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Allocation solutions for secondary material production and end of life recovery: Proposals for product policy initiatives

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ABSTRACT

This paper aims at analysing how secondary materials production and end of life recovery processes are modelled in life cycle-based environmental assessment methods in order to discuss their suitability in product policy-support contexts, with a focus on Sustainable Consumption and Production (SCP) policies. The equations prescribed in three published, widely recognised standards are evaluated. In addition, more recent modelling approaches that have been adopted in the context of two EU product policy initiatives (the Product Environmental Footprint (PEF) and the Resource Efficiency Assessment of Products (REAPro)) are similarly analysed. All of the methods are scrutinised against eight criteria which we deem to be important in product policy-support contexts, including comprehensiveness, accommodation of open-loop and closed-loop product systems, and consideration of recyclability/recoverability rates, to name a few. Based on this analysis, it is suggested that the PEF and REAPro modelling approaches appear to be better suited for use in product policy-support contexts than do the currently widely endorsed methods that we considered.

1. Introduction

1.1. Modelling secondary material production and end of life stages in Life Cycle Assessment

Allocation issues arise in life-cycle based environmental accounting exercises when a system produces multiple product outputs or uses inputs stemming from another product's life cycle. The related input flows and emissions occurring across the life cycle must then be attributed to the co-products in a principled manner. Similarly, allocation is needed when modelling end of life (EoL) processes, including recycling, reuse, energy recovery and disposal in case more than one product is involved. The former instances are particularly challenging in that the environmental benefits and burdens associated with input and output flows must potentially be assigned in relation to multiple product systems both upstream and downstream of the product life cycle of concern. The term "allocation" as it is used in this paper refers to allocating the environmental impacts tied to secondary materials production and EoL processes when several 'subsequent' products are involved. It does not cover allocation between two 'simultaneous' products from the same production process.

Defining system boundaries related to recycled product or recycling at EoL and related allocation methods have been long-debated in the life cycle assessment (LCA) community. Klöpffer (1996), for example, provides an overview of different allocation rules and discusses these in terms of mathematical "neatness", feasibility, and justice/incentives for both producers and users of secondary raw materials. Different allocation approaches related to recycled products were proposed by different researchers such as a market-based approached (Ekvall, 2000), the EVR model of Vogtländer et al. (2001) and a material-quality-based approach by Kim et al. (1997). The ISO 14044:2006 standard for LCA describes this issue in general terms, and provides a conceptual framework to guide practitioners in modelling EoL processes (ISO, 2006b). This conceptual framework distinguishes between open-loop product systems (material from one product system is recycled in a different product system) versus closed-loop product systems (material from a product system is recycled in the same product system). In addition to the allocation solution hierarchy and requirements for general allocation problems specified in ISO 14044:2006, practitioners are required to take into account any changes in the inherent properties of materials. Still, the framework is general and leaves room for interpretation (Ardente and Cellura, 2012; Pelletier and Tyedmers, 2011).

Since the publication of ISO 14044 in 2006, the issue of EoL modelling has continued to receive significant attention amongst practitioners of LCA and comparable methods, with numerous

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approaches to modelling allocation at EoL described in the literature to date. Methodological aspects such as the definition of system boundaries for recycling and incineration and the related allocation issues have been extensively discussed for several cases, including waste paper (Merrild et al., 2008), recycling of PET bottles into fibres (Shen et al., 2010) and cement (Chen et al., 2010). Frischknecht (2010) also recently discussed two intensely debated approaches on modelling the recycling of materials in LCA: the recycled content approach and the EoL recycling approach. The author concluded that harmonisation of the two approaches is unlikely, mainly due to the value assumptions underpinning these alternative strategies, and that there is actually "*no need to reach consensus in this respect*" (Frischknecht, 2010, p. 6). The author moreover concluded that the appropriate modelling approach should be defined by the commissioner of the study.

Building on this research and on the ISO framework, existing guidelines, technical specifications, and methods for environmental assessment of products – including carbon footprinting (e.g. WRI/WBCSD, 2011) and category rules for Environmental Product Declarations (EPD) (e.g. EN:15804, 2012) – have heterogeneously adopted these competing approaches. As a result, there is currently no single, widely accepted approach to modelling EoL and related secondary material production. This seems to be justified as long as different goal and scope of approaches and their application require different approaches to these allocation problems. More consistency seems to be desirable, however, if product policies within the Sustainable Consumption and Production (SCP) context are the focus.

1.2. EU policy initiatives for resource efficiency

A central aim of the European Commission's "Europe 2020 Strategy", as described in the "Roadmap to a Resource Efficient Europe", is to increase resource productivity and to decouple economic growth from resource use and its environmental impact (European Commission, 2011). Several strategies linked to "*transforming the economy onto a resource-efficient path that will bring increased competitiveness and new sources of growth and jobs through cost savings from improved efficiency, commercialisation of innovations and better management of resources over their whole life cycle*" have been identified. These include: "*sustainable consumption and production*" and "*turning waste into a resource*" (European Commission, 2011, p. 7).

In support of the sustainable production and consumption objective, the European Commission is currently engaged in two policy initiatives. The first is to: "*Establish a common methodological approach to enable Member States and the private sector to assess, display and benchmark the environmental performance of products, services and companies based on a comprehensive assessment of environmental impacts over the life-cycle ('environmental footprint')*" (European Commission, 2011, p. 7). The resulting Environmental Footprint (EF) Guides (Product Environmental Footprint – PEF, Organisation Environmental Footprint – OEF) provides a method for modelling the environmental impacts of the flows of material/energy and the emissions and waste streams associated with a product or organisation throughout its life cycle (European Commission, 2013a). The second initiative, the REAPro method, has been specifically developed to be used in the framework of various product policies, including the EcoDesign Directive (European Union, 2009), EU Ecolabel (European Union, 2010) and Green Public Procurement (European Commission, 2008). These two life cycle-based methods developed for product policy support necessarily includes specifications for modelling EoL and secondary material production processes.

1.3. Aims of the paper

This paper aims at analysing how EoL and secondary material production processes are modelled in environmental assessment methods of one product through its life cycle. The overall aim of this analysis is to discuss the suitability of different modelling approaches in product policy-support contexts. Towards this end, Section 2 introduces a subset of widely recognised methods (and associated equations) that were evaluated, along with the PEF and REAPro methods. In this section, the general approach for comparison of the methods is also presented. In Section 3, the original equations are re-expressed using a set of common terms in order to enable comparison. Section 4 presents the analysis and comparison of the equations prescribed in each of these methods against a set of relevant criteria. Section 5 discusses the relative merits and limitations of the PEF and REAPro methods compared to the other methods. Section 6 draws conclusions and provides perspective on future research needs.

2. Presentation of the methods and parameters

2.1. Selection of the methods

Three methods (and seven associated equations) which constitute a representative sample of recent international methods, as well as the PEF and REAPro methods (and four associated equations) were considered in our analysis.

The first method, called PAS2050:2011 (Publically Available Specification – Specification for the assessment of the life cycle greenhouse gas emissions of goods and services) was developed in the UK, co-sponsored by several departments of the UK government and published by BSI in September 2011 (BSI, 2011b). The method is an attempt to define an integrated and consistent approach for assessing the life cycle greenhouse gas emissions of products for use in the broad community and industry (BSI, 2011b; Sinden, 2009).

The second method, called BP X30-323, was developed in France under the laws Grenelle I of 2009 and Grenelle II of 2010 and was published in June 2011 (AFNOR, 2011). The method aims at defining harmonised practices when implementing the legislative request of quantifying environmental impacts of products throughout their life cycle, with the aim of declaring them to consumers.

The third method, defined in the ISO/TS 14067 Technical Specifications, aims at establishing internationally recognised principles, requirements and guidelines for the quantification and the communication of the carbon footprint of products (ISO, 2013). The method aims, in particular, to allow industries, governments, communities and other parties to consistently and transparently quantify emissions.

For the PEF Guide and REAPRO methods we refer to the ones in the introductory section (Section 1.2).

2.2. General approach of comparison

In the subsequent section, each of these selected methods is described in terms of (a) the objectives and scope of the method (including the system boundaries and specifically targeted products if any) and (b) the modelling approach for the production (i.e. use of virgin and recycled materials) and EoL stages (including the mathematical representation, i.e. "production/EoL" equations).

It should be pointed out that the analysis considers recycling and energy recovery but not (partial) re-use. The possibility to address re-use is, however, mentioned in the scope of each method, where relevant. The impact categories accommodated by each of the methods (and the related characterisation factors) are not addressed, neither is the required data type (i.e. generic or specific). Finally, it is important to note that the equations from the original sources have not been re-interpreted by the authors but have been re-expressed using a set of common terms (i.e. notation and definition) in order to allow for comparison. In consequence, the equations in this paper are not direct citations from the original sources. The set of common terms is largely based on the terms used in the PEF method and is summarised in Table 1. Additional terms specific to each equation are defined after each equation.

3. Analysis of the methods for comparison

3.1. PAS 2050 method

3.1.1. Objectives and scope of the PAS 2050 method

PAS 2050 is "*a method for assessing life cycle greenhouse gas (GHG) emissions of goods and services*" (BSI, 2011a, p. 1). The method is applicable to a wide range of products although supplementary requirements, not reported in this article, can be defined for specific product categories or sectors (BSI, 2011b).

3.1.2. Modelling approach of the PAS 2050 method

EoL treatment options considered in PAS 2050 include re-use of components, material recycling, energy recovery and disposal.

The PAS 2050 method recognises that the "recycling of materials and the use of recycled material both have the potential to reduce the amount of virgin materials that needs to be produced" (BSI, 2011a, p. 39), and hence the related GHG emissions. It also argues that "the reduction in emissions must, however, either be allocated to the acquisition of the recycled material or to recycling of this material at the end of the products' life – but not to both" (BSI, 2011a, p. 39). The PAS method hence proposes two separate approaches to deal with recycled content and recycling at the EoL (BSI, 2011a,b, pp. 31–32).

The first approach, called "*recycled content*" *method* should be applied – "*if the recycled material does not maintain the same inherent properties as the virgin material input*", for example to plastics and other complex products. The equation adopted is (1):

$$E = (1 - R_1) \times E_V + R_1 \times E_{recycled} + (1 - R_2) \times E_D \tag{1}$$

The second approach, called "closed-loop approximation" method, should be applied "if the recycled material maintains the same inherent properties as the virgin material", for example for most metals. This method is also called "the end-of-life approach, recyclability substitution, and/or the 0-100 output method" (BSI, 2011a, p. 31). The equation adopted is (2):

$$E = (1 - R_2) \times E_V + R_2 \times E_{recycled} + (1 - R_2) \times E_D \tag{2}$$

Eq. (2) can be re-written as follows:

$$E = E_V + R_2 \times (E_{recycled} - E_V) + (1 - R_2) \times E_D \tag{3}$$

Other conditions for applying one approach or the other are also mentioned in PAS 2050, for example, concerning the control of the manufacturer over the recycled content, or the saturation of the market for a given recycled material (BSI, 2011a). These are not further discussed in this article.

Incineration is considered by PAS 2050 as a disposal option (i.e. PAS 2050 includes incineration in the term E_D). If energy is recovered from incineration, no emissions of the incineration plants should be considered. If this is not the case, emissions from incineration should be calculated on the basis of the carbon content of the material (BSI, 2011a, p. 41).

Table 1
Common terms used in the equations.

Term	Unit	Definition
E	[e.g. kg CO_2, kg SO_2, kg Au, kg water, etc.][b]	Resources consumed/emissions for the production and the EoL stages of one product life cycle[a]
E_V		Resources consumed/emissions for the acquisition and pre-processing of virgin material
E'_V		Resources consumed/emissions for the actual virgin material substituted through open-loop recycling
E^*_V		Resources consumed/emissions for the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials. If only closed-loop recycling takes place: $E^*_V = E_V$; if only open-loop recycling takes place: $E^*_V = E'_V$
$E_{recycled}$		Resources consumed/emissions for the production process of the recycled material, including collection, sorting and transportation processes
$E_{recyclingEoL}$		Resources consumed/emissions for the recycling process at the EoL, including collection, sorting, transportation and recycled material production processes. In some cases, when technologies used are similar, $E_{recycled}$ can be similar to $E_{recyclingEoL}$
E_D		Resources consumed/emissions for disposal of waste material (e.g. landfilling, incineration, pyrolysis)
E_{ER}		Resources consumed/emissions for the energy recovery process
E_{SE}		Avoided resources consumed/emissions for the specific substituted energy source
$E_{SE,heat}$ $E_{SE,elec}$		Avoided resources consumed/emissions for the specific substituted energy source, heat and electricity respectively
R_1	[Dimensionless]	"Recycled content of material" is the proportion of material input to the production process that has been recycled in a previous system $(0 = < R_1 < = 1)$
R_2		"Recyclability rate" is the proportion of the material in the product that will be recycled in a subsequent system (i.e. the rate between recycled output and virgin material input). R_2 takes into account any inefficiencies in the collection and recycling processes $(0 = < R_2 = <1)$
R_3		The proportion of material in the product that is used for energy recovery (e.g. incineration with energy recovery) at EoL $(0 = < R_3 = <1)$
LHV	[e.g. J/kg]	Lower Heating Value of the material in the product that is used for energy recovery
X_{ER}	[Dimensionless]	The efficiency of the energy recovery process $(0 < X_{ER} < 1)$ (i.e. the ratio between the energy content of output (e.g. output of electricity) and the energy content of the material in the product that is used for energy recovery). X_{ER} takes into account the inefficiencies of the energy recovery process

Table 1 (*Continued*)

Term	Unit	Definition
$X_{ER,heat}$ $X_{ER,elec}$		The efficiency of the energy recovery process ($0 < X_{ER} < 1$) for both heat and electricity (i.e. the ratio between the energy content of output (e.g. output of heat or electricity) and the energy content of the material in the product that is used for energy recovery). X_{ER} takes into account the inefficiencies of the energy recovery process
K	[Dimensionless]	Ratio for any differences in quality between the secondary material and the primary material ("down-cycling"). $K = Q_S/Q_P$, where Q_S is the quality of the secondary material and Q_P the quality of the primary material. In line with the general allocation hierarchy defined in ISO 14044 (2006), identifying a relevant, underlying physical relationship as a basis for the quality correction ratio is the preferred option. If this is not possible, some other relationships have to be used, for example, economic value. In this case, the market prices of primary versus secondary materials are assumed to serve as a proxy for quality

[a] For this paper, other life cycle stages (e.g. use stage, distribution) are not considered as they do not pose any production/EoL allocation problem.

[b] All E terms of this paper are expressed in the same unit and are per functional unit of the product analysed.

3.2. ISO/TS 14067 method

3.2.1. Objectives and scope of the ISO/TS 14067 method

The international Technical Specifications developed in the ISO framework ISO/TS 14067 specify "*Principles, requirements and guidelines for the quantification and communication of the carbon footprint of a product (CFP)*" (ISO, 2013). CFP is defined as "*the sum of GHG emissions and removals in a product system, expressed as CO*$_2$ *equivalent and based on a life cycle assessment*" (ISO, 2013, p. 2). Although ISO/TS 14067 considers the life cycle of products, guidance is also provided for conducting partial CFP studies, i.e. assessments of one or more selected process(es) of a product system. The Technical Specifications are applicable to all types of products. However, more specific CFP-product category rules can be developed by programme operators, if appropriate.

3.2.2. Modelling approach of the ISO/TS 14067 method

If the EoL stage of a product is included in the scope of the study, ISO/TS 14067 requires that all GHG emissions and removals arising from this stage be included in a CFP study. According to ISO/TS 14067, the EoL stage begins when the used product is ready for recovery and/or disposal. In its informative Annex C, ISO/TS 14067 includes possible procedures for dealing with the EoL modelling based on the requirements and guidelines in ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), and the examples in ISO/TR 14049 (ISO, 2012).

The ISO/TS 14067 differentiates between closed-loop product system and open-loop product system EoL options. A further differentiation is made in the open-loop product system EoL options (ISO, 2013, pp. 55–58). Type A open-loop refers to material that is recycled without changes to inherent properties. Type B open-loop refers to recycled material that undergoes changes to inherent properties.

The method differentiates between two modelling approaches. The first, the "closed-loop allocation" approach applies to both closed-loop product systems and to type A open-loop product systems. The following equation is proposed in (ISO, 2013) with all parameters as defined in Table 1.

$$E = (1 - R_2) \times E_V + E_{EoL} \tag{4}$$

with E_{EoL} defined as the resources consumed and emissions for EoL operations (being part of the product system which delivers recycled material).

To allow cross-comparison this equation needs to be re-expressed using the same set of terms. Considering that E_{EoL} can be re-written as follows,

$$E_{EoL} = R_2 \times E_{recyclingEoL} + (1 - R_2) \times E_D \tag{5}$$

Eq. (4) becomes:

$$E = E_V + R_2 \times (E_{recyclingEoL} - E_V) + (1 - R_2) \times E_D \tag{6}$$

The "open-loop allocation procedure" method applies to type B open-loop product systems only. The most general equation proposed in (ISO, 2013) is re-expressed in Eq. (7):

$$E = R_1 \times E_{recycled} + (1 - R_1) \times E_V + E_{EoL} + (R_1 - R_2) \times A \times E_V \tag{7}$$

with A [dimensionless] defined as a dimensionless allocation factor.

Using again Eq. (5), Eq. (7) can be re-written as follows:

$$E = E_V \times (1 - R_1 \times (1 - A)) + R_1 \times E_{recycled} + R_2 \times (E_{recyclingEoL} - A \times E_V) + (1 - R_2) \times E_D \tag{8}$$

For the allocation factor 'A', ISO/TS 14067 cites ISO 14044:2006 (ISO, 2006b) and therefore states that the allocation procedure "*should use, as the basis for allocation, if feasible, the following order: physical properties (*e.g. *mass); economic value (*e.g. *market value of the scrap material or recycled material in relation to market value of primary material); the number of subsequent uses of the recycled material*" (ISO, 2013, p. 47). ISO/TS 14067 also offers some further possible interpretation of these provisions.

Eqs. (7) and (8) only apply "if the allocation factor for the recycled materials is identical with the allocation factor of the recycled material which leaves the product system" (ISO, 2013, p. 49).

3.3. BP X 30-323-0 method

3.3.1. Objectives and scope of the BP X 30-323-0 method

The BP X 30-323-0 is a repository of good practices that establishes principles and provides guidelines for environmental communications for products. The overarching goal of the environmental communication is "*to allow the consumer to use the information concerning the environmental impacts of a product throughout its life cycle as a choice criterion when deciding on a purchase*" (AFNOR, 2011, p. 5). In addition, the environmental communication "*must allow comparison of products belonging to the same category and, when relevant, between product categories*" (AFNOR, 2011, p. 5). BP X 30-323-0 can be applied to all mass market products, excluding building sector products.

A decision hierarchy is established to perform allocation of environmental impacts among co-products, which reads: allocation according to distinct processes, allocation according to relevant physical relationships, system expansion, economic allocation, and a combination of the previous rules.

3.3.2. Modelling approach of the BP X 30-323-0 method

The BP X 30-323-0 method provides detailed guidance on how to calculate the environmental impacts associated with the production and EoL stages of a given product. This accounts for a number of processes, including extraction and processing of raw materials, collection of waste, recycling operations, and disposal operations such as incineration (with or without energy recovery) and landfilling.

As a first step of the guidance provided, it must be identified whether "*the material is recycled in a closed loop or an open loop system*" (AFNOR, 2011, p. 18). A general calculation equation is provided for both.

"Closed-loop recycling"[1] *method*

The resources consumed and emissions should be calculated as in Eq. (9):

$$E = (1 - R_1) \times E_v + R_1 \times E_{recycled} + R_3 \times (E_{ER} - X_{ER,heat} \times LHV \times E_{SE,heat} - X_{ER,elec} \times LHV \times E_{SE,elec}) + I \times (1 - R_2 - R_3) \times E_{INC} + (1 - I) \times (1 - R_2 - R_3) \times E_D \quad (9)$$

with all parameters as defined in Table 1. In addition, I [dimensionless] is the national rate of household waste incineration. E_{INC} is the net resources consumed and emissions from the incineration process of household waste (assuming that the average national energy mix has been substituted by the energy produced by the incineration process).

"Open-loop recycling" method

Based on the market rates for the considered raw material, two approaches are distinguished in open-loop recycling situations.

First option: "*if the raw materials market is in disequilibrium because producers are demanding secondary raw materials which are in short supply, then there are grounds for offering incentives to producers of recycled products in order to pull the market. All of the EoL impacts are allocated to the producer*" (AFNOR, 2011). In this case, the equation proposed (cf. Eq. (10)) differs from that given for closed-loop recycling for (a) the recyclability rate at EoL, which is here intended as the national recyclability rate for the proposed application (R_2, instead of the process specific recycled content (R_1)); (b) the avoided resources consumed and emissions refer to the substituted product instead of the analysed product (E'_V instead of E_V).

$$E = E_v - R_2 \times E'_V + R_2 \times E_{recycled} + R_3 \times (E_{ER} - X_{ER,heat} \times LHV \times E_{SE,heat} - X_{ER,elec} \times LHV \times E_{SE,elec}) + I \times (1 - 0.5 \times R_1 - 0.5 \times R_2 - R_3) \times E_{INC} + (1 - I) \times (1 - R_2 - R_3) \times E_D \quad (10)$$

Second option: "*if the market shows no visible disequilibrium (lack of secondary raw materials [. . .]), then the advantage should be split equally between the producer using recycled material and the producer producing a recycled product: 50/50 allocation split*" (AFNOR, 2011, p. 19). In this case, the equation provided (cf. Eq. (11)) considers ($0.5R_1 + 0.5R_2$) rather than either R_1 or R_2 as in the previous cases and, again, the avoided resources consumed and emissions refer to the substituted product (E'_V).

$$E = E_V - (0.5 \times R_1 + 0.5 \times R_2) \times E'_V + (0.5 \times R_1 + 0.5 \times R_2) \times E_{recycled} + R_3 \times (E_{ER} - X_{ER,heat} \times LHV \times E_{SE,heat} - X_{ER,elec} \times LHV \times E_{SE,elec}) + I \times (1 - 0.5 \times R_1 - 0.5 \times R_2 - R_3) \times E_{INC} + (1 - I) \times (1 - 0.5 \times R_1 - 0.5 \times R_2 - R_3) \times E_D \quad (11)$$

The BP X 30-323-0 method makes the following key assumptions when calculating the resources consumed and emissions for the production/EoL stages of a product: (a) the energy (electricity and/or heat) substituted by the energy produced in an energy recovery process at EoL (e.g. incineration with energy recovery) is the average national mix; (b) the fraction of material that is neither recycled nor used in a specific energy recovery process ($1 - R_2 - R_3$) is treated in two ways: (b1) one part, proportional to the national rate of household waste incineration (I), is incinerated with or without energy recovery; (b2) the remaining part ($1 - I$) is landfilled.

3.4. PEF method

3.4.1. Definition, objectives and intended applications of the PEF method

The PEF method is a multi-criteria measure of the environmental performance of virtually any type of product throughout its life cycle (European Commission, 2013a). It has been developed by the Joint Research Centre of the European Commission and published as an annex of the recommendation linked to the Communication "*Building the Single Market for Green Products – Facilitating better information on the environmental performance of products and organisations*" (European Commission, 2013b). PEF information is produced for the overarching purpose of seeking to reduce the environmental impacts of products taking into account supply chain activities (from extraction of raw materials, through production and use, to final waste management). The PEF method provides guidance for modelling the environmental impact of the flows of material/energy and the emissions and waste streams associated with a product throughout its life cycle. One of the objectives of the PEF is to move closer towards comparability of different products fulfilling the same function (European Commission, 2013a).

Potential applications of PEF studies include in-house applications (e.g. support to environmental management, identification of environmental hotspots and environmental performance improvement and tracking) and external applications (e.g. Business-to-Business (B2B) and Business-to-Consumers (B2C) communications). The latter cover a wide range of possibilities, from responding to customer and consumer demands, to marketing, benchmarking, environmental labelling, supporting eco-design throughout supply chains, green procurement, and responding to the requirements of environmental policies at European or Member State level.

3.4.2. Scope of the PEF method

The system boundary in PEF studies follows a general supply-chain logic, including all stages from raw material extraction through processing, production, distribution, storage, use and EoL treatment of the product (i.e. cradle-to-grave), as appropriate to the intended application of the study. In addition to general guidance and requirements described in the PEF method (European Commission, 2013a), Product Environmental Footprint Category Rules may be developed in order to increase the reproducibility, consistency (and therefore comparability between PEF calculations within the same product category), and relevance of PEF studies.

3.4.3. Modelling approach of the PEF method

EoL treatment options considered in the PEF method include (partial) re-use, material recycling, energy recovery and disposal.

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[1] BP X 30-323-0 provides a separate equation for closed-loop system recycling for the specific case where two closed-loops are nested together. This equation is disregarded in this paper in order to enable the comparison with the other methods discussed.

The PEF method provides a single EoL equation which is applicable for both open-loop and closed-loop recycling; and can accommodate both the recycled content (R_1) and recyclability rate (R_2), if relevant.

The resources consumed and emissions are calculated as (12),

$$\begin{aligned} E = {} & \left(1-\frac{R_1}{2}\right)\times E_V+\frac{R_1}{2}\times E_{recycled}+\frac{R_2}{2}\times(E_{recyclig,EoL}-E_V^{*}\times K) \\ & + R_3\times(E_{ER}-LHV\times X_{ER,heat}\times E_{SE,heat}-LHV\times X_{ER,elec}\times E_{SE,elec}) \\ & + \left(1-\frac{R_2}{2}-R_3\right)E_D-\frac{R_1}{2}\times E_D^{*} \end{aligned} \qquad (12)$$

with all parameters as defined in Table 1 and E_D^{*} defined as follows.

E_D^{*} is defined as the resources consumed and emissions for the disposal of waste material (e.g. landfill, incineration, pyrolysis) at the EoL of the material from which the recycled content is derived.

3.5. REAPRo method

3.5.1. Definition, objectives and intended application of the REAPro method

The REAPro method has been developed by the Joint Research Centre of the European Commission to support transparent identification of potential resource efficiency measures for products and assessment of their improvements potentials based on a life cycle perspective. It has been developed for a wide range of possible users, including researchers, analysts involved in product policy making, designers and verification bodies.

Product performance is assessed according to six sets of resource efficiency and waste management criteria (Ardente and Mathieux, 2012a). The criteria include (1) a set of indices that address the “re-usability/recyclability/recoverability rates” (per mass) of a product and (2) a set of “environmentally based re-usability/recyclability/recoverability rates” (per unit of environmental impact[2]). These rates are calculated considering a given EoL treatment scenario (or several given scenarios) to be applied to the EoL of the product. Set (3) covers the “recycled content rate” of a product (per mass) while set (4) addresses its “environmentally based recycled content rate” (per unit of environmental impact). Set (5), called “use of hazardous substances”, covers the management of potentially hazardous substances during the life cycle of the product. Set (6) addresses “durability”, aiming at assessing the relevance of the environmental benefits (if any) due to a given potential extension of the life time of the product (Ardente and Mathieux, 2014). This article focuses only on the options “recycling/energy recovery” and “recycled content” respectively represented by sets (2) and (4).[3]

3.5.2. Scope of the REAPro method

The REAPro method is potentially applicable to any type of product. To date, it has been tested on Energy using Products (EuP) only (i.e. washing machines, TV-sets and imaging equipment (Ardente and Mathieux, 2012b)). Applicability and usefulness of the method for other product groups will be evaluated in the future.

For sets (2) and (4), the following life cycle stages are considered: the production stage (including raw material extraction and processing/manufacturing) and the EoL stage. However, the indices have been specifically defined to assess the relevance of potential environmental benefits that could be achieved by the recovery/recycling of the products.

3.5.3. Modelling approach of the REAPro method

The REAPro method is applicable for both open-loop and closed-loop recycling and considers both recycled content and recyclability. The latter two are, however, addressed separately (i.e. by using different sets of indices) because product requirements can be set for one or more criteria. In order to assess the relevance of a product requirement, the total benefit engendered by the requirement is compared to the life cycle environmental impact of a reference product (i.e. containing no recycled material and not potentially recyclable). In practice, this is done in two steps: (a) the resources consumed and the life cycle emissions due to recyclable/recoverable parts or recycled materials are subtracted from the life cycle resources consumed and emissions for the *reference* product; (b) the obtained result is compared to the life cycle resources consumed and emissions for the *reference* product.

The indices on recyclability rate, energy recovery and recycled content can be written as in Eqs. (13)–(15) respectively:

$$E_{recyclability}=E_v+R_2\times(E_{recyclingEoL}-E_V^{*}\times K)+(1-R_2)\times E_D \qquad (13)$$

$$\begin{aligned} E_{energy\ recoverability} = {} & E_v+R_3\times[E_{ER}-LHV\times(X_{ER,elec} \\ & \times E_{SE,elec}+X_{ER,heat}\times E_{SE,heat})]+(1-R_3)\times E_D \end{aligned} \qquad (14)$$

$$E_{recycled\ \ content}=(1-R_1)\times E_V+R_1\times E_{recycled}+E_D \qquad (15)$$

with all parameters as defined in Table 1.

In addition, $E_{recyclability}$ is the resources consumed and emissions for the life cycle of a product that will be recycled at the EoL. $E_{energy\ recovery}$ is the resources consumed and emissions for the life cycle of a product that will be used for energy recovery at the EoL. $E_{recycled\ content}$ is the resources consumed and emissions for the life cycle of a product that contains recycled content.

These indices can be subtracted from the resources consumed and emissions for the life cycle of the reference product, giving the following “ΔE_i” indices (where i refers to one of the three criteria, i.e. recyclability, recoverability and recycled content):

$$\begin{aligned} \Delta E_{recyclability} & = E_{recyclability(R_2=0)}-E_{recyclability(R_2)} \\ & = [R_2\times(E_v^{*}\times K+E_D-E_{recyclingEoL})] \end{aligned} \qquad (16)$$

$$\begin{aligned} \Delta E_{energy\ recovery} & = E_{energy\ recovery(R_3=0)}-E_{energy\ recovery(R_3)} \\ & = R_3\cdot[LHV\cdot(X_{ER,elec}\cdot E_{SE,elec}+X_{ER,heat}\cdot E_{SE,heat})-E_{ER}+E_D] \end{aligned} \qquad (17)$$

$$\begin{aligned} \Delta E_{recycled\ content} & = E_{recycled\ content(R_1=0)}-E_{recyclecontent(R_1)} \\ & = [R_1\times(E_V-E_{recycled})] \end{aligned} \qquad (18)$$

with all parameters as defined in Table 1 and as in Eqs. (13)–(15). In addition, $\Delta E_{recyclability}$, $\Delta E_{energyrecovery}$ and $\Delta E_{recycled\ content}$ represent the differences in resources consumed and emissions compared to a reference product due to the recyclability of its parts, the potential energy recovery of the product and the recycled content respectively. Each of these “ΔE_i” indices can be compared to the life cycle environmental impacts of the reference product, in order to assess the relevance of the potential recycling/recovery. This is done by calculating the following parameter:

$$\frac{\Delta E_i}{E_{LC}} \qquad (19)$$

with E_{LC} the resources consumed and emissions for the life cycle of the reference product.

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[2] The set (2) of indices transforms the indices (1) expressed in mass into environmental impacts indices through Life Cycle Impact Assessment method.

[3] It is highlighted that set of indices (2) and (4) are however strictly linked respectively to sets (1) and (3).

Table 2
Summary of components (by thematic blocks) of the production/EoL equations considered.

Method	Main thematic blocks (per source of resources consumed and emissions) employed in the production/EoL equations				
	Block A Input: production of virgin material	Block B Input: recycled content	Block C Output: recycling at EoL minus credits from avoided primary production	Block D Output: energy recovery at EoL minus credits from avoided energy production	Block E Output: disposal
PAS 2050 Recycled content	$(1-R_1)\times E_V$	$R_1\times E_{recycled}$	/	/	$(1-R_2)\times E_D$
PAS 2050 Closed-loop approximation	E_V	/	$R_2\times(E_{recycled}-E_V)$	/	$(1-R_2)\times E_D$
ISO/TS 14067 Closed-loop procedure	E_V	/	$R_2\times(E_{recyclingEoL}-E_V)$	/	$(1-R_2)\times E_D$
ISO/TS 14067 Open-loop procedure	$[1-R_1\times(1-A)]\times E_V$	$R_1\times E_{recycled}$	$R_2\times(E_{recyclingEoL}-A\times E_V)$	/	$(1-R_2)\times E_D$
BPX 30-323-0 Closed-loop	$(1-R_1)\times E_V$	$R_1\times E_{Recycled}$	/	$R_3\times(E_{ER}-X_{ER,heat}\times LHV\times E_{SE,heat}-X_{ER,elec}\times LHV\times E_{SE,elec})$	$I\times(1-R_2-R_3)\times E_{INC}+(1-I)\times(1-R_2-R_3)\times E_D$
BPX 30-323-0 Open-loop with market disequilibrium	E_V	/	$R_2\times(E_{Recycled}-E'_V)$	$R_3\times(E_{ER}-X_{ER,heat}\times LHV\times E_{SE,heat}-X_{ER,elec}\times LHV\times E_{SE,elec})$	$I\times(1-R_2-R_3)\times E_{INC}+(1-I)\times(1-R_2-R_3)\times E_D$
BPX 30-323-0 Open-loop with no market disequilibrium (50/50)	$E_V-0.5R_1\times E'_V$	$0.5\times R_1\times E_{Recycled}$	$0.5\times R_2\times(E_{recycled}-E'_V)$	$R_3\times(E_{ER}-X_{ER,heat}\times LHV\times E_{SE,heat}-X_{ER,elec}\times LHV\times E_{SE,elec})$	$I\times(1-0.5\times R_1-0.5\times R_2-R_3)\times E_{INC}+(1-I)\times$ $(1-0.5\times R_1-0.5\times R_2-R_3)\times E_D$
PEF	$(1-0.5\times R_1)\times E_V$	$0.5\times R_1\times E_{recycled}$	$0.5\times R_2\times(E_{recyclingROL}-E^*_V\times K)$	$R_3\times(E_{ER}-LHV\times X_{ER,heat}\times E_{SE,heat}-LHV\times X_{ER,elec}\times E_{SE,elec})$	$(1-0.5\times R_2-R_3)\times E_D-0.5\times R_1\times E^*{}_D$
REAPro Recyclability index	E_V	/	$R_2\times(E_{recyclingROL}-E^*_V\times K)$	/	$(1-R_2)\times E_D$
REAPro Energy Recoverability index	E_V	/	/	$R_3\times[LHV\times(X_{elec}\times E_{SE,elec}+X_{heat}\times E_{SE,heat})-E_{ER}]$	$(1-R_3)\times E_D$
REAPro Recycled content index	$(1-R_1)\times E_V$	$R_1\times R_{recycled}$	/	/	E_D

4. Analysis of the production/EoL equations

Different thematic blocks were identified in the equations. At the input side (i.e. input flows) of the product, two thematic blocks were distinguished: (block a) production of virgin material and (block b) recycled content. At the output side (i.e. output flows) of the product, three thematic blocks were defined: (block c) recycling at EoL minus credits from avoided primary production; (block d) energy recovery at EoL minus credits from avoided energy production and (block e) disposal. The equations considered are summarised by thematic blocks in Table 2. The equations can be broadly grouped into three classes: the "recyclability substitution" approach (also referred to as the "0-100" approach, or the "closed-loop approximation" approach); the "recycled content" approach (also referred to as the "cut-off" or "100-0 output" approach); and the "50/50 allocation" approach.

The "recyclability substitution" approach assumes that the recycled materials that will be produced at the EoL of the product will retain the properties of the original material input to the life cycle, and credits the product for displacing virgin material production in proportion to the recyclability rate. The actual content of recycled material in the product is not considered. The "PAS 2050 closed-loop approximation", the "ISO/TS 14067 closed-loop procedure", the "BPX 30-323-0 open-loop with market disequilibrium", the "REAPro recyclability index" and "REAPRO energy recoverability index" equations use this approach. For the "recycled content" approach, in contrast, the environmental impacts of virgin material production are attributed entirely to the product in which the material is first used, whereas environmental impacts of collection and recycling are attributed entirely to the products providing the recycled materials. The "PAS 2050 recycled content", the "ISO/TS 14067 open-loop procedure", the "BPX 30-323-0 closed-loop" and the "REAPro recycled content" equations use this approach.

The "50/50 allocation" approach assigns burdens from the recycling processes in equal proportion to the previous and subsequent product in which the material is used. The burdens from virgin production and disposal are allocated to the different products of the overall system. The "BPX 30-323-0 open-loop with no market disequilibrium" and the PEF equations use this approach.

As argued by Pelletier et al. (2013), life cycle-based methods to be used for product policy support should provide for a (1) multi-criteria, (2) life cycle-based approach that considers all relevant activities across the value chain, (3) provides for reproducibility and comparability over flexibility, and (4) ensures physically realistic modelling. Criteria (1) is out of the scope of this paper (see Section 2.2). The criteria (2)–(4) are of particular relevance in modelling EoL processes and secondary materials production processes. In the interest of evaluating more precisely the five methods in terms of their suitability for use in product policy support contexts, we further elaborate these three general criteria into a more specific set of eight criteria. The criteria are described and their relevance from a European policy perspective is discussed. The latter is discussed in the following sections for general environmental policies (e.g. Waste framework Directive (European Union, 2008), Roadmap to a Resource Efficient Europe (European Commission, 2011)) as well as for product-specific policies (e.g. Ecodesign Directive (European Union, 2009), Waste Electric and Electr(on)ic Directive (European Union, 2012)). The suitability of the methods for each of these criteria is also analysed in each section. The analysis is then summarised in Table 3.

4.1. Comprehensiveness

Comprehensiveness refers here to including all relevant aspects of the life cycle of the considered product, including both upstream and downstream processes – which is essential to satisfying the

Table 3
Summary of the evaluation of the production/EoL equations against the eight analysis criteria.

Criteria	PAS-2050 recycled content	PAS-2050 and ISO/TS 14067 closed-loop approximation	ISO/TS 14067 open-loop	BPX 30-323-0 closed-loop	BPX 30-323-0 open-loop with market disequilibrium	BPX 30-323-0 open-loop with no market disequilibrium (50/50)	PEF	REAPro recyclability	REAPro energy recoverability	REAPro recycled content
1. Comprehensiveness (includes all blocks)	No	No	No	No	No	Yes	Yes	No	No	No
2a. Accommodates open-loop product system	Yes	No	Yes	No	Yes	Yes	Yes	Yes	NA	NA
2b. Accommodates closed-loop product system	No	Yes	No	Yes	No	Yes (although intended for open-loop)	Yes	Yes	NA	NA
3. Distinguishes % virgin/recycled content inputs	Yes	No	Yes	Yes	No	Yes	Yes	NA	NA	Yes
4a. Considers recyclability rate	No	Yes	Yes	No	Yes	Yes	Yes	Yes	NA	NA
4b. Considers energy recovery	No	No	No	Yes	Yes	Yes	Yes	NA	Yes	NA
5a. Includes material credits	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
5b. Includes energy credits	No	No	No	Yes	Yes	Yes	Yes	NA	Yes	NA
6. Account for changes in inherent properties of materials and/or down-cycling	No	NA	Yes	NA	No	No	Yes	Yes	NA	NA
7. Avoids double counting at a system level	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
8. One formula-fits-all	No	No	No	No	No	No	Yes	No	No	No

general criteria of following a life cycle approach as well as achieving physically realistic outcomes. Specifically, on the input side this requires considering resource flows and emissions associated with the production of virgin material as well as any recycled content. On the output side, resource flows and emissions, as well as any potential credits for avoided production must be accommodated both for material recycling processes as well as energy recovery processes. Emissions related to EoL treatment processes in the current life cycle of concern need also be accommodated.

From a European policy perspective, this criterion is crucial to ensure that "citizens and public authorities have the right incentives to choose the most resource efficient products and services", "based on the life-cycle impacts and costs of resource use", as called by the European Union in its Roadmap to a Resource Efficient Europe, in the Milestone "Sustainable consumption and production" (European Commission, 2011, pp. 6–7). Considering both virgin/recycled contents and recycling/recovery potentials is also encouraged in the Milestone "Turning waste into a resource" of the same strategic document, in the discussion on the stimulation of the secondary materials market, on the re-use/recycling/recovery targets and on minimum recycled material rates (European Commission, 2011, p. 9). The Waste Framework Directive also emphasizes this criterion, in particular at the product level, by re-iterating the "Extended producer responsibility" (Article 8), by defining re-use/recycling/recovery targets (Articles 10 and 11) and by encouraging the secondary materials market via defining "end-of-waste status" (Article 6) (European Union, 2008). A product policy such as the EcoDesign Directive similarly requires comprehensiveness, stating that life cycle stages such as "raw material selection and use, manufacturing (. . .) end-of-life" should be considered when significant environmental aspects are to be defined for product groups (European Union, 2009, p. 23).

Of the equations evaluated, only the BPX 30-323-0 Open Loop with No Market Disequilibrium (50/50) and the PEF may be considered comprehensive, in that they accommodate all of the thematic blocks that we deem to be necessary in order for production/EoL equations to achieve comprehensive life-cycle based modelling (see Table 1). Specifically, emissions related to the recycled content fraction of inputs are considered only in the PAS-2050 recycled content, the ISO/TS 14067 open-loop procedure, the BPX 30-323-0 closed-loop and the REAPro Recycled content equations. In contrast, PAS-2050 recycled content, BPX 30-323-0 closed-loop and REAPro Recycled content equations do not consider emissions/credits associated with recycling at EoL. Finally, the ISO/TS 14067 method does not accommodate emissions/credits related to incineration at EoL. PAS 2050 considers emissions of incineration if the energy is not recovered, but does not consider emissions/credits of incineration if the energy is recovered. Energy recovery credits are included in all three of the BPX-30-323-0 equations, in the PEF equation and in the REAPro energy recoverability index.

4.2. Accommodating open-loop and closed-loop product systems

Accommodating both open-loop and closed-loop product systems is necessary to satisfying the criteria of following a life cycle approach as well as achieving physically realistic outcomes.

Looking at European environmental policy, this criterion is closely related to the Waste Framework Directive, with the application of the waste hierarchy (prevention, then preparation for re-use, then recycling, then other recovery, then disposal) (Article 4) and with the promotion of the "*high quality recycling*" (Article 11) (European Union, 2008).

All of the methods considered accommodate both open-loop and closed-loop systems. However, with the exception of the PEF method, they all require the use of separate EoL equations for these applications.

4.3. Distinguishing % virgin and % recycled content of inputs

Distinguishing the % virgin and % recycled content of inputs is similarly essential both to the life cycle approach and to providing for physical realism.

At the European policy level, the Roadmap to a Resource Efficient Europe explicitly mentions the need to consider recycled material rates (European Commission, 2011, pp. 8–9) as a mean to turn waste into a resource and hence to transform the economy.

Besides the PEF and the REAPro recycled content equations, four of the equations considered – the PAS-2050 Recycled Content equation, the ISO/TS 14067 open-loop procedure, the BPX 30-323-0 closed-loop equation and the BPX 30-323-0 open-loop with No Market Disequilibrium (50/50) equations – satisfy this criterion.

4.4. Considering recyclability and energy recovery rates

The recyclability and energy recovery rates refer to the proportion of the material in the product that will be recycled in a subsequent system or used for energy recovery, respectively. Accounting for these elements is essential both to the life cycle approach and to physically realistic modelling.

Considering these rates is clearly consistent with various European policies, including the Roadmap to a Resource Efficient Europe, which calls for boosting "*the material resource efficiency of products*", e.g. through recyclability and recoverability potentials (European Commission, 2011, p. 8). It is also consistent with the Waste Electric and Electronic Equipment Directive (European Union, 2012) and the End-of-life Vehicles Directive (European Union, 2000), which define re-use/recycling/recovery targets for the product categories. It is also relevant to the Waste Framework Directive (European Union, 2008), which defines recycling and recovery targets for various waste flows.

All of the equations reviewed other than the PAS-2050 Recycled Content equation, the BPX 30-323-0 closed-loop equation and the REAPro energy recoverability and REAPro recycled content indices consider the recyclability rate of the material. Beside the PEF equation and the REAPro energy recoverability index, only the three BPX 30-323-0 equations allow for the consideration of energy recovery.

4.5. Including material and energy credits

Ascribing material and/or energy credits recognises displacement/substitution effects associated with recycling and/or energy recovery processes at the overall system level. Accounting for these elements is necessary for ensuring physical realism. This is closely related to avoidance of double counting at the overall system level (Section 4.7).

Looking at European policies, the importance of considering materials and energy credits is highlighted, for example in Article 4 of the Waste Framework Directive, which calls for the identification of the "options that deliver the best overall environmental outcome", including "the overall impacts of the generation and management of such waste" (European Union, 2008).

Including material credits is a common practise and is accommodated by all of the equations considered other than the PAS-2050 Recycled Content equation; the BPX 30-323-0 closed-loop equation; and the REAPro energy recoverability and REAPro recycled content indices. In contrast, accounting for energy recovery and assigning corresponding energy credits is less common. Besides the PEF equation and the REAPro energy recoverability index, only the three *BPX 30-323-0* equations accommodate this variable.

4.6. Accounting for changes in inherent properties of materials and/or down-cycling

Recycling processes often produce materials that are different from the original material (i.e. with different physical properties). Any such changes may determine subsequent uses of the materials, the products that may be displaced, the energy that may be recovered, as well as the conditions of final disposal. For this reason, it is necessary to accurately reflect these changes when modelling EoL processes in order to maintain physically realistic modelling outcomes.

It was not possible to identify any European policy explicitly mentioning this criterion. However, changes of inherent properties of materials are directly related to the open-loop and closed-loop product system criterion (Section 4.2) and to the material/energy credits criterion (Section 4.5). This criterion is hence indirectly relevant to several European Commission policies.

When looking at the equations, it is somewhat surprising that, besides the PEF and the REAPro recyclability equations, only the ISO/TS 14067 Open Loop procedure equation accommodates these considerations.

4.7. Physical correctness of flows at product versus overall system level

The correct modelling of physical flows at both the individual product and overall (product cascade) system level are important issues. A product level considers all processes related to the life cycle of that specific product, while a system level considers several products which are interrelated through EoL processes (e.g. recycling). Unavoidably, one is required to prioritise between the two levels. Physical correctness of flows at the product level, for example, inherently results in double counting at the system level and thus leads to physical incorrectness at the overall system level. This can be illustrated by a product consisting of 100% recycled content that is 100% recycled at EoL. To calculate the flows in a physically correct manner, the recycling process should be considered at the start of the product's life cycle and a second recycling process should be considered at its EoL. This results in two recycling processes in total at the individual product level. However, at the overall system level this leads to double counting, as the recycling process at the start of the product's life cycle was also considered at the EoL of the previous product, and similarly the recycling process at the product's EoL will also be considered at the start of the life cycle of the subsequent product.

This criterion is highly relevant when considering a combination of various types of policies, as recommended by the Roadmap to a Resource Efficient Europe. In its strategic headline "Turning waste into Resources" it is, for example, stated that a combination of policies (e.g. product-centred policies, waste policies) "*should help create a full recycling economy*" (European Commission, 2011, p. 9). Moreover, some European policies of different kinds are conceived as complementary: for example, a system level policy such as the Waste Framework Directive defines some recovery objectives for various materials flows, without mentioning the EoL products generating these flows. At the same time, a system and product level policy such as the WEEE Directive sets some specific collection and recycling targets for some product waste flows (respectively Article 7 and Article 11) and loosely calls for their better design (Article 4) (EU, 2012). Similarly, a product level policy such as the Ecodesign Directive aims at defining ecodesign product criteria, including recyclability criteria. The different natures and objectives of the European policies and the need to combine them make physical correctness both at the system level (e.g. overall waste flows) and at the product level (e.g. recyclability of a product) relevant. The appropriate modelling of physical flows needs to be defined considering the objectives of the policies.

Among the equations considered, several approaches are possible to avoid double counting at the overall (product cascade) system level, such as accounting only for the recycled content (100:0 approach) or accounting only for recycling at EoL (0:100 approach) or by distributing the impacts of the recycling process over the previous and subsequent product (50:50 approach). In consequence, these approaches do not guarantee physically correct modelling at the product level (e.g. for products with recycled content being recycled at their EoL). All of the equations considered avoid double counting at the overall system level.

4.8. Enabling consistency for a wide range of application

Achieving reproducibility/consistency rather than providing flexibility and choices to the analyst is deemed essential for life cycle-based methods to be used in a consistent way in product policy-support contexts. The method must be applicable to all products potentially considered within the context of either voluntary or mandatory applications. It must also ensure that the results of product system studies are generated in a comparable manner, and hence provide comparable results. This is, for example, necessary for the purpose of gauging performance relative to benchmarks, or meeting specific labelling requirements.

This criterion is self-explanatory from a policy perspective. This need has been, however, re-emphasized in the Roadmap to a Resource Efficient Europe. Here, the headline objective "Transforming the economy" seeks "*to remove barriers to improved resource efficiency, whilst providing a fair, flexible, predictable and coherent basis for business to operate*" (European Commission, 2011, p. 4).

To enable consistency for a wide range of applications, the method should offer a "One-Equation-Fits-All". None of the reviewed equations are intended to accommodate all possible applications, except for the PEF equation.

5. Discussion

The analysis clearly shows that none of the equations of the three widely recognised standards considered meet the criteria for the production/EoL equation which we have defined as important for life cycle-based methods intended for use in product policy-support in the SCP context. The BPX 30-323-0 Open Loop with No Market Disequilibrium (50/50) equation, however, seems to fulfil the majority of the requirements except for "accounting for changes in inherent properties of materials and/or down-cycling". In particular, it addresses in a single equation the recycled content of a product as well as its recyclability and energy recoverability rates. The equation has, however, several limitations because it does not differentiate between the processes related to recycled content ($E_{recycled}$) and recycling at EoL ($E_{recyclingEoL}$), which might be different in reality; and it does not take into account possibly different disposal processes when several products belong to the product cascade system.

The production/EoL equation adopted by the PEF method leads to an overall good performance according to the eight analysis criteria (see Table 3).

Each of the three indices of the REAPro method is internally consistent and was conceived for a different specific scope. In consequence, none of them (considered in isolation) satisfies all of the eight criteria considered. However, taken together, the equations of the REAPro method do allow for analysing the performance of a product in terms of different production/EoL aspects in a fairly comprehensive manner. The fact that one single equation in the REAPro method cannot fit all cases is hence not a problem for its product policy-support purpose. Rather, the method has been purposefully developed to support analysis of different kinds of product efficiency measures (for example, minimum thresholds for recyclability/recoverability rate or minimum thresholds for recycled content) (Ardente and Mathieux, 2013; Ardente et al., 2013).

6. Conclusions and perspectives

Modelling secondary material production and end of life recovery is challenging in life cycle based environmental assessment of products. Although some general rules have been defined for LCA by ISO 14044 (2006), several competing and divergent approaches exist. This undermines the potential for consistent application of one method or another, in particular in support to product policy-making and decision-making. This paper focuses on the needs of production/end of life equations for product policy support and analyses several equations of existing methods with respect to these needs.

Eight criteria were identified as relevant for modelling secondary material production and end of life recovery in the context of EU environmental policies, including general policies (e.g. Waste framework Directive, Roadmap to a Resource Efficient Europe) and product-specific policies (e.g. Ecodesign Directive, Waste Electric and Electr(on)ic Directive). Eleven production/end of life equations proposed in three published, widely used methods (i.e. PAS 2050, ISO/TS 14067 and BP X 30-323-0) and two EU policy-driven methods (i.e. the Product Environmental Footprint (PEF) method and the Resource Efficiency Assessment of Products (REAPro) method) have furthermore been analysed against the identified set of relevant criteria.

The analysis revealed how the equations model production and end of life stages in different ways. Moreover, the analysis demonstrated that the PEF and REAPro methods – designed for use in product policy support applications – are, in fact, better-suited for use in product policy-support contexts than are the other methods considered.

Future research work related to these production/end of life equations could address the associated need for broader availability of quality-assured data for recyclability rates and down-cycling factors. In order to improve the potential for physical realistic modelling, further methodological development could also try to accommodate the average number of times a material or product is recycled, for example using the work presented in the ILCD Handbook (EC-JRC, 2010, p. 350).

Note

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