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Towards a circularity indicator to assess products' materials and lifetime: In-use occupation

Gustavo Moraga[a,*], Sophie Huysveld[a], Steven de Meester[b], Jo Dewulf[a]

[a] Research Group Sustainable Systems Engineering (STEN), Ghent University, Coupure Links 653, 9000, Ghent, Belgium
[b] Department of Green Chemistry and Technology, Ghent University, Graaf Karel de Goedelaan 5, 8500, Kortrijk, Belgium

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ABSTRACT

Slowing and closing loop strategies have the ultimate goal of avoiding materials' losses, hibernation, and emissions, therefore all kind of actions that hamper useful applications. Consequently, there is a need to develop indicators that can deal with mass and time. A way to indicate circularity is by measuring the in-use occupation of resources, that is, keeping materials in a useful state, avoiding dissipation, and adverse effects, such as burden transfer. The objective of this work is to advance in-use occupation as an indicator for the circularity of products; therefore, we schematically present a framework and parameters for such indicators.

1. Introduction

Circular Economy (CE) is an umbrella concept (Blomsma and Brennan, 2017; CIRAIG 2015) that covers the reduction of material input and waste generation (EEA 2016) to decouple the economic growth from the use of natural resources (Pauliuk, 2018). Although CE may not be considered a new concept (BSI 2017), it includes the use of existing strategies in a new way, promoting a paradigmatic shift in the economy (Blomsma and Brennan, 2017; BSI 2017). Indicators are useful tools to assess the progress towards CE transition (Geng et al., 2012). However, a review showed that only a limited fraction of recent CE studies focuses on the development or discussion of indicators (Ghisellini et al., 2016). Most of the existing indicators evaluate nations, regions and industrial parks, but indicators to evaluate circularity in business and products are appearing (Pauliuk, 2018). Recently, the European Union (EU) established an action plan to implement CE (EC 2015).

Considering the plurality of CE meanings, lack of clarity in indicators may drive to different or incoherent outcomes. To better understand what CE indicators are measuring, Moraga et al. (2019) developed a framework to classify indicators according to CE strategies and measurement scope. The authors applied the framework on several CE indicators at the product level as a representation for the micro-scale assessment. Their framework showed that several indicators analyse only materials, and there are indicators yet to be built. Pauliuk (2018) claims that material cycles (natural resource depletion, in-use stock, and lifetime) should be the foundation of CE indicators. Noticeably, although CE considers lifetime as essential to keep products in a useful state, few indicators deal with time as a parameter.

We argue that two main components are necessary to measure the circularity of products: the materials' mass and the time that products are in the in-use state. This paper proposes a possible approach for an alternative indicator that captures mass and time. The outline is as follows: Revision of existing CE indicators measuring time (Section 2), in-use occupation as alternative CE indicator measuring time and mass (Section 3), the definition of parameters and preliminary indicator for in-use occupation (Section 4), and finally we address conclusions and future perspective (Section 5).

2. CE indicators that consider time as a parameter

Mass related indicators are commonly used to assess CE in products, e.g. with recycling, collection, and recovery rates or other resource efficiency metrics. Many of those indicators are based on works that are previous to the term 'circular economy'. Indeed, a review of the period between the 1970s and 1990s showed a relevant development of material flows indicators (Fischer-Kowalski and Hüttler, 1998). Blomsma and Brennan reason that strategies in this period evolved from handling waste and its pollution effects, e.g. waste-to-energy, to considering waste as a resource in more complex solutions, e.g. cascading (Blomsma and Brennan, 2017).

* Corresponding author.
E-mail address: gustavo.moraga@ugent.be (G. Moraga).

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As CE intends to retain materials for as long as possible, the time dimension is also of concern; however, this dimension has received less attention. Nonetheless, researchers and companies developed some indicators to deal with the lifetime of materials and products in closed-loop supply chains prior to the 'circular economy' term. For example, the number of times materials are used in different products was calculated through Markov chain (Matsuno et al., 2007; Eckelman and Daigo, 2008); companies developed specific indicators to estimate the percentage of returned products and lifetime of products and distribution systems, such as containers and crates (Flapper et al., 2005). More recently, despite a growing number of new circularity indicators on product level (Pauliuk, 2018), indicators often do not take time as a central aspect of CE. On the product level, two notable examples consider time (Moraga et al., 2019). First, the Material Circularity Indicator (MCI) from the Ellen McArthur Foundation (EMF 2015) and, second, the Longevity indicator (Figge et al., 2018). We use those works as examples of currently developed circularity indicators including time, other indicators before the use of 'circular economy' term exist but they are not described here for the sake of brevity.

The MCI (dimensionless) aims to improve decision-making in the design phase of products. MCI (Eq. (1)) measures circularity by aggregating in a dimensionless indicator the so-called *Linear Flows Index* (LFI), *lifetime* and the *intensity of use*. LFI is a relation of the used virgin material and generated waste divided by the product's total mass and the waste fraction from the upstream and downstream processes. The *lifetime* is the ratio of the product's lifetime (L) over the industry average (L_{av}). The *intensity of use* is the ratio of the product's functional unit (U) over the industry average (U_{av}). MCI results can be shown disaggregated per material or in the final index for the entire product (weighting the materials on their mass contribution). Elia et al. (2017) found that among other indicators and methodologies, MCI is the only one that attempts to assess the loss of materials and product durability. The indicator, however, focuses only on the restoration of materials and 'fails to address other circular economy issues' (CIRAIG 2015). Indeed, MCI only analyses the product in its lifetime perspective and misses how the product contributes to saving resources in a broader time horizon perspective.

$$MCI = 1 - LFI \times \left(\frac{L}{L_{av}}\right) \times \left(\frac{U}{U_{av}}\right) \quad (1)$$

Longevity (in time, e.g. months or years) is an eco-efficiency indicator that measures the amount of time a resource is used; that is, according to the authors, a value-oriented approach rather than burden-oriented one, such as the approaches considering environmental impacts. The indicator (Eq. (2)) is a sum of the lifetime of the product's first use (L^A), the increased lifetime if the product returns for remanufacturing (L^B), and the increased lifetime if the material is recycled in a new but same product by the company (L^C). Longevity indicator is focused on the analysis of the resource use considering the decision making from a company perspective, but disregard the burdens from material losses inside the company or along the value chain. Similarly to MCI, this indicator does not account for the product's contribution to saving resources in a wider time perspective.

$$Longevity = L^A + L^B + L^C \quad (2)$$

A perspective with a broader time horizon could show pertinent information with previous or future products' cycles, that is, material circularity in different cycles. Furthermore, a time horizon longer than one product's cycle could deliver the call made by Blomsma and Brennan (2017), i.e. to move away from assessments of singular CE strategies by showing them in sequence and parallel configurations. Indicators that assess strategies within one product or business level could help decision in this particular boundary, but they are less helpful on policymaking and social level. Similarly, Elia et al. (2017) highlighted that they are still in the infancy in measuring CE, and most of the indicators are related to the resource-use dimension, but that CE calls for a bigger picture. We understand that more comprehensive monitoring of CE could be made through indicators measuring the use of resources in product chains.

3. In-use occupation as alternative CE indicator measuring time and mass

Scarcity of natural resources is of proper importance as the goal of CE is 'to manage all natural resources efficiently and, above all, sustainably' (EEA 2016). Particularly for the micro-level, the ultimate scarcity of materials relates to earth's stock of virgin natural resources (Figge et al., 2017). Therefore, managing resources is vital, principally, for non-renewable abiotic ones. Although abiotic resources cannot be destroyed (except by energy transformation and one-way space missions), they can indeed be dispersed into either environment or technosphere (Frischknecht, 2016). Meaning that the extraction process does not necessarily imply unavailability: the not-yet-dispersed abiotic resources are rather borrowed and could be potentially restored thereafter (Frischknecht, 2016; Zampori and Sala, 2017). Instead of depletion, we could assess the inaccessibility of resources caused by human-made 'compromising actions' (van Oers et al., 2019). Those actions regard e.g. exploration, environmental dissipation, technosphere hibernation, and in-use occupation.

In-use occupation is a concept of particular interest for CE. Managing resources efficiently means, in other words, maximising the occupation in use, that is, avoiding dispersion and losses of any kind. Occupy a resource in in-use products is the purpose of any extracted resource (van Oers et al., 2019). In-use occupation becomes of increased relevance to CE because similarly to 'land occupation' it could be assessed with the aid of a time dimension. For example, as proposed by van Oers et al. (2019), kg•year.

Moreover, the inclusion of different cycles of products, or a cascading of materials in a sequential use of products, could show specific details for dissipation of resources, as specific characteristics of products can influence the dissipation, e.g. design, use, reparability, collections and treatment system. In that sense, product cycles with higher circularity avoid dissipation of resources and increase their in-use lifetime. We claim that circularity should contribute to more in-use occupation of resources, that is, keeping materials in a useful state, avoiding dissipation, and adverse effects, such as burden transfer. We aim to elaborate further on the concept of in-use occupation with possible parameters and leading indicators. For the moment, we restrict the scope to the analysis of material and time, but future work will consider the potential adverse effects (increased energy use, emissions, etc.) of circularity.

4. Definition of parameters and preliminary indicator for in-use occupation

For a virgin-raw material retained in a cascading of products, at least three occupation phases can be depicted in each cycle (Fig. 1): supply, in-use, and hibernation. Supply occupation includes all processes of transformation of resources (primary or secondary) into in-use products. In the life cycle assessment framework, this would closely relate to a cradle-to-grate system boundary that includes market activities, such as retail. Similarly, the supply occupation encompasses the reverse and forward channels of distribution of reverse supply chain models, that is, producers, distributors, collectors, and recyclers (see e.g. Fleischmann et al., 1997). The in-use occupation is the phase where the product is effectively used; it starts after the retail process and ends before the hibernation.

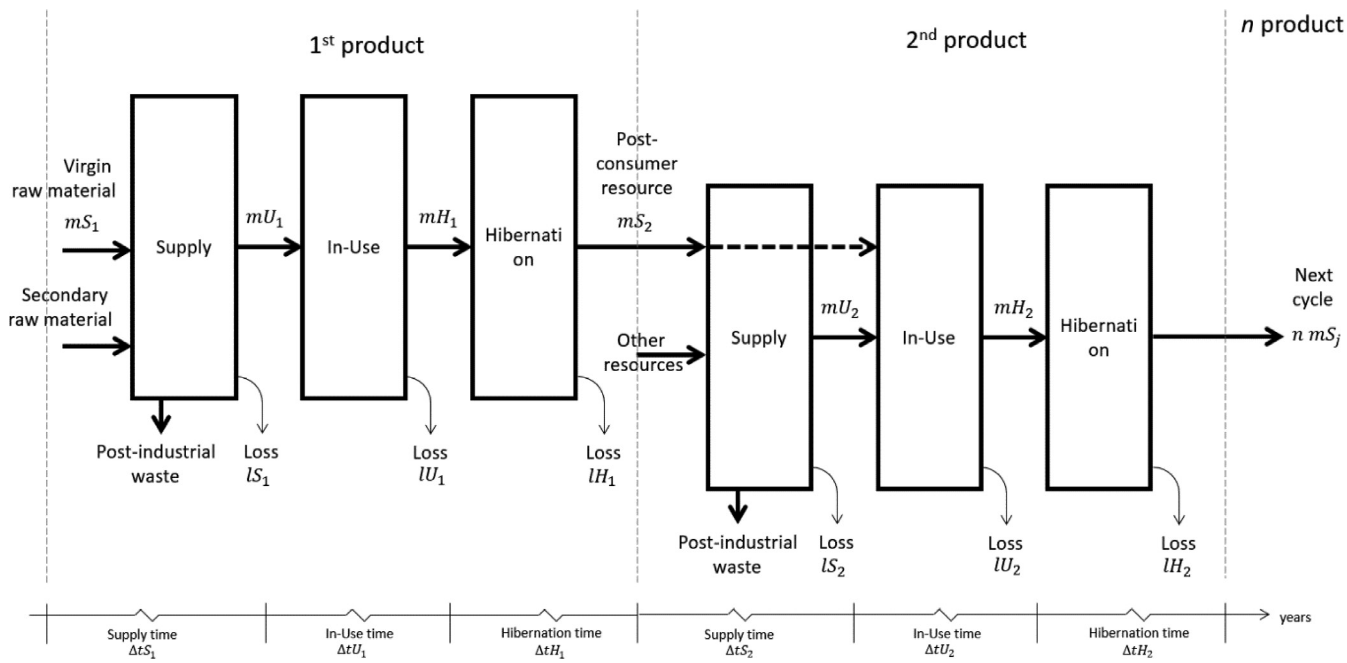

Fig. 1. Input and output mass (m), material losses (l) and time duration (Δt) parameters for *n* cycles of a material in a product j.

The hibernation phase stands for the products that are not in-use but waiting for a new supply phase or end-of-life, e.g. a PET bottle between the discard (in the trash bin) and the EoL collection for either final disposal or treatment, or a forgotten non-functional battery in a shelf also represents the hibernation phase.

Note that supply phase of the 2nd product and following products can include any strategies to increase the lifetime of products (e.g. repair, reuse, and refurbishment) or any strategies to recover the material in the products (e.g. recycling). Therefore, after the hibernation phase, a product could virtually go to the in-use phase (e.g. stockpiled mobile phone that is reused without any repair activity). In this way, the cascading of products can consider CE strategies in a sequential configuration.

For each occupation phase, it is possible to track the mass of virgin raw material (m) dedicated initially to the first product that is kept into the economy in other products. The supply phase begins with raw-material production as defined by Dewulf et al. (2015). Each phase has an identifier for this input mass of material (mS, mU, mH). Also, each occupation can have losses by the dissipation/dispersion of the evaluated material (lS, lU, lH). Most of the losses are likely to happen in the supply phase; however, some losses may also happen in the other phases, and they need to be taken into account (e.g. oxidation). Moreover, each occupation has associated time durations (ΔtS, ΔtU, ΔtH) measured in accordance with their time occurrence.

After this schematic definition of the parameters, it possible to draft a preliminary indicator for the in-use occupation that considers both mass and time (Eq. (4)) and the additional occupations (Eqs. (3) and (5)). $OccS_j$, $OccU_j$, and $OccH_j$ are respectively the supply, in-use, and hibernation occupation of a material in product j (kg.year). mS_j, mU_j, and mH_j are respectively the input mass of a material into the supply, in-use, and hibernation phase of product *j* (kg). lS_j, lU_j, lH_j are respectively the loss of a material due to the supply, in-use, and hibernation occupation (kg). ΔtU_j, ΔtU_j, and ΔtU_j are respectively the supply, in-use, and hibernation time of a product *j* (year).

$$OccS_j = \left(mS_j - \frac{lS_j}{2} \right) \cdot \Delta tS_j \tag{3}$$

$$OccU_j = \left(mU_j - \frac{lU_j}{2} \right) \cdot \Delta tU_j \tag{4}$$

$$OccH_j = \left(mH_j - \frac{lH_j}{2} \right) \cdot \Delta tH_j \tag{5}$$

The equations show two components: a mass relation and the time parameter. Those components are a two-dimensional relation with time as x-axis and mass as y-axis (Fig. 1) that results in the occupation 'area'. Therefore, the calculation is similar to the right-trapezium area (two right angles) in which parallel sides relate to the mass, and non-parallel sides relate to time. The trapezium area equation is the product of the average lengths of the parallel sides (mass) by the distance between the parallel sides (time). The mass relation component in the Eqs. (3)–(5), mass at the initial time of occupation minus half of the losses, is mathematically equal to the average of mass at the initial and final time of occupation.

5. Conclusion and perspectives

Circularity should go beyond the measurement of the mass of resources; the lifetime of products is essential to indicate CE in the micro-scale. In this paper, we present a brief review of indicators that include time as parameter, both MCI and Longevity present scope limitations that need to be addressed, such as, the product's contribution to saving resources and a wider time perspective. Here we present a rationale for in-use occupation as a starting point for the development of a CE indicator that addresses these issues. We expect that this indicator could be useful for two stakeholders: (1) to industry for the design of products and the acknowledgement of the occupation of materials in each phase; therefore, improving the occupation of one product cycle. (2) To policymakers for the assessment of the use of materials in different cascading scenarios; therefore, prioritising policy that could increase the occupation of materials in more than one product cycle.

This paper depicts the ongoing development of a research project aimed to assess the circularity of products. Moreover, we propose and advance the in-use occupation as an indicator of the circularity of materials in products. For the time being, the introduced indicators could be used in one product cycle to test the importance of the in-use occupation concerning the supply and hibernation occupations. For example, a one-use plastic grocery bag would have a lower in-use lifetime than a reusable plastic grocery bag; if the supply time were the same, the reusable bag would have a better in-use occupation. Future work can expand the assessment through performance equations able to compare the whole occupation of materials in different cycles of product considering a cascading perspective. For example, the indicator could measure the occupation of the plastic bag that would be recycled or reused in different cycles considering specific lifetimes and losses.

Other aspects are necessary to advance, i.e. the transition between cycles could be made with performance indicators comparing each cycle; the overall cascading of materials in different product cycles could indicate the fraction of materials retained over a specific time horizon; the assessment of energy-using products, environmental impacts, and energy trade-offs for each occupation could improve the meaningfulness of the results by including environmental concerns. Additionally, we intend to extend this research with case studies from literature and industry. Therefore, it will be relevant to increase the literature review to comprehend product development and management, e.g. lifetime prediction, reverse logistics, and cannibalisation, that will affect the case study examples.

CRediT authorship contribution statement

Gustavo Moraga: Conceptualization, Methodology, Investigation, Visualization, Writing - original draft, Writing - review & editing. **Sophie Huysveld:** Conceptualization, Writing - review & editing. **Steven de Meester:** Conceptualization, Supervision, Writing - review & editing. **Jo Dewulf:** Conceptualization, Funding acquisition, Supervision, Writing - review & editing.

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