# To what extent is the Circular Footprint Formula of the Product Environmental Footprint Guide consequential?

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## Abstract

With the ambition to increase the comparability of LCA results, the European Commission developed the Product Environmental Footprint (PEF) Guide. This Guide contains a formula to model a product's end-of-life, allowing for waste treatment, energy recovery, and recycling: The Circular Footprint Formula (CFF). The CFF considers the market situation of recycled materials and models recycling via substitution, which is in line with a consequential LCA (CLCA) approach. Therefore, the question that is raised is *"Is the CFF is indeed consistent with CLCA, and if not, what are the main differences between the CFF and CLCA approaches?"* To facilitate this comparison, a Causal Loop Diagram (CLD) has been developed that summarizes current CLCA practice. From this CLD, a formula has been derived: the market-driven substitution approach, which is compared to the CFF. We conclude that the CFF is partially consistent with a consequential approach. The main discrepancies of the CFF compared to a consequential approach are 1) the lack of differentiation between the marginal production processes and users and the specific value chain of the life cycle under study, 2) limitations in the extent to which substitution can be modeled, and 3) an incomplete modeling of the effects of recycling when demand is constrained. Furthermore, some parameters in the CFF combine several consequences, which could result in misinterpretations and a lack

of transparency of the modeled substitutions. We suggest improvements to the CFF, contributing to harmonizing the application of substitution and the comparability of products assessed according to the PEF Guide.

## 1. Introduction

Comparability of LCA results beyond pre-defined studies is an important requirement for consumers to make environmentally informed decisions in the marketplace. However, comparability of results is often limited by the numerous choices that an LCA practitioner can make throughout his or her study. One of these choices having a large impact on the final results is how the end of life of a product is modeled, especially when this product is recycled (Laurent et al., 2014; Merrild et al., 2008). The European Commission has as ambition to develop an LCA approach that can be applied consistently to a large range of products, presented in the Product Environmental Footprint (PEF) Guide (European Commission, 2013). The guidance presented in 2013 included an end-of-life formula, applicable to a wide range of end-of-life scenarios, such as landfilling, energy recovery, and recycling. Environmental burdens and credits due to recycling were equally shared between the producer and the user of the recycled material, following the "50/50 method". However, this 50/50 method has led to much criticism in the LCA domain. The 50/50 method models environmental impacts that are in some cases unrealistic, since it requires that specific waste treatments at the end of life (e.g. by landfilling) be modeled, even if this waste treatment does not take place in reality (Finkbeiner, 2013). Stakeholders in the metals sector argued that the 50/50 method favors incineration over recycling, since the benefits of energy recovery are modeled with 100% credit to the producer of the material. Furthermore, modeling environmental benefits of recycling (by avoiding the primary production of a material) only by 50% is not representative for many metals, since recycling might in some cases substitute primary production by 100% (Eurofer et al., 2013). Also (Schrijvers et al., 2016a) highlighted that the application of the 50/50 method does not consider the different market situations of recycled materials.

In response to such criticism and user feedback, the European Commission continued the development of an end-of-life formula for the PEF Guide, and proposed an updated formula in 2016: the Circular Footprint Formula (CFF) (Zampori et al., 2016). The CFF is now integrated into more recent guidance to develop PEF Category Rules (PEFCRs) (European Commission, 2018). The main difference to the 50/50 method is that the environmental burdens and benefits of recycling are now not always equally shared between the user and the producer of the recycled material, but are shared according to a market-parameter *A*. This parameter reflects whether the demand for the recycled material is high or low compared to the production rate. In this way, the CFF resembles the substitution methods that are applied in consequential modeling (Schrijvers et al., 2016b). Therefore, the question that is raised in this paper is whether the CFF is consistent with a consequential LCA approach, and if not, what are the main differences between the CFF and full consequential modeling? It should be noted that the CFF does not explicitly claim to follow a consequential modelling approach. However, answering this question can help to identify whether the CFF can be used outside the scope of the PEF Guide, and whether recycling can lead to environmental consequences that are currently not represented in a Product Environmental Footprint.

## 2. Methods

The CFF is presented in the form of a formula. In order to evaluate whether the CFF follows a consequential approach, we express the consequential LCA (CLCA) method in the form of a formula as well. The formula for CLCA, which we call “the market-driven substitution method”, is established by first developing a Causal Loop Diagram (CLD) that summarizes the effects that are modeled in a CLCA – covering the application of CLCA as described by Ekvall and Weidema (2004), Weidema et al. (2009), and as implemented in ecoinvent v.3 (Weidema et al., 2013). Subsequently, the elements of the CLD are expressed in mathematical terms. The Supporting Information (SI) provides an illustrative application example of the “market-driven substitution method”. The CFF is presented, and the terms of the CFF are linked to the terms of the market-driven substitution method. This permits to see in detail where the formulas differ or concur. Finally, the differences and their consequences are discussed.

# 3. Results and discussion

## 3.1. A Causal Loop Diagram for modeling a consequential LCI

The consequences of a demand for a certain function, which generally leads to the demand for, or supply of, products, can be summarized in a Causal Loop Diagram (CLD) as shown in Figure 1. While CLDs have been used before in the context of CLCA to represent specific effects, such as the rate at which a recycled material can displace a primary material (Zink et al., 2016), the diagram of Figure 1 is comprehensive by visualizing all the effects that must be taken into consideration in the assessment of a changed demand for a function a CLCA.

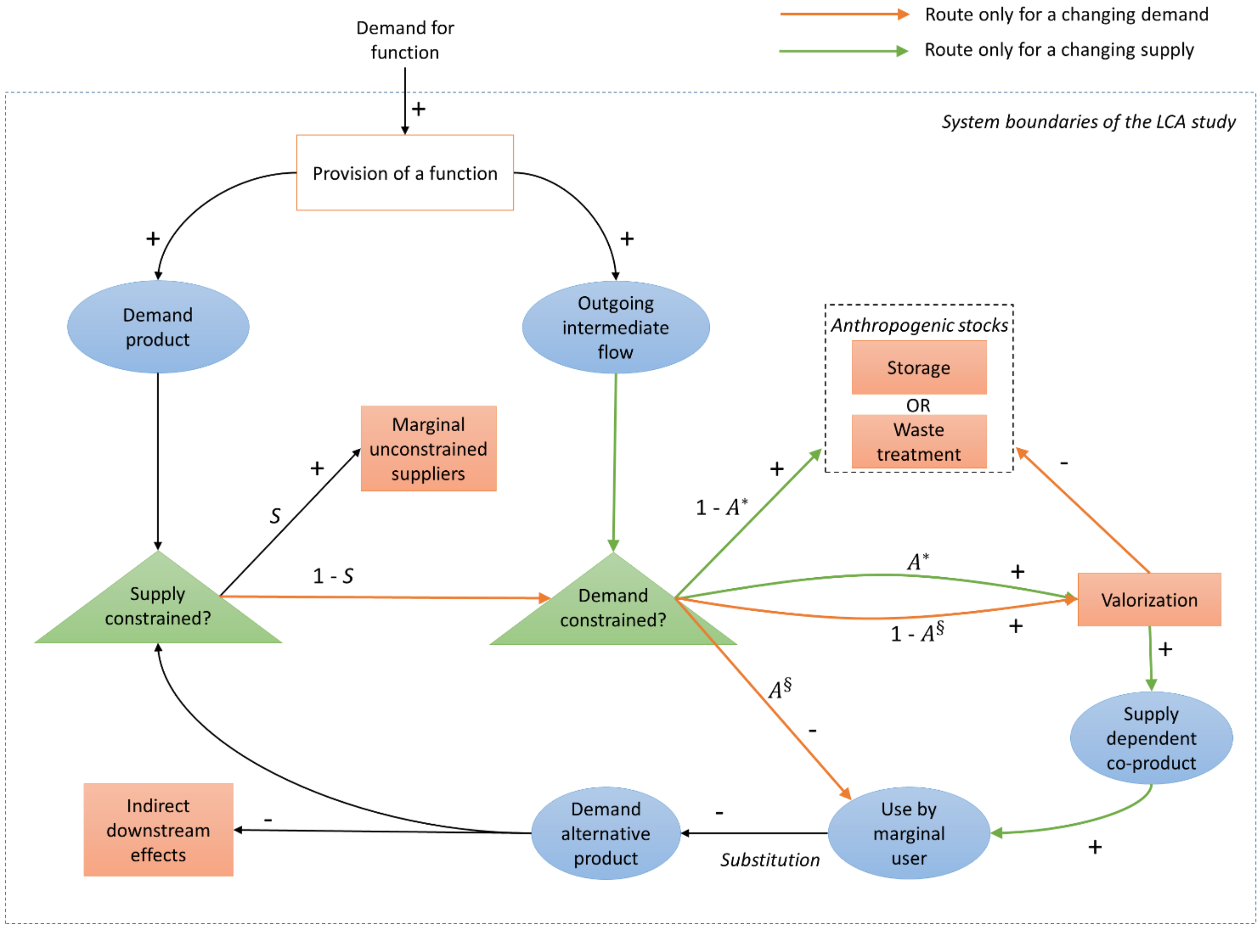

*Figure 1 Causal Loop Diagram showing the market-induced consequences of a changing demand for a function. The arrows reflect causal relationships which can be positive (increased X causes an increased Y; indicated by a plus) or negative (increased X causes a decreased Y; indicated by a minus). Blue circles refer to flows of material/energy. Green triangles indicate context-dependent economic factors, which affect the expected consequences. Orange boxes refer to activities that are modeled in the LCI; each solid filled box represents a set of incoming and outgoing intermediate flows.* S *represents the level of supply constraints for a demanded product:* S *= 1 for unconstrained supply,* S *= 0 for fully constrained supply. The green arrows and* $A^{*}$ *represent an outgoing intermediate flow and the orange arrows and* $A^{\S}$ *represent an incoming intermediate flow:* $A^{*/\S}$ *= 1 for unconstrained demand,* $A^{*/\S}$ *= 0 for fully constrained demand.*

### 3.1.1. Elements of the Causal Loop Diagram

*Provision of a function:* The demand for a function leads to a fulfilment of this function, which is can be considered as a unit process with elementary flows (not indicated in the CLD), incoming product flows, and outgoing intermediate flows. For example, the demand for the function "obtaining news from a newspaper" has the incoming flow of the demanded newspaper, and the outgoing intermediate flow of the end-of-life newspaper. If the effects of an incoming waste flow need to be modeled, the incoming waste is modeled as a negative outgoing intermediate flow.

*Demand product:* The functional unit in a CLCA is often represented by an increasing or decreasing demand for one or more (recycled or primary) products – i.e. the reference flow, which results in a cascade of increased or decreased demands for intermediate flows related to the production of this reference flow. "Demand product" represents one of these increased or decreased demands at a time. The consequences of the changing demand of each product is assessed separately. If a product contains both primary and recycled materials that can be distinguished as such and this is communicated on the market, these are considered to be two separate materials that need to be analyzed independently as well.

*Outgoing intermediate flow:* The intermediate flows that result from the provision of the function are modeled as "outgoing intermediate flow", which contain wastes, materials that need further processing, or dependent co-products, if no further processing is needed (in that case, the LCI of "valorization" could be zero). Outgoing intermediate flows affect marginal valorization, when an economically viable valorization activity exists that transforms the intermediate flow into a dependent co-product for which there is unmet demand. Otherwise, the flow affects marginal waste treatment or storage.

*Supply constrained:* The existence of supply constraints determines the first line of consequences of the changing demand for a product. The level of supply constraints is indicated in Figure 1 with the value $S$. If supply is unconstrained, $S = 1$. If the supply is fully constrained, $S = 0$. The level of supply constraints is often generalized for determining and dependent co-products. A determining co-product is defined as a co-product *"for which a change in demand will affect the production volume of the co-producing unit process"* (Weidema et al., 2009), and thus not supply constrained. Guidance in the identification of the determining co-product is provided by Consequential-LCA (2015). Generally, it is assumed in LCI, as well as in the ecoinvent 3 database, that the supply of a determining co-product is fully elastic (i.e. $S = 1$) (Weidema et al., 2013), meaning that a change in demand is followed by an equal change in supply. This assumption is valid for competitive markets in the long term (Weidema et al., 2009). For dependent co-products, supply is ultimately constrained by the demand for the determining co-product. Therefore, the default value for recycled products and by-products is $S = 0$.

*Marginal unconstrained suppliers:* To the extent that supply is unconstrained, the demand for a product will result in a corresponding increase in production by the marginal supplier.

*Demand constrained:* Dependent co-products, either demanded to provide a function, or supplied by a valorization activity, can be in high demand or in low demand, indicated by Parameter A. If the demand for the product is larger than the constrained supply, the demand is unconstrained and $A = 1$. If, however, the market is saturated and an additionally available unit of the product will not be used, demand is constrained and $A = 0$. The situation $0 < A < 1$ may occur in the short term, when markets are affected by short-term constraints, but since a marginal change in demand for a material that is supply constrained does not affect the long-term opportunity costs (the costs of valorization, storage and waste treatment), the long-term situation will tend towards $A=0$, i.e. the entire additional demand will be met by decreasing marginal storage or waste treatment. The situation $0 < A < 1$ may also occur as an average over geographical areas or time periods, where $A=1$ in some subset of geographical areas or time periods, and $A=0$ in other subsets. A changed demand for a product with unconstrained demand (i.e. $A = 1$) affects the use of this product by the marginal user, who can substitute the use of this product by an alternative product. If the demand is however constrained, a changed demand affects the valorization of this product from anthropogenic stocks (i.e. waste or stored materials). A changed supply of an intermediate flow affects either waste treatment/storage, or the valorization of this flow resulting in the production of the dependent co-product, which serves in the determination of A. If there is unmet demand ($A = 1$), the intermediate flow will be valorized and the dependent co-product is used by its marginal user. If the demand is lower than the availability of the intermediate flow (A<1), only waste treatment and storage – not valorization – are affected.

*Use by marginal user:* If the demand for a supply-constrained product is not constrained, i.e. if the demand exceeds the constrained supply, the consequence of an additional demand for this product is a reduced use of this supply-constrained product in another product value chain. The marginal user that is affected could be identified by a high elasticity of demand, meaning that a small change in the price of a product will lead to a large change in demand for this product. The user of this product can most easily accept a reduction in use or substitute the supply-constrained product for an alternative material or product that fulfills the same function.

*Demand alternative product:* The decreased or increased use of a supply-constrained product in other applications can lead to the increased or decreased demand for an alternative product, respectively – i.e. substitution. This alternative product could be identified by cross-price elasticities of the materials that show whether a change in the price of one product results in a change in demand for the alternative product. Note that this alternative product is the one consumed by the marginal user, which is not necessarily the same user as the operator of the foreground subsystem of the CLCA.

*Indirect downstream effects*: Due to the use of an alternative product, indirect effects could take place downstream, in distribution, use, and end-of-life treatment, when the substituted products do not have exactly the same properties. If substitution does not take place on a one-to-one elemental level, but on a product function or technology level, differences in technology efficiencies and system design must be considered as well. Note that, due to the negative causal relation between "demand alternative product" and "indirect downstream effects", these downstream effects are defined as the downstream inventory related to the product under study *minus* the downstream inventory related to the alternative product. Also rebound effects can be considered within the box "indirect downstream effects".

*Anthropogenic stocks*: Anthropogenic stocks are the marginal supplier of dependent co-products for which demand is less than the supply. If anthropogenic stocks are affected, this is modeled as the storage of the dependent co-products that are not taken into use yet, or as the potential waste treatment of end-of-life products.

*Valorization*: Valorization of a material comprises all activities that take place to make a waste or a co-product a valuable material. This includes sorting and recycling activities, or the incineration activity that is required for energy recovery (energetic valorization).

*Supply dependent co-product*: The valorization activity supplies a dependent co-product. Demand constraints (i.e. the determination of A) are identified for this material to evaluate the consequences of a changing supply of an outgoing intermediate flow.

### 3.1.2. End-of-life recycling rate within the CLD

The CLD shows activities that are likely to take place when an intermediate flow is taken from, or put on the market. It can be noticed that the CLD does not contain a recycling rate – here defined as the share of an outgoing intermediate flow which is sent to a valorization activity. The supply of, or demand for, a material affects valorization via market mechanisms if there is an economically viable valorization activity that supplies a product which is in high demand. Whereas the share of a material flow that is sent to recycling can be determined by players within a value chain (e.g. by the collective action of individuals, through policy, or by a company), the total amount of recycled material (i.e. the supplied dependent co-product) that is finally used in products or applications, and which can substitute a primary material, is determined by market mechanisms. If the amount of material that is sent to valorization within a certain product system is known, the valorization process is modeled within the foreground subsystem – which contains processes that are known to be directly affected by the functional unit, as shown in Figure 2. The dependent co-product that is supplied by the valorization activity is put on the market, and the CLD can be used to model the subsequent effects of this action.

The recycled material can be supplied, regardless whether there is a demand for this material. Therefore, it should be considered that the recycled material produced by the processes within the foreground subsystem might either substitute a virgin material (if the demand for the recycled material is high), or a recycled material from other product value chains (if the demand is low). Following the CLD, the node “demand alternative product” should first be evaluated for recycled materials from other value chains. If demand is high (i.e. A = 1), this recycled material will be increasingly used to substitute a primary material in a second iteration of consequences. If demand is low (A < 1), the valorization and waste treatment of this alternative recycled material will be affected.

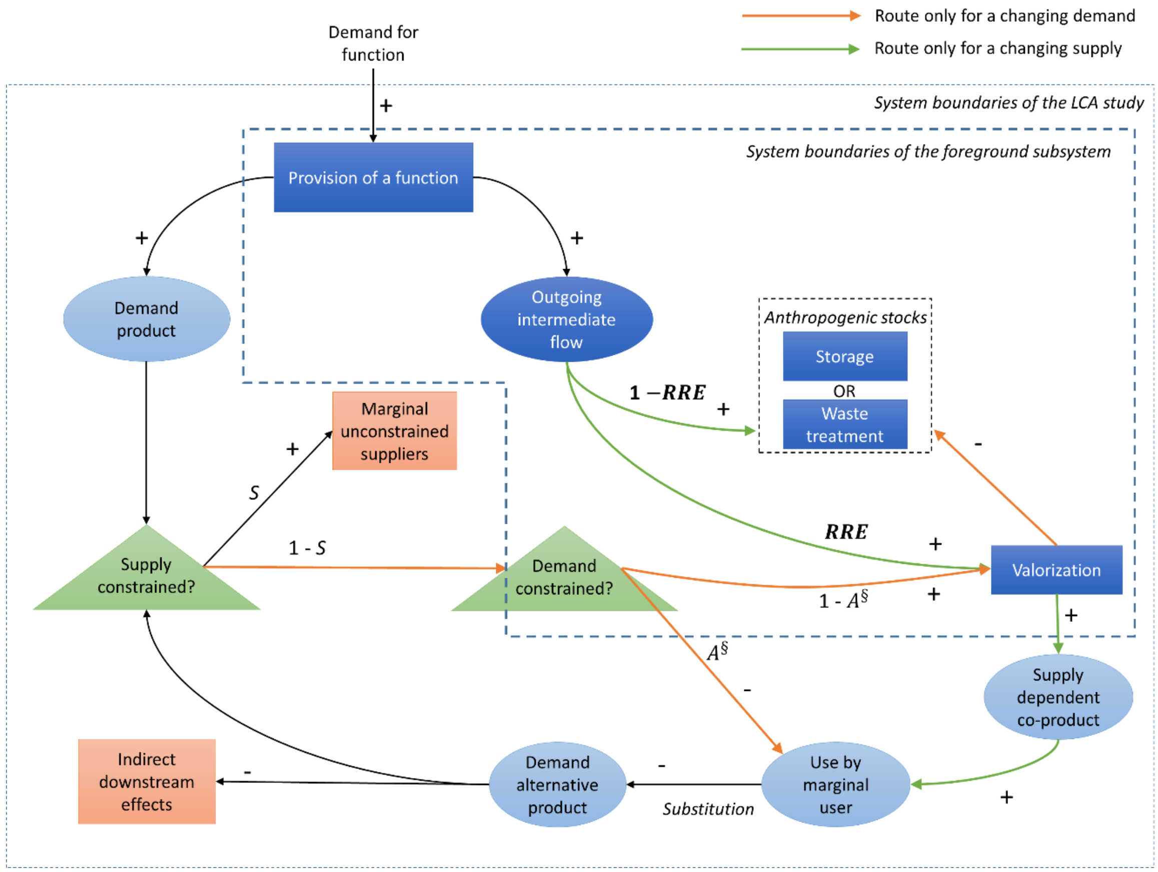

*Figure 2 Causal Loop Diagram showing the system boundaries of the foreground subsystem with a determined end-of-life recycling rate (RRE) of an outgoing intermediate flow. Processes that are part of the foreground subsystem are indicated by a dark blue color.*

### 3.2. The market-driven substitution method

In this section, the effects that are modeled by the CLD of Figure 1 are captured by a mathematical formula. The SI presents an example illustrating the link between the CLD and the formula. To enable the comparison with the CFF in Section 3.4, the market-driven substitution formula is presented in a modular form in Equations E1-E4. Whereas each input and output material should be modeled separately in a CLCA, Equation E2 reflects a combined case where one primary material and one recycled material are used, and where one recycled material is supplied at the end of life, which may or may not be the same as the consumed recycled material. The parameters of the formula are given in Table 1.

E1. $$E_{tot} = E_{tot,material} + E_{tot,energy} + E_{tot,disposal}$$

E2. $$E_{tot,material} = (1 - RC) * E_v + RC * \left( (1 - A^{\S}) * \left( E_r^{\S} - \frac{E_d^{\S}}{C^{\S}} \right) - A^{\S} * \frac{Q^{\S}}{Q_v^{\S}} * \left( \Delta E_\alpha^{\S} - E_v^{\S} \right) \right) + RRE_{rec} *$$

$$C_{rec} * \left( E_{r,rec} - (1 - A^*) * \left( E_r^* - \frac{E_d^*}{C^*} \right) + A^* * \frac{Q^*}{Q_v^*} * (\Delta E_\alpha^* - E_v^*) \right)$$

E3. $$E_{tot,energy} = RRE_{inc} * (E_{RRE,inc} - C_{elec} * E_v^*)$$

E4. $$E_{tot,disposal} = (1 - RRE_{inc} - RRE_{rec}) * E_d$$

*Table 1 Explanation of terms of the market-driven substitution method presented in Equations E2-E5*

| Term of the market-driven substitution method | Explanation | Value |
|---|---|---|
| $E_{tot}$ | Life Cycle Inventory (LCI) caused by the demand for the product under study via a consequential LCA | LCI / unit of analysis |

| | | |
|---|---|---|
| $E_v$ | LCI caused by the extraction and processing of primary (virgin) materials via the marginal production process (including processing inefficiencies) | LCI / unit of primary material |
| $E_v^{\S}$ | LCI caused by the extraction and processing of the primary (virgin) materials that are substituted by the marginal user of the demanded material (including processing inefficiencies) | LCI / unit of primary material |
| $E_v^*$ | LCI caused by the extraction and processing of the primary (virgin) materials that are substituted by the marginal user of the supplied material (including processing inefficiencies) | LCI / unit of primary material |
| $E_{r,rec}$ | LCI caused by the production of the supplied recycled material (including LCI of losses during the recycling process) | LCI / unit of produced recycled material |
| $E_r^{\S}$ | LCI caused by the production of the demanded recycled material via the marginal valorization process (including LCI of losses during the recycling process) | LCI / unit of produced recycled material |
| $E_r^*$ | LCI caused by the production of the supplied recycled material via the marginal valorization process (including LCI of losses during the recycling process) | LCI / unit of produced recycled material |
| $E_{RRE,inc}$ | LCI caused by the incineration of the end-of-life product (including LCI of losses during the recovery process) | LCI / unit of incinerated end-of-life product |

|  |  |  |
|---|---|---|
| $E_d$ | LCI caused by waste treatment or storage | LCI / unit of discarded or stored material |
| $E_d^{\S}$ | LCI caused by the waste treatment or storage of the demanded recycled product via the marginal treatment process | LCI / unit of discarded or stored material |
| $E_d^{*}$ | LCI caused by the waste treatment or storage of the supplied recycled product via the marginal treatment process | LCI / unit of discarded or stored material |
| $\frac{Q^{\S}}{Q_v^{\S}}$ | Quantity-correction factor that indicates the amount of a primary material that is substituted by the demanded recycled material by its marginal user | Unit of substituted primary material / unit of recycled material |
| $\frac{Q^{*}}{Q_v^{*}}$ | Quantity-correction factor that indicates the amount of a primary material that is substituted by the supplied recycled material by its marginal user | Unit of substituted primary material / unit of recycled material |
| $\Delta E_\alpha^{\S}$ | LCI due to additional (+) and/or decreased (-) downstream intermediate or elementary flows related to the distribution, use, and disposal of the recycled material instead of a primary material by the marginal user of the demanded recycled material | LCI / unit of substituted primary material |
| $\Delta E_\alpha^{*}$ | LCI due to additional (+) and/or decreased (-) downstream intermediate or elementary flows related to the distribution, use, and disposal of the recycled material instead of a primary material by the marginal user of the supplied recycled material | LCI / unit of substituted primary material |

| | | |
|---|---|---|
| $RC$ | Recycled content (recycled or recovered material input per unit of analysis) | $0 \leq RC \leq 1$ |
| $RRE_{rec}$ | End-of-life recycling rate (share of the product at the end of life that is sent to recycling) | $0 \leq RRE_{rec} \leq 1$ |
| $RRE_{inc}$ | End-of-life incineration rate (share of the product at the end of life that is sent to incineration) | $0 \leq RRE_{inc} \leq 1$ |
| $C_{rec}$ | Conversion efficiency of the end-of-life product into a recycled material | Unit of useful output / unit of input material |
| $C_{elec}$ | Conversion efficiency of the end-of-life product into recovered electricity | Unit of useful output / unit of input material |
| $C^{\S}$ | Conversion efficiency of the end-of-life product into a recycled material via the marginal valorization process of the demanded recycled material | Unit of useful output / unit of input material |
| $C^{*}$ | Conversion efficiency of the end-of-life product into a recycled material via the marginal valorization process of the supplied recycled material | Unit of useful output / unit of input material |
| $A^{\S}$ | Indicator for demand constraints of the used recycled material ($A^{\S}$ = 0 reflects fully constrained demand; $A^{\S}$=1 reflects fully unconstrained demand) | $0 \leq A^{\S} \leq 1$ |
| $A^{*}$ | Indicator for demand constraints of the supplied recycled material ($A^{*}$ = 0 reflects fully constrained demand; $A^{*}$=1 reflects fully unconstrained demand) | $0 \leq A^{*} \leq 1$ |

### 3.3. Circular Footprint Formula

The European Commission (European Commission, 2018; Zampori et al., 2016) proposed a Circular Footprint Formula (CFF) to replace the End-of-Life formula of the PEF Guide (European Commission, 2013). The latest version of this formula shows similarities with the formulas provided in Section 3.2 of this paper. The CFF is a combination of three equations that calculate the impacts and benefits related to the use and supply of materials, the recovery of energy, and disposal (Equations E6-E9). The terms of these equations are explained and compared with the terms of the market-driven substitution method in Table 2.

E5. $$CFF_{total} = CFF_{material} + CFF_{energy} + CFF_{disposal}$$

E6. $$CFF_{material} = (1 - R_1) * E_v + R_1 * \left(A_{CFF} * E_{recycled} + (1 - A_{CFF}) * E_v * \frac{Q_{Sin}}{Q_P}\right) + (1 - A_{CFF}) * R_2 * \left(E_{recyclingEoL} - E_v^* * \frac{Q_{Sout}}{Q_P}\right)$$

E7. $$CFF_{energy} = (1 - B) * R_3 * \left(E_{ER} - LHV * X_{ER,heat} * E_{SE,heat} - LHV * X_{ER,elec} * E_{SE,elec}\right)$$

E8. $$CFF_{disposal} = (1 - R_2 - R_3) * E_d$$

*Table 2 Terms of the Circular Footprint Formula and their equivalence with the terms of the market-driven substitution formula*

| Term of the CFF | Explanation (European Commission, 2018) | Equivalent term of the market-driven substitution method |
|---|---|---|
| $CFF_{total}$ | Life Cycle Inventory (LCI) caused by the demand for the product under study via the Circular Footprint Formula | $E_{tot}$ |
| $A_{CFF}$ | Allocation factor of burdens and credits between supplier and user of recycled materials | $(1 - A^{\S})$ and $(1 - A^*)$ |
| $B$ | Allocation factor of energy recovery processes: it applies both to burdens and credits | $(1 - A^*)$ |

| | | |
|---|---|---|
| $Q_{Sin}$ | Quality of the ingoing secondary material, i.e. the quality of the recycled material at the point of substitution | $Q^{\S}$ |
| $Q_{Sout}$ | Quality of the outgoing secondary material, i.e. the quality of the recyclable material at the point of substitution | $Q^{*}$ |
| $Q_P$ | Quality of the primary material, i.e. quality of the virgin material | $Q_v^{\S}$ and $Q_v^{*}$ |
| $R_1$ | Proportion of material in the input to the production that has been recycled from a previous system | $RC$ |
| $R_2$ | Proportion of the material in the product that will be recycled (or reused) in a subsequent system. R2 shall therefore take into account the inefficiencies in the collection and recycling (or reuse) processes. R2 shall be measured at the output of the recycling plant | $RRE_{rec} * C_{rec}$ |
| $R_3$ | Proportion of the material in the product that is used for energy recovery at EoL | $RRE_{inc}$ |
| $E_{recycled}$ | Specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process | $E_r^{\S}$ |
| $E_{recyclingEoL}$ | Specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL, including collection, sorting, and transportation process | $E_{r,rec}$ and $E_r^{*}$ |

| | | |
|---|---|---|
| $E_v$ | Specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material | $E_v$ and $E_v^{\S}$ |
| $E_v^*$ | Specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials | $E_v^*$ (if $E_v^{\S} = E_v^*$) or $E_v^* * \frac{Q^*}{Q_v^*}$ (if $E_v^{\S} \neq E_v^*$) |
| $E_{ER}$ | Specific emissions and resources consumed (per functional unit) arising from the energy recovery process (e.g. incineration with energy recovery, landfill with energy recovery, …) | $E_{RRE,inc}$ |
| $E_{SE,heat}$ and $E_{SE,elec}$ | Specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source, heat and electricity respectively | $E_v^*$ |
| $E_d$ | Specific emissions and resources consumed (per functional unit) arising from disposal of waste material at the EoL of the analysed product, without energy recovery | $E_d$ |
| $X_{ER,heat}$ and $X_{ER,elec}$ | The efficiency of the energy recovery process for both heat and electricity | $C_{heat}$[1] and $C_{elec}$ |
| $LHV$ | Lower Heating Value of the material in the product that is used for energy recovery | |

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[1] In our formula for the market-driven substitution method there is no explicit parameter for recovered heat, but this would be calculated in the same way as for recovered electricity.

## 3.4. Comparison of the Circular Footprint Formula with the market-driven substitution method

The differences and similarities between the CLCA method (via the market-driven substitution method) and the CFF are identified, term by term, in Table 3. The main differences and their consequences are discussed below.

### *3.4.1. Marginal processes and marginal users*

In CLCA, processes in the background subsystem are marginal production and treatment processes, while this is not an explicit requirement in the CFF. Therefore, the LCA practitioner applying the CFF might select a production or treatment process that is different from the marginal process. The CFF would only be consistent with the CLCA approach when all the processes within the value chain of the product under study are also the marginal processes.

The primary material that is used in the product under study ($E_v$ in the market-driven substitution method) is not necessarily the same as the primary material that is used by the marginal user of this recycled material. This is taken into account in the CFF by the substitution of an alternative primary material, denoted as $E_v^*$, by the supplied recycled material. However, this is not considered for the recycled content. This can be, for example, relevant when the recycled material is "upcycled" (substituting a high-value primary material) in the application under study, whereas it would otherwise be "downcycled" (substituting a low-value primary material) by the marginal user (see the example in the SI). In the CFF, it would be assumed that the marginal user substitutes the same primary material as the user in the foreground subsystem. Consequently, the CFF does not consider any other downstream effects that the marginal user experiences when switching back to a primary alternative instead of using the recycled material (i.e. the use of additives in the example of the SI). The lack of differentiation between the primary material in the life cycle under study and the primary material used by the marginal user of the recycled material and the lack of inclusion of downstream effects are only justified in the specific situation where the life cycle under study represents the marginal user of the recycled material.

### 3.4.2. Factor A and Factor B

The *A*-factor of the CFF represents, similar to the *A*-factors of the market-driven substitution method, the market situation of the recycled material. However, there are differences between the CFF and the market-driven substitution method in how *A* is determined and what consequences are considered to take place, depending on the market-situation of a recycled material.

In the CFF, if there is a low offer of the recycled material and a high demand, $A_{CFF}$ = 0.2. If there is a high offer of the recycled material and a low demand, $A_{CFF}$ = 0.8. $A_{CFF}$ can never have a value of 0 or 1, hence, full substitution is never an option. The European Commission provides a list of *A*-values for different materials, such as metals, paper, plastics, glass and wood, which is established and updated by the European Commission (European Commission, 2018). Freedom to determine *A* based on the context at hand could be preferable as different material grades, locations or contexts could provide different demand constraints. Besides, this could allow for the modeling of full substitution by enabling values of 0 and 1. Moreover, the CFF does not distinguish between demand constraints of the consumed recycled material and demand constraints of the produced recycled material, while two separate terms for this exist in the CLCA method. As shown in the example of the SI for CLCA, the consumed recycled materials do not necessarily have the same market situation as the supplied recycled materials, which is especially relevant in the case of open-loop recycling.

Regarding the consequences that are modeled via Factor *A*, the CFF considers that the demand for a recycled material might be low, and that the additional demand or the additional supply for a recycled material with low demand leads to additional or decreased recycling of this material, respectively. However, the CFF does not consider that this additional or decreased recycling could lead, in turn, to avoided or increased waste treatment, respectively, while this consequence is included in the market-driven substitution method.

Energy recovery is not represented by an $A$-factor, but instead by a Factor $B$. In contrast to the input of recycled material, the input of recovered energy is not included in the formula. This is not necessarily a problem, as the default value for $B$ for recovered energy is 0. However, if this value would be different, the use of recovered energy should be modeled as well, similar to the recycled content of materials. The equation of the CFF does not include a term for this.

### 3.4.3. Quality correction

The CFF integrates quality ratios for the recycled content and the end-of-life recycling rate. This quality ratio of the CFF is determined by the price ratio of the secondary compared to the primary material. The market-driven substitution method does not model the relative quality of the recycled material. Instead, a factor is included that reflects the *quantity* of the primary material that is displaced by the recycled material. The price ratio as used in the CFF could give a misinformed view on the relative quality of a material, because the price ratio can be based on several other considerations, such as substitution in different market segments, downstream effects, or demand constraints. The use of a physical parameter in the market-driven substitution method ensures the mass balance of the resulting inventory, which is not ensured in the CFF.

In the case of open loop recycling (when $E_v \neq E_v^*$ in the CFF, or $E_v^{\S} \neq E_v^*$ in the market-driven substitution method), the quality factor is omitted from the CFF, because the parameter $E_v^*$ should reflect *"how much, how long, [and] how well"* the recycled material substitutes a primary material (European Commission, 2018). However, $E_v^*$ as defined by the CFF in Table 2 only refers to the primary materials that are substituted, and does not explicitly mention any changes during transport, the use phase, or the end-of-life disposal due to the substitution. In the market-driven substitution method, the parameter $E_v^*$ only reflects the specific inventory of the substituted primary production process. The quantity correction factor ($\frac{Q^{*}}{Q_{v}^{*}}$) represents "how much" is substituted, and an additional term for indirect downstream effects ($\Delta E_{\alpha}^{*}$) is included that represents "how long and how well", including differences in other life cycle stages. The ambition to include all such effects into a single term in the CFF has as a risk that downstream effects are not systematically taken into consideration, as the LCA practitioner could be contented with the identification of a single raw material without posing further questions.

### *3.4.4. Calculation of the end-of-life recycling rate*

The CFF calculates the end-of-life recycling rate as the output material flow from the recycling process, and recycling inefficiencies are part of the LCI of the recycling process ($E_{recyclingEoL}$). However, the expression of $CFF_{disposal}$ (Equation E8) considers the waste treatment of recycling inefficiencies as well, which are, therefore, double counted. To illustrate this, imagine that 5 kg of plastic waste is treated by a recycling process, with the output of 3 kg of recycled plastic. The 2 kg of plastic waste generated during the recycling activity are modeled in $E_{recyclingEoL}$, and the recycling rate $R_2$ is defined as 60%. Following Equation E8, final disposal is modeled for 1-R2, i.e. 40%, which reflects the same quantity of waste disposal that is already covered by $E_{recyclingEoL}$.

### *3.4.5. Overall assessment of the CFF*

The comparison between the CFF and the market-driven substitution method in Table 3 shows that, despite the large overlap between the two formulas, the CFF does not follow a full consequential method. The main difference lies in the fact that the CFF does not explicitly refer to the marginal production and treatment processes and marginal users of recycled materials. Another difference is the consideration of (avoided) waste treatment when the demand for a recycled material is constrained. This factor was included in the previous version of the CFF (the 50/50 method (European Commission, 2013)) and eliminated from the CFF to simplify the approach. Other discrepancies between the CFF and the market-driven substitution method might also be the result of simplifying choices – such as the predetermined values for $A_{CFF}$. This paper contributes in highlighting the consequences of such simplifications and providing alternative modeling options that could be applied in sensitivity analyses.

As stated above, the CFF does not explicitly claim to follow a consequential modelling approach. The PEF Guide could be seen as a mix between an attributional and a consequential LCA approach (European Commission, 2013). Whether such a mix is desirable has been discussed in other papers (Schrijvers et al., 2016a). Even if a consequential approach is not pursued, the comparison of this article could inspire method developers and users to consider whether their method is in line with the objective of the method. Furthermore, a few inconsistencies were highlighted that merit being checked by the European Commission for future use of the CFF, regarding the quality correction factor and the calculation of the end-of-life recycling rate.

*Table 3 Comparison of the consequences modeled in CLCA (as formulated in the market-driven substitution method) and in the CFF. Different terms are highlighted in red.*

| # | Modeled in CLCA | Term CLCA | Term CFF | CFF expressed in terms of CLCA | Difference |
|---|---|---|---|---|---|
| 1 | Production of primary materials by the marginal production process | $+(1-RC)*E_v$ | $+(1-R_1)*E_v$ | $+(1-RC)*E_v$ | CFF does not specify that $E_v$ represents the marginal process |
| 2 | Production of the demanded recycled material by the marginal valorization process, to the extent that the demand for the recycled material is constrained | $+RC*\left(1-A^{\S}\right)*E_r^{\S}$ | $+R_1*A_{CFF}*E_{recycled}$ | $+RC*\boldsymbol{\left(1-A^{\S}\right)}*E_r^{\S}$ | - General differences regarding the factor A, see text<br>- CFF does not specify that $E_r^{\S}$ represents the marginal process |
| 3 | Avoided waste disposal or storage of the demanded recycled material by the marginal treatment process, to the extent that the demand for the recycled material is constrained | $-RC*\left(1-A^{\S}\right)*\frac{E_d^{\S}}{C^{\S}}$ | NA | **NA** | - Consequence not considered in the CFF |

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|---|---|---|---|---|---|
| 4 | Avoided downstream effects for the marginal user related to the use of the demanded recycled material instead of an alternative material, to the extent that the demand for the recycled material is unconstrained | $-RC * A^{\S} * \frac{Q^{\S}}{Q_v^{\S}} * \Delta E_\alpha^{\S}$ | NA | **NA** | - Consequence not considered in the CFF |
| 5 | Production of an alternative material for the marginal user of the demanded recycled material, to the extent that the demand for the recycled material is unconstrained. | $+RC * A^{\S} * \frac{Q^{\S}}{Q_v^{\S}} * E_v^{\S}$ | $+R_1 * (1 - A_{CFF}) * \frac{Q_{Sin}}{Q_P} * E_v$ | $+RC * \boldsymbol{A}^{\S} * \frac{\boldsymbol{Q}^{\S}}{\boldsymbol{Q}_{\boldsymbol{v}}^{\S}} * \boldsymbol{E}_{\boldsymbol{v}}$ | - General differences regarding the factor A, see text<br>- General differences regarding the quality correction factor, see text<br>- CFF does not differentiate between $E_v^{\S}$ (production of an alternative material for the marginal user of the recycled material) and $E_v$ (production of a primary material for the life cycle under study) |

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| 6 | Production of the supplied recycled material via the recycling process within the foreground subsystem | $+RRE_{rec} * C_{rec} * E_{r,rec}$ | $+R_2 * E_{recyclingEoL}$ | $+RRE_{rec} * C_{rec} * E_{r,rec}$ | - No difference between CLCA and CFF. |
| 7 | Avoided valorization of recycled materials by the marginal valorization process, to the extent that the demand for the supplied recycled material is constrained | $-RRE_{rec} * C_{rec} * (1 - A^*) * E_r^*$ | $-R_2 * A_{CFF} * E_{recyclingEoL}$ | $-RRE_{rec} * C_{rec} * \boldsymbol{(1 - A^*) * E_{r,rec}}$ | - General differences regarding the factor A, see text<br>- CFF does not differentiate between $E_r^*$ (valorization of the recycled material via the marginal process) and $E_{r,rec}$ (valorization of the recycled material via the process in the foreground subsystem). |
| 8 | Waste disposal or storage of recycled materials from other product value chains by the marginal disposal process to the extent that the demand for the | $+RRE_{rec} * C_{rec} * (1 - A^*) * \frac{E_d^*}{C^*}$ | NA | **NA** | - Consequence not considered in the CFF |

| | | | | | |
|---|---|---|---|---|---|
| | supplied recycled material is constrained | | | | |
| 9 | Downstream effects for the marginal user related to the use of the supplied recycled material instead of an alternative material, to the extent that the demand for the recycled material is unconstrained | $+RRE_{rec} * C_{rec} * A^* * \frac{Q^*}{Q_v^*} * \Delta E_{\alpha}^*$ | NA | **NA** | - Consequence not considered in the CFF, although certain of these factors might be covered by the term $E_v^*$ (see Section 3.4.4.) |
| 10 | Avoided production of an alternative material for the marginal user of the supplied recycled material, to the extent that the demand for this recycled material is unconstrained. | $-RRE_{rec} * C_{rec} * A^* * \frac{Q^*}{Q_v^*} * E_v^*$ | $-R_2 * (1 - A_{CFF}) * \frac{Q_{Sout}}{Q_P} * E_v^*$ | $-RRE_{rec} * C_{rec} * \boldsymbol{A^*} * \boldsymbol{\frac{Q^*}{Q_v^*}} * \boldsymbol{E_v^*}$ | - General considerations regarding the factor A, see text<br>- General considerations regarding the quality correction factor, see text |

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|---|---|---|---|---|---|
| 11 | Incineration process within the foreground subsystem | $+RRE_{inc} * E_{RRE,inc}$ | $+(1-B) * R_3 * E_{ER}$ | $+RRE_{inc} * E_{RRE,inc}$ | - The extent to which incineration is modeled in the CFF depends on the factor $B$. The default value for $B$ is 0, resulting in modeling of the same LCI in CLCA and CFF. If a different value for $B$ would be authorized, the CFF would decrease the LCI of the incineration process. |
| 12 | Avoided production of conventional electricity by the marginal production process<br>*Key assumptions:*<br>- Demand for electricity is unconstrained<br>- No indirect effects take place by using recovered | $-RRE_{inc} * C_{elec} * E_v^*$ | $-(1-B) * R_3 * LHV * X_{ER,elec} * E_{SE,elec}$ | $-RRE_{inc} * C_{elec} * E_v^*$ | - The extent to which incineration is modeled in the CFF depends on the factor $B$. The default value for $B$ is 0, resulting in modeling of the same LCI in CLCA and CFF. This corresponds to the key assumption that the demand for electricity is unconstrained. |

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| | instead of conventional electricity<br>- 1 MJ of recovered electricity substitutes 1 MJ of conventional electricity | | | | - CFF does not specify the other key assumptions, which is, in the case of recovered energy, acceptable<br>- CFF contains a specific term for recovered heat. As heat and electricity are modeled in the same way in CLCA, heat is not separately specified in the market-driven substitution method |
| 13 | Waste disposal process within the foreground subsystem | $+(1-RRE_{rec}-RRE_{inc})*E_d$ | $+(1-R_2-R_3)*E_d$ | $+(1-RRE_{rec}*\boldsymbol{C_{rec}}-RRE_{inc})*E_d$ | - In the CFF, $R_2$ is measured at the output of the recycling process, while in CLCA, $RRE_{rec}$ represents the input flow of the recycling process. The definition of $R_2$ in the CFF suggests that waste disposal is calculated for both the share of the material that is not recycled, as well as for |

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| | | | | | inefficiencies of the recycling process. Recycling inefficiencies are also included in $E_{recyclingEoL}$, and are therefore double counted. |

## 4. Conclusions and perspectives

The recently presented Circular Footprint Formula (European Commission, 2018) has been developed to model recycling in LCA in order to make Product Environmental Footprints comparable. The CFF integrates the criticism that was raised after presenting the 50/50 method in the first version of the Product Environmental Footprint Guide (European Commission, 2013), such as the consideration of the market situation of recycled materials. As the CFF models recycling by substitution, a modeling technique that is often associated with consequential LCA, in this paper the question is raised to what extent the CFF is in line with a consequential approach. In order to investigate this, the effects that are generally modeled in a consequential LCA (CLCA) are expressed in the form of a formula, comparable to the CFF.

In the process of establishing this formula for CLCA, the causal relationships that are modeled in a CLCA have been visually presented in the form of a Causal Loop Diagram. This demonstrates the added value of the CLCA, as it stimulates the development of a complete LCI without imposing *ex ante* cut-off criteria of potential consequences. The CLD that is presented in this paper can be used as a tool to identify the consequences of a changing demand for a product.

The differences between the market-driven substitution method and the CFF of the European Commission demonstrate that the CFF has the potential to, but at the moment does not provide a full consequential approach. Main discrepancies between the CFF and the market-driven substitution method are 1) the lack of differentiation between the marginal supplier and marginal user of materials on the one hand, and the specific value chain of the life cycle under study on the other hand, 2) predetermined limitations to the extent that substitution can be modeled, and 3) an incomplete modeling of the effects of recycling when demand is constrained. Furthermore, combining several effects into a single parameter, such as a single market parameter for both the recycled content and the end-of-life recycling rate, the unclear differentiation between the material entering and exiting a recycling process, and lumping together the

LCI of the substituted primary material, quality correction, and other indirect effects could result in misinterpretations and a lack of transparency of the modeled substitutions.

These missing specifications, lacking or predetermined parameters, and lack of freedom to interpret the method to the context at hand, imply that the outcome of the CFF can be significantly different than the outcome of the CLCA approach, depending on the experience and rigor of the LCA practitioner. However, the CFF is an improvement compared to the End-of-Life formula of the PEF Guide (European Commission 2013) due to a consideration of the recycled material markets (Schrijvers et al., 2016a). Further improvement of the CFF could be achieved by explicitly integrating the differences that are highlighted in this paper, so that the consequences of using or producing a recycled material are more systematically assessed. Such guidance should not be integrated in industry-specific PEFCRs, but rather in an overarching PEF document, as open-loop recycling could lead to material and energy exchanges among different industries. Integrating the suggested improvements would contribute to the harmonization of the application of substitution and the comparability of products assessed according to the PEF Guide.

## Supporting Information

The Supporting Information contains an illustrative example to demonstrate the link between the Causal Loop Diagram and the market-driven substitution method.

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## Disclosure

The authors declare no competing financial interest.

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