lifetime, the plants die and decompose. During their decomposition the soil is often enriched by mineralization, humification, atmospheric nitrogen fixation, etc. [85,86]. Thus, the nutrients originally collected in the biomass are returned to the environment and are further available for use. If these plants are extracted, transferred to the technosphere and used, e.g., for energy production through gasification of biomass, only few of these nutrients can be returned to the biological cycle by digestates as fertilizer for agricultural production. As a result, most of the nutrients collected in the biomass are inevitably lost to the ecosystem. As biomass is a limited resource (due to limited land availability and soil quality), its use in the technosphere leads to additional scarcity of nutrients for soil quality as well as challenges regarding land availability. Concluding, the example illustrates the relevancy of including land use aspects in the C2CP awarding criteria to adequately address this important environmental aspect.

The second principle of C2CP also contributes to the neglect of relevant impact categories. The use of renewable energy is defined as the most significant factor for effective design while energy efficiency aspects (referring to overall amount of energy used by a company or process as well as the relative amount of energy used per product unit) are not taken into account [17,18,21,29]. Thus, the absolute as well as relative (per product unit) amount of energy consumed is not accounted for, because it is assumed that, when using renewable energy sources, other parameters (e.g., the actual energy consumption) are no longer relevant for determining environmental impacts. However, at a point in time when all energy is produced from renewable sources (thus, endorsement of renewable energy resources is no longer required), increased energy efficiency would be one of the leading parameters to decrease emissions, especially considering that the use of renewable energy sources is also associated with harmful emissions, e.g., metal extraction for producing solar panels [87]. Thus, not considering energy efficiency next to the energy source might lead to more absolute energy use as well as energy use per product unit [21,29,33].

Alongside of not considering energy efficiency aspects, C2CP allows for off-setting of all GHG emissions through off-setting schemes [17]. The reliability of offsetting schemes has been questioned repeatedly (e.g., [88–90]). Shortcomings are related to the way off-setting measures are established, e.g., GHG emission reduction can be achieved by relatively random projects in developing countries aiming at a contribution to sustainable development rather than to the reduction of GHG emissions. Further, different offsetting schemes vary significantly in price, reflecting the diverse off-setting approaches applied by the providers. In general, instead of supporting the offsetting of emissions, other solutions focused to optimize production processes to reduce GHG emissions should be promoted. Thus, due to the above described shortcomings and impediments within the C2C framework to cover all relevant environmental impacts, the answer to the respective sub-criterion for the C2CP is *no*.

According to the ISO 14040/14044 standards LCA practitioners are required to include all relevant impacts to fulfill the LCA principles (comprehensiveness and environmental focus). Thus, sub-criterion 3b *relevant environmental impacts are addressed* (of criterion *environmental relevance*) is answered with *yes* for LCA. The PEF method, however, considers environmental impacts to be only relevant when they contribute to a certain extent to the overall impact assessment result after normalization and weighting [38]. Thus, it cannot be guaranteed that in the end all relevant impacts will be considered [6] and the sub-criterion is answered with as *partly*. The MFA method, which is not established to determine environmental impacts, cannot fulfill this requirement and the sub-criterion is answered with *no*.

Next, the *consideration of the entire life cycle* (sub-criterion 3c of criterion *environmental relevance*) is analyzed. C2CP does not cover the complete life cycle of a product at all certification levels [21,28,29]. This is shown in Figure 2, where an overview of the considered life cycle stages within LCA-based methods (this includes LCA as well as PEF), cradle-to-gate approach, gate-to-gate approach and C2CP is provided (differentiation is made between C2CP quality categories and certification levels). It can be seen that, even at the highest certification level (Platinum), the use phase as well as extraction phase and accompanying impacts are not considered. Kausch et al. (2016) [26] argued that only life cycle stages are included for which primary data can be obtained. While collecting primary data over the full life cycle can be challenging [28,38,91], environmental hotspots can lie anywhere along the supply chain, emphasizing the importance of including all life cycle stages for an accurate environmental assessment. For example, extraction of raw materials often arises as the life cycle stage with the highest impact (e.g., [92–94]). Thus, instead of excluding certain life cycle stages, the awarding criteria should be defined for all life cycle stages and recommendations for data collection should be provided.

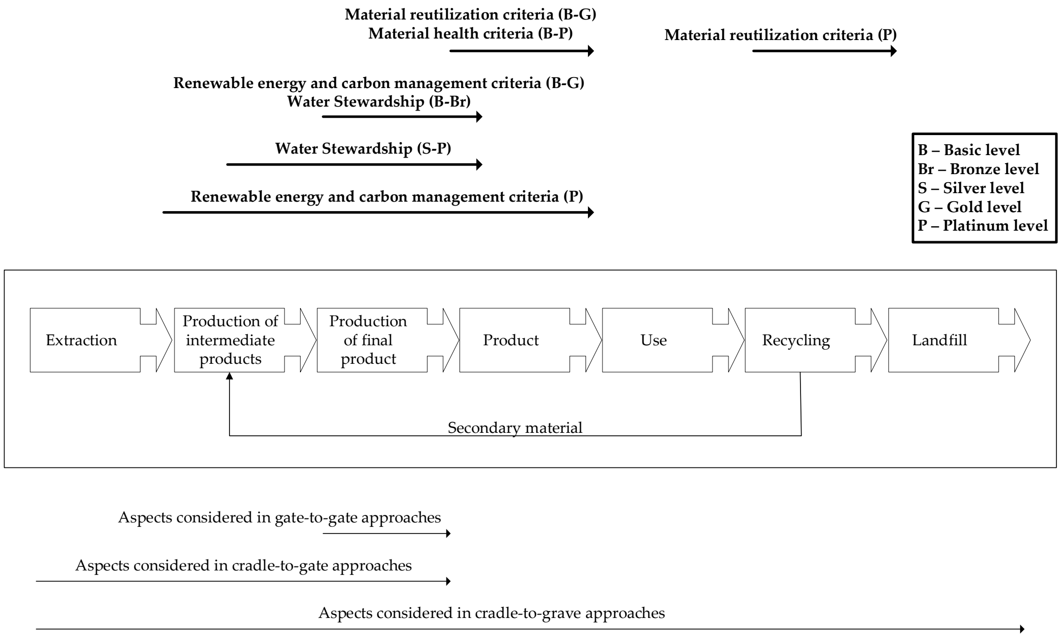


**Figure 2.** Overview of considered life cycle stages within LCA and LCA-based methods (e.g., PEF), cradle-to-gate, gate-to-gate (shown with thin arrows) and C2CP (differentiations are made between the categories and certification levels; shown with thick arrows).

It can be seen that, only for the category "Renewable energy and carbon management" at Platinum level, emissions from cradle-to-gate are taken into account. However, so far only one out of more than 500 products was actually able to achieve Platinum level [20]. By not considering the life cycle of products, trade-offs between different life cycle stages cannot be identified [21,25,29,95]. For example, the environmental product declaration of a synthetic dispersion paint [96] shows that the environmental impacts of the first supply chain stage (raw materials) are higher than the impacts occurring in the manufacturing of the paints (i.e., at the gate). Thus, if the company changes the composition of the paint, e.g., by using different pigments, to achieve lower impacts in the manufacturing stage, whether these new pigments have a higher impact during their production would not be considered.

Aside from its shortcoming to include all life cycle stages, the end-of-life phase and the use of secondary materials is not adequately addressed in C2CP. Certain materials can be recycled many times (e.g., steel, aluminum and glass) whereas other cannot be recycled at all (e.g., plastics when they are not fully separated) or only a few times (e.g., paper). However, according to C2CP, a material is defined as recyclable when it can be recycled once [17]. Thus, the benefit of multiple recyclability is not properly accounted for [28,29]. Besides, it is often the case that some products and/or materials have lower quality after recycling compared to their previous function (also known as downcycling). According to the C2CP philosophy, downcycling should be prevented ([17], see pages 1 and 99), whereas in the awarding criteria of the certification program quality aspects are not addressed ([17], see Section 4). The C2CP philosophy thus contradicts the awarding criteria. An example for the need of such quality aspects when accounting for recycling is the use of bottles made of plastic, bio-plastic or glass. Due to the difficulties to remove organic waste off of plastic bottles, they are often recycled to lower quality pellets which can no longer be used for food or beverages. In contrast, glass bottles can virtually be recycled and reused endlessly without any quality losses [97,98].

Finally, incineration of renewable sourced materials is considered as recycling in C2CP [17]. Thus, material recycling is set equal to incineration, even though in the case of material recycling the raw material is recovered, whereas it is "lost" when it is incinerated. This is contradictory to the Waste Framework Directive of the European Union [99], which ranks material recycling higher than energetic utilization. Given all the above shortcomings, the sub-criterion is given the answer *no* for C2CP.

As stipulated by ISO 14040/44 standards, both LCA and PEF fulfill the requirement of sub-criterion 3c (entire *life cycle is considered*) and can therefore be assigned *yes* as answer. MFA tracks resources throughout the economy, starting with the extraction of raw materials over the recycling and use of secondary materials. Thus, the entire life cycle of the considered material is considered (sub-criterion is answered with *yes*).

### *4.4. Scientific Soundness*

Next, criterion 4, *scientific soundness*, is analyzed, which consists of three sub-criteria. Sub-criterion 4a refers to a *scientific review, which the method has undergone.* Two publications in peer reviewed journals are found that summarize the C2CP concept and the awarding criteria of the product standard [100,101], which only address certain aspects of the product standard. Further, as already addressed in sub-criterion *stakeholder participation* (sub-criterion 1c of criterion *stakeholder acceptance*), even though it is foreseen that external stakeholders can provide inputs during the revision of the method [57], for the current revision of the method, public stakeholder consultations were not yet conducted [25]. Thus, it cannot be determined if a comprehensive scientific review took/takes place and the sub-criterion is answered with *partly*.

The LCA method has undergone several scientific reviews during its implementation by the scientists involved in its preparation as well as during the public consultations on ISO level. A similar concept has been applied for establishing the PEF method. However, compared to LCA the final methodological decisions for PEF are not based on vote, but on the decision of the EC [6,38]. However, the sub-criterion is answered with *yes* for both methods. The establishment of the MFA method is less organized as several different groups use it simultaneously, determining their own set of rules. Some basic rules are outlined in the ÖNORM S 2096 (Material flow analysis—Application in waste management) [40], which has undergone scientific review. Thus, the criterion is determined as *partly*.

The next sub-criterion *method is object of scientific* work (sub-criterion 4b of criterion *scientific soundness*) is answered with *partly* for C2CP, because it is mostly analyzed by other scientists and only few publications by the method developers are available. The overall amount of publications is rather low and recommendations on how the standard can be improved are rare. Further, existing recommendations by other scientists (e.g., [19–21,31]) analyzing C2CP, e.g., to include energy efficiency have not been included in C2CP so far. For LCA, several publications are published every year, e.g., alone in the year 2013, 1978 papers were published [102] and therefore the sub-criterion is answered with *yes*. For PEF some publications address challenges and benefits of the method (e.g., [37,39,67,71,103]). Thus, the sub-criterion is determined as *partly*. The MFA method meets the sub-criterion and is answered with *yes*, because several different scientists apply the method and publish their results (e.g., [41–45]).

C2CP *allows for reproducibility* (sub-criterion 4c of criterion *scientific soundness*) of results (more specific: the same certification level will be reached, independent of who is carrying out the study) and therefore the sub-criterion is answered with *yes*. The awarding criteria defined in the product standard, are transparent and evaluation based on them can be carried out by other users. As transparency is one of the LCA principles, every LCA and PEF study should be reproducible. This also applies to MFA, where underlying data and model principles are communicated with the results. Thus, for all methods this sub-criterion is answered with *yes*.

### *4.5. Applicability*

Criterion 5 addresses the *applicability* of the method and considers three sub-criteria. Sub-criterion 5a refers to the method being *globally valid*, meaning the method can be applied for products/materials and companies around the world without adaptation. This is the case for C2CP, because all defined awarding criteria are valid independent of the location. Thus, the sub-criterion is answered with *yes*. LCA as such does not prohibit the use of regional impact assessment methods. Thus, the sub-criterion is answered with *partly*. Same applies for PEF, where several of the predefined methods are based on regional (European) impact pathways. Depending on which of the categories are relevant, the results are globally valid or only for a specific region. MFA can be applied worldwide. Thus, the sub-criterion is answered with yes. However, depending on the scope of the study, regional economies can also be analyzed.

Next, the *effort to collect data* (sub-criterion 5b of criterion *applicability*) is determined. It is analyzed as *high* for C2CP, because every material bigger than 1000 ppm has to be accounted for. However, how much effort this actually is highly depends on the complexity of the product. For products consisting of only few materials, the data collection effort is low, whereas it will increase with the amount of materials to be taken into account. The *effort to collect data* is determined as high for LCA and PEF studies as well. For MFA case studies the effort depends on the regional scope and applied level of detail of the study, but can also be *high*. Therefore, this sub-criterion is answered with yes for all four methods.

For C2CP, there are no *tools available* (sub-criterion 5c of criterion *applicability*) on the corresponding website to support the method applicability available for external stakeholders. Thus, the sub-criterion is answered with *no*. However, it cannot be precluded that tools do not exist. The assessment body assigned to the company carrying out the conformity assessment often has a lot of experience with C2CP. Therefore, internal tools might exist. These are not available for a company, which just wants to apply C2CP internally or unofficially. For LCA and PEF several software tools and databases exist, which support the modeling (e.g., GaBi [104], ecoinvent [105], OpenLCA [106], Simapro [107], etc.). TU Wien provides a freeware that helps to perform material flow analysis according to the Austrian standard ÖNorm S 2096 called STAN (short for subSTance flow ANalysis) [108]. Thus, the sub-criterion is answered with *yes* for all three methods.

### *4.6. Overall Results and Recommendations*

Based on the presented literature review (see Section 2) as well as criteria-based assessment (see Section 3), the following shortcomings of C2CP, which undermine its reliability to determine the environmental performance of products, are identified:

- Biological nutrients are considered as beneficial independent of their amount emitted in nature [20,29,31,32].
- Quality loss of recycled products and materials is not considered [18,21,33].
- Energy efficiency is not considered, because the long-term goal is to only use renewable energy, which is presumed by C2CP developers to have no emissions [18,20,29,31,33].
- Scarcity of renewable resources is not taken into account [20,29].
- C2CP does not cover the complete life cycle of a product at all certification levels [25,28–30].
- The awarding criteria of C2CP are not product-specific, but generic and equal for all products [25].
- Uncertainties of the method are not addressed sufficiently.
- Biological nutrients are defined as being biodegradable [17].
- It is not considered how many times a material can be recycled.
- A product/material is defined as being recyclable, when it is recycled once [17].
- Quality loses due to recycling are not reflected sufficiently by the awarding criteria.
- For renewable sourced materials, incineration counts as recycling [17].
- Offsetting of GHG emissions is given priority over energy efficiency measures, although the effectiveness of existing offsetting schemes is not proven beneficial.
- Relevant environmental impacts are not considered [28].
- Method has not undergone sufficient scientific review and debate.

When comparing all four methods—C2CP, LCA, PEF and MFA—the following recommendations can be made to improve the performance of C2CP in determining environmental impacts of products:

- Consider all relevant emissions and therefore also revise the assumption that all nutrients introduced in the environment are beneficial.
- Consider the entire life cycle in the awarding criteria.
- Consider the development of product-specific awarding criteria.
- Consider absolute as well as relative (per product unit) amount of used energy.
- Consider how many times a material and/or a product can be recycled and their possible quality losses.
- Incineration of renewable materials should be excluded from the awarding criteria (or has to be specified for different materials).
- Better specify in the program's rules the process of stakeholder consultation and the involvement of stakeholders (e.g., notification procedure, etc.) to involve more stakeholders during the update of the Product Standard.
- Transparently communicate the uncertainties of the method and how they can be determined.
- Debate specifics of the C2CP method in a larger circle of stakeholders via, e.g., peer-reviewed journals or other means.
- Provide tool for application.

## 5. Conclusions

In summary, even though C2CP considers some relevant emissions and environmental impacts (e.g., climate change), 15 shortcomings were identified impacting the ability of the approach to reliably determine the environmental performance of products. Thus, it can be concluded that, in the current state, C2CP is not scientifically reliable enough and does not assure that certified products are actually environmentally preferable. For all identified shortcomings, recommendations are provided by consulting the LCA, PEF and MFA methods. The proposed recommendations for improvement can be integrated into C2CP and, if adopted, the reliability of C2CP would be significantly enhanced.

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