Circular Economy of Packaging and Relativity of Time in Packaging Life Cycle

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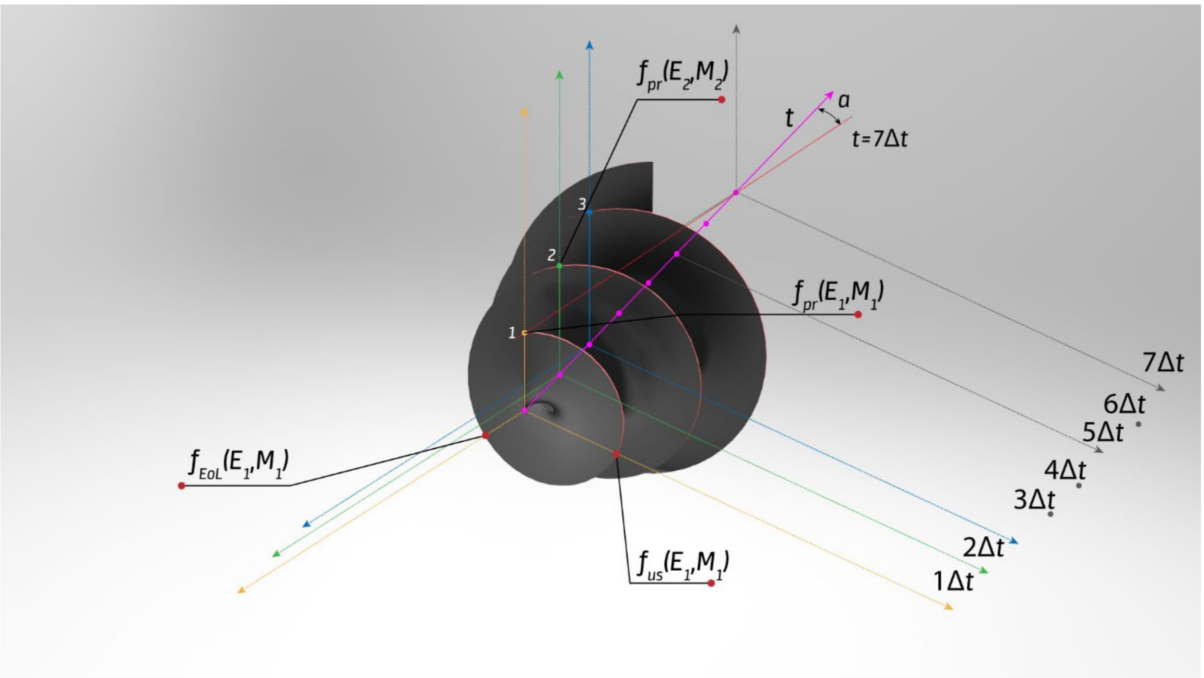
GRAPHICAL ABSTRACT



ABSTRACT

The circular economy paradigm aims to improve the use of material and decrease the negative impacts of the life cycle of products on the environment. In line with the broad variety of conceptualizations and definitions used to describe the circular economy, there are also numerous circularity indicators available in the literature. For analyses that focus on the speed of recycling, we introduce a new methodology. This paper applies the three variables that define the value creation principles in the widely accepted definition of circularity provided by the Ellen MacArthur Foundation: material, energy and time. We show that including time in the LCA methodology may improve the understanding of the system under study, especially for products such as packaging that have a relatively short usage time in the technosphere compared to their recycling time. For this purpose we develop a formula that includes the time necessary for obtaining the secondary material needed for the production of "$n+1$" product. The paper shows that we need to consider the production of additional packaging products and that the quantity of these products depends on the time needed for recycling in the waste management system. This aspect has traditionally been neglected when developing comparative LCAs between systems that serve the same function. The proposed approach to packaging LCA contributes to an important scientific debate over the allocation of credits and burdens between several consecutive life cycles of a material.

Key words

Circularity Metrics, Time, LCA, Life Cycle

1. Introduction

Over the past 50 years, the European Union (EU) has placed particular emphasis on the need for efficient and sustainable usage of resources, beginning with the adoption of the first EU Environment Action Programme in 1972 (Hey, 2005). The first legislative change related to packaging waste was introduced in 1985 with the Council Directive on containers of liquids for human consumption (Council of the European Union, 1985), since when the EU has introduced several mandatory legislation changes for its member states related to packaging (European Commission, 2018a; European Union, 1994). Based on these legislative requirements, the percentage of recycled and recovered packaging material in the EU has been steadily increasing (Eurostat, 2018). However, the amount of packaging waste generated has been increasing at the same pace (Eurostat, 2018).

The introduction of the circular economy paradigm has changed the European Commission (EC)'s approach to and stimulated development of strategic actions for reducing packaging waste. The EC's first Circular Economy Action Plan (2015–2020) had the following three aims: (i) introducing circular design and circular production processes to packaging; (ii) empowering customers by focusing on product and organizational environmental footprint; and (iii) changing the legislative framework for waste and closing the loop on recovered packaging materials (European Commission, 2019a). With the adoption in 2019 of the so-called "Single-use Plastics Directive" and its circularity principles, the EC introduced a systematic sectoral approach to packaging for the first time (European Commission, 2019b). The new Circular Economy Action Plan adopted in 2020 aims to reduce (over)packaging and packaging waste by promoting new designs for re-use and recyclability, reducing the complexity of packaging materials, introducing labelling for correct separation, and revising the regulations on the shipment of waste (European Commission, 2020).

Life cycle assessments (LCA) are commonly conducted by industry and scientists as a comprehensive tool for assessing the environmental impacts of different packaging products (Batlle-Bayer et al., 2019; Ferrara and De Feo, 2018; Gomes et al., 2019; Molina-Besch et al., 2019). A specific challenge in monitoring the circularity of packaging relates to the application of appropriate circularity metrics. The literature divides these metrics into three groups according to the robustness of the analysed systems: micro-scale (product, company); mezzo-scale (industrial systems); and macro-scale (city, regional, national or beyond) (Geng et al., 2012; Janik, 2017).

The past decade has seen intense scientific debate regarding possible solutions for calculating the circularity of products and services, with a strong focus on the role of packaging. Among the important outcomes of this scholarship, García-Barragán et al. (2019) have developed a mathematical approach for comparing the linear economy and the circular economy and defining circular economic growth, while Di Maio et al. (2017) have proposed a market value approach that calculates the value-based resource efficiency of products and services that are returned after the end of life as a metric for circularity.

Numerous methods and indicators have been devised for assessing circularity, especially the circularity of products, on a micro-scale. For example, Pauliuk et al. (2017) have extended the regional scope of the MaTrace model to follow steel flows and assess losses at the end of life through multiple product life cycles. Specifically, they have developed a circularity index that takes account of the purity, quality and recoverability of the material present within the system within a fixed time interval. Linder et al. (2017) developed a circularity indicator and practically combined this with the environmental impacts, while a later study by Linder et al. (2020) developed an indicator calculated as the ratio between the economic value of the recirculated components and the economic value of the entire product, thus taking into consideration all the aspects of recirculation, i.e. reusability, remanufacturing, repurpose and recycling. In addition, a recent study by Cordella et al. (2020) has assessed material efficiency as an aspect contributing to the circular economy in the existing Ecolabel criteria.

One of the circularity indicators most widely used or compared in the scientific literature is the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation and Granta Design (Bracquené et al., 2020; Glogic et al., 2021; Lonca et al., 2020; Mantalovas and Di Mino, 2020; Muñoz et al., 2020). The MCI is based on material flow analysis and measures the maximum restorative flow and the minimum linear flow of a product (Ellen MacArthur Foundation, 2015). However, the MCI has been criticized for its limited application of the aggregation principles (Linder et al., 2017) and for the static perspective of assumption (Pauliuk et al., 2017).

In LCA, two issues must be distinguished with regard to materials scarcity:

(a) materials that are wasted in a system, e.g. by emissions, dispersion, or landfill at end-of-life (the issue of "waste is food" in C2C);
(b) materials that are present in a system as "materials hold-up" (related to the residence time of the materials).

Issue (a) is dealt with in the most used indicators for materials scarcity (in ReCiPe, CML, Environmental Footprint, Eco-costs). An overview of the basic philosophies behind these indicators and its consequences are given in (Vogtländer et al., 2019). Issue (b) is not often dealt with in LCA, since it is seldom that this issue is scope of the study.

In addition to the methods of circularity assessment listed above, more than fifty other circularity indicators can be found in both the academic and the “grey” literature (Saidani et al., 2019), all of which are applied for different purposes, scopes and usages. A variety of conceptualizations and terminologies used to describe the circular economy paradigm have been reported in various reviews (Corona et al., 2019; Linder et al., 2020) and research papers (Kravchenko et al., 2020; Llorente-González and Vence, 2019). As many as 114 different definitions of the paradigm of the circular economy were identified in a study by Kirchherr et al. (2017), leading the authors to predict a possible collapse of the concept due to such broad interpretations. Achieving a unique and simple metrics to serve as a general concept for monitoring the circularity of packaging and for calculating this at macro, mezzo or micro scales of the analysed system is thus an essential and challenging task.

In this paper we address this challenge by defining simple metrics for packaging using the previously defined concept for value creation in the circular economy and by combining existing variables from this concept. In particular, we introduce the concept of the time that material exists in the technosphere as a method to enhance of traditional LCA models, aiming at providing new insights to inform scientific debate on the allocation of credits and burdens between several consecutive life cycles of a product.

2. Methods

In developing new circularity indicators for assessing the circularity of packaging, we used the concept and basic principles defined in two international standards for life cycle assessment: ISO Standard 14040 (ISO 14040:2006(E), 2006) and ISO Standard 14044 (ISO 14044:2006(E), 2006). In addition, we considered the main variables defined in the principles proposed by the Ellen MacArthur Foundation for value creation in the circular economy (Ellen MacArthur Foundation, 2013). The Ellen MacArthur Foundation report published in 2013 defined the following four principles for value creation in the circular economy: (i) the power of the inner circle; (ii) the power of circling longer; (iii) the power of cascaded use; and (iv) the power of pure circles (non-toxic, or at least easier-to-separate inputs). The aim of the circularity principles is to address one-off negative effects of providing material supply in a short period of time. The added value lies in the cumulative advantages of circularity principles compared to the linear economic principles (Ellen MacArthur Foundation, 2013). All four principles hence aim at preserving material (i.e. products, components and material) in the technosphere while maximizing its energy performance over time. On this basis, the three main variables we use for assessing value creation in a circular economy are energy (E), material (M) and time (t).

Following the basic circularity principles and the three variables, we developed the equation for calculation of function of the material and energy needed to produce $n + 1$ product. We illustrate it with a simple case study to present the impacts of time on the traditional linear LCA model. The case study shows the additional material and energy needed for a product to fulfil the same function, but when the time in the technospere is different, which is influenced solely by different time of the end of life stage of the product.

2. Results and Discussion

3.1. Inclusion of time in life cycle

In our efforts to present the interrelation between energy, material and time in the life cycle of a product, we use the adopted view of circularity and develop a new calculation metric derived from these three variables.

We distribute three vectors (axes) in one geometric plane with the following conditions:

$$\vec{x} + \vec{y} + \vec{z} = \vec{0}$$

$$|\vec{x}| = |\vec{y}| = |\vec{z}| = 1$$

$$\sphericalangle \vec{x}\,\vec{y} = \sphericalangle \vec{x}\,\vec{z} = \sphericalangle \vec{y}\,\vec{z} = 120°$$

On axis $\vec{x}$ we distribute the function of energy and material, which depends on the production $f_{pr}(E, M)$ of the packaging. On axis $\vec{y}$ we present the function of energy and material used in the use stage $f_{us}(E, M)$ with the added constant from the previous stages. On axis $\vec{z}$ we provide the function of energy and material used at the end of life (EoL) $f_{EoL}(E, M)$ with the added constant from the previous stages of the life cycle. The EoL stage here covers all aspects and impacts incurred after the usage of the packaging product, i.e. its sorting, collection, treatment, recycling, the reincorporation of secondary materials, and the treatment of waste (littering, incineration and landfilling).

Figure 1 presents the relations between the three functions in closed-loop recycling, where Point *1* presents the value of the production function of the 1st packaging product(s) and $f_{pr}(E, M)$ equals:

$$f_{pr1}(E, M)\vec{z} = f_{pr}(E_1, M_1)\vec{z},$$

where E_1, M_1 are the energy and material needed for producing the 1st product. Point *2* presents the value of the production function of the 2nd consecutive product and after one full life cycle of the product; the value of $f_{pr}(E, M)$ equals:

$$f_{pr2}(E, M)\vec{z} = [f_{pr}(E_2, M_2) + f_{pr}(E_1, M_1) + f_{us}(E_1, M_1) + f_{Eol}(E_1, M_1)]\vec{z}\text{ , or}$$

$$f_{pr2}(E, M)\vec{z} = [f_{pr}(E_2, M_2) + f_1(E_1, M_1)]\vec{z}\text{, where}$$

$$|f_1(E_1, M_1)| = |f_{pr}(E_1, M_1)| + f_{us}(E_1, M_1)| + |f_{Eol}(E_1, M_1)|\text{, or}$$

$f_1(E_1, M_1)$ is the sum of the functions of all material and energy in the first life cycle of the product. The value of $f_1(E_1, M_1)$ is higher than in all of the consecutive life cycles due to the high value of $f_{pr}(E_1, M_1)$, since it is during the first cycle that the largest proportion of the material is introduced in the life cycle to serve the function and functional unit determined by the producer. The extended producer's responsibility of the packaging corresponds to this amount of material (Monier et al., 2014). The function $f(E, M)$ in general is an ever-growing function due to the accumulation of impacts arising from the additional energy and material needed for the product to keep serving the same function.

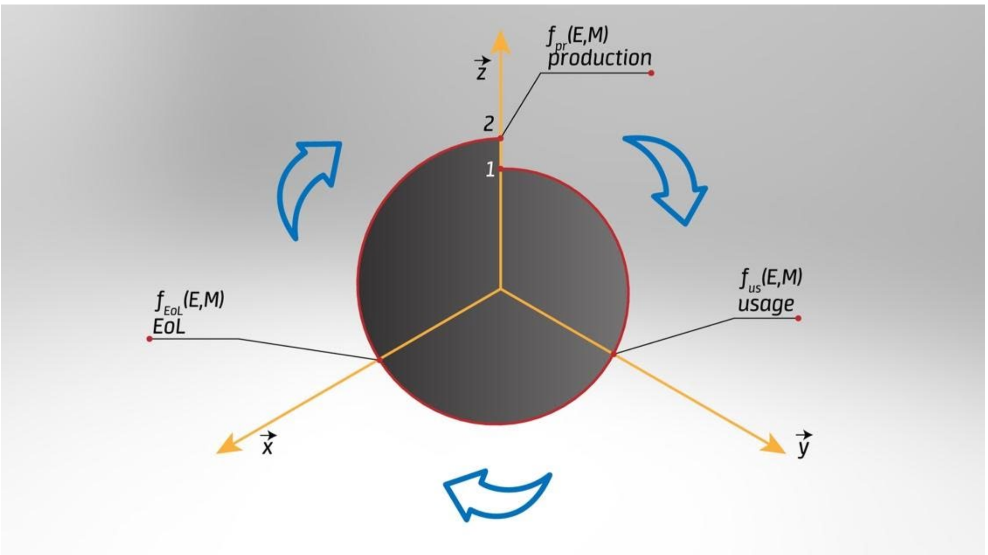


Figure 1. Ever-growing function with accumulation of impacts in a single life cycle of a product

Ever since the introduction of the Life Cycle Analysis (LCA) standards (ISO 14040:2006(E), 2006; ISO 14041:1998(E), 1998; ISO 14044:2006(E), 2006) there has been an intense debate as to the appropriate allocation of impacts amongst the consecutive life cycles. Ekvall and Finnveden (2001), for example, have discussed the solution of this allocation problem in terms of subdivision, system expansion, and physical causal relationships. A study by Frischknecht (2010) assessed two different approaches to the end of life allocation: (i) the recycled content, or cut-off approach, and (ii) the end-of-life recycling, or avoided burden approach, concluding that the cut-off approach has a stronger impact on sustainability. In addition, Ekvall (2000) developed a circularity concept that takes into account the influence of the market in allocation procedures in open-loop recycling, while Werner and Richter (2000) discussed the implications of using an economic model of allocation. Bala et al. (2015) have analysed the influence of the quality of the secondary material in the calculation of credits through material recovery and substitution ratios. Allacker et al. (2014) have scrutinized five accepted standards against eight criteria to assess the holistic approach, concluding that Product Environmental Footprint (PEF) is one of two modelling approaches better suited for the creation of product policies. In a more recent study, Allacker et al. (2017) have explained the rationale behind the PEF selection of the end of life allocation modelling between the first life cycle and previous and sequent cycles. Based on the present PEF Guidance (European Commission, 2018b), different allocation factors are defined for different materials and all previously discussed aspects are incorporated in the equation. This represents the most recent attempt of standardisation of the environmental impact on a product level in the EU.

With an ambition to tackle and solve this long-discussed issue in the LCA scientific field, we include a third important variable defined in the value creation principles of the circular economy, introducing an additional axis perpendicular to the plane on which the axes $\vec{x}, \vec{y}, \vec{z}$ are defined. This variable is defined as the time axis *t* of the process, as presented in Figure 2a. By introducing axis *t,* the three-dimensional coordination system with the function of energy and material in production, usage, and EoL, is geometrically translated in time, and the time of one life cycle is Δt (Figure 2b). *Δt* is constant because we use a simplified example of closed-loop recycling in the theoretically identical waste management system.

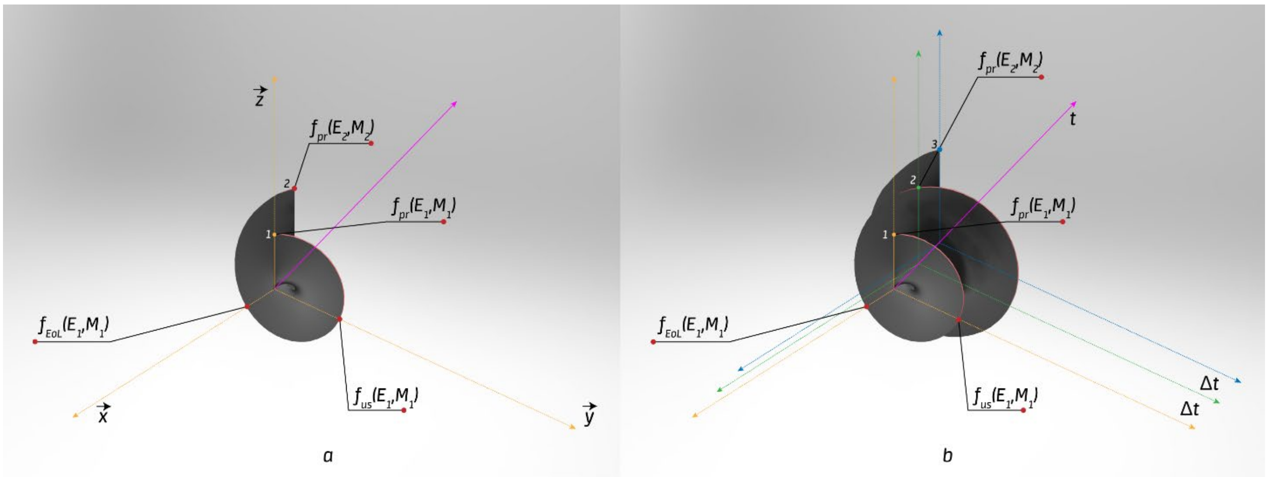


Figure 2. The inclusion of time in the life cycle of a product. Figure 2 a) presents a single life cycle. Figure 2 b) presents two full life cycles of a product, with point *3* representing the value of the production function of the third consecutive product, in accordance with the predefined criteria.

On this basis, we propose the following equation:

$$f_3(E_3, M_3)\vec{z} = [f_{pr}(E_3, M_3) + f_1(E_1, M_1) + f_2(E_2, M_2)]\vec{z},$$

or we can work with the absolute values and deduct the vector $\vec{z}$ from the equation

$$f_3(E_3, M_3) = f_{pr}(E_3, M_3) + f_1(E_1, M_1) + f_2(E_2, M_2)$$

This equation can be transformed to present the "n^{th}" full cycle of the product as:

$$f_{n+1}(E_{n+1}, M_{n+1}) = f_{pr}(E_{n+1}, M_{n+1}) + \sum_{i=1}^{n} f_i(E_i, M_i) \qquad (\textit{Equation 1})$$

Presenting the life cycle of the product and the three important variables (energy, material and time) for value creation in the circular economy enables the extraction of several circularity indicators, as elucidated below.

3.2. Circularity Indicators

3.2.1. Angle of circularity in the production of packaging

The first indicator derived from introducing time into the geometrical representation of a product life cycle relates to the quality of the material in recycling and to changes in the quality of material over time $\frac{dQ}{dt}$. The scientific literature has provided some examples of the limitations of packaging materials in closed-loop recycling. For example, Niero and Olsen (2016) have reported problems in the alloying composition of closed-loop recycled aluminium cans, limiting its recycling to a maximum of seven cycles due to the lack of magnesium and manganese for the production of the lids of such cans. (This specific case, with a maximum of seven recycling cycles, is presented in *Figure 3*.)

The literature further suggests that the standard practice of mechanically recycling plastics results in quality losses due to changes in the molecular weight of the complex polymer molecule of the secondary material (Grigore, 2017). For example, the use of secondary glass in closed-loop recycling has been shown to require a significant amount of post-treatment to meet the quality standards of the industry production chain due to different glass types and impurities (Deschamps et al., 2018), meaning laboratory testing of the mechanical, chemical, physical and optical properties of the material is needed to assess the qualitative changes of the material in closed-loop recycling.

The possible number of life cycles in closed-loop recycling of a product's packaging before the material stops being suitable to serve the same purpose, in relation with the $f_{pr}(E_1, M_1)$ as a function of the material and energy needed for the production of the first packaging product, can be considered as an *angle of circularity in production*. The smaller the angle the more circular the packaging product. In Figure 3 the angle of circularity in production is presented as $\sphericalangle\alpha$.

A specific feature in the case of this indicator is that we do not add additional mass in any stage of the life cycle because of the closed-loop recycling without additional mass. This means that:

$$M_1, M_2, \ldots., M_n = 0$$

for all stages of the life cycle, production, usage and EoL.

a)

b)

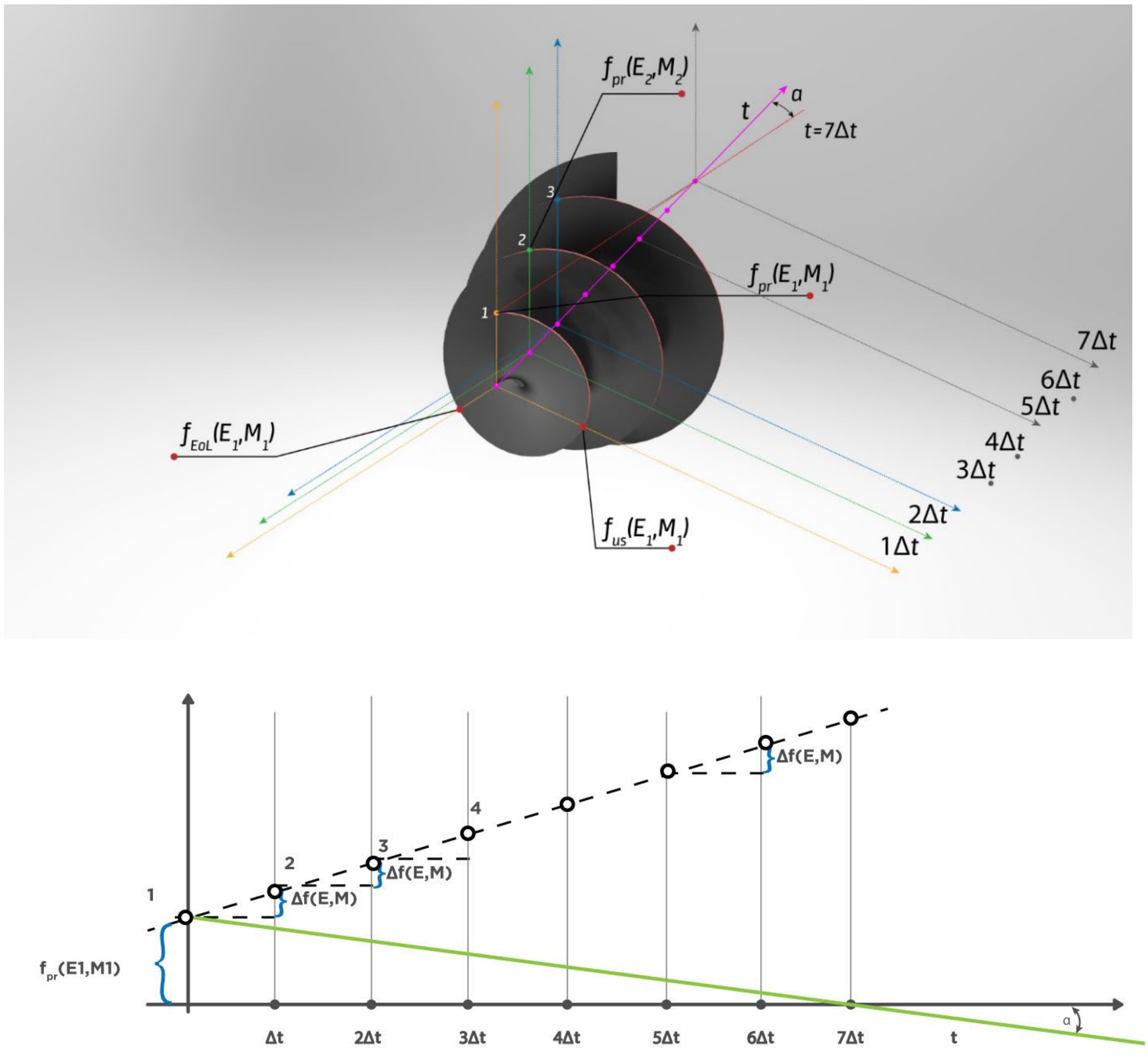


Figure 3: Angle of circularity ($\sphericalangle\alpha$) in production after seven recycling loops (Fig. 3a) and presentation in $f_{pr}(E_n, M_n)$ and *t* coordinate system (Fig. 3b)

3.2.2. Angle of circularity of the packaging life cycle

The scientific literature has recognized the importance of taking multiple loops into account in designing life cycle assessments of packaging (Niero et al., 2016; Sazdovski et al., 2021). For products such as packaging that have a short usage time in the technosphere, considering multiple cycles can marginalize the problem of allocating burdens and credits amongst consecutive cycles. The specific theoretical case of equation 1, where $n \rightarrow \infty$, would thus render the EoL allocation insignificant in the overall life cycle assessment.

The specific case for this indicator is that we add additional mass in every stage of the life cycle in order to keep the same function of the material for all stages of the life cycle, production, usage and EoL. This means that:

$$M_1, M_2, \ldots., M_n \neq 0$$

Packaging produced from metals and glass has a relatively high value of $f_{pr}(E_1, M_1)$ for the production of the first product due to the energy-intensive production process involved. However, such packaging has relatively low values of $f_{pr}(E_{n+1}, M_{n+1})$ for consecutive life cycles compared to plastic and paper packaging due to the quality of the material in recycling, the recycling yields, the influence of the recycled content and the small material losses incurred in the recycling process. To find a breakeven point of the number of cycles for different packaging materials that serve the same function and functional unit, we can use a sensitivity analysis of the number of circles of the equation (1).

From the graphical presentation in Figure 2 that shows the three main variables that influence value creation in the circular economy, we can identify one new indicator of circularity that we name the *angle of circularity of the packaging*.

The relations between the three consecutive life cycles of the product, $n, n+1 \; and \; n+2$, are represented graphically in Figure 4.

Here we consider a simplified case in which the material for the production of $(n+1)^{th}$ of a product has the same quality as the material used for the production of n^{th} product, serves the same function, and is produced under the same conditions. We assume that the addition of the virgin material is constant for the sake of simplification, although in reality the recycled part will be dirtier.

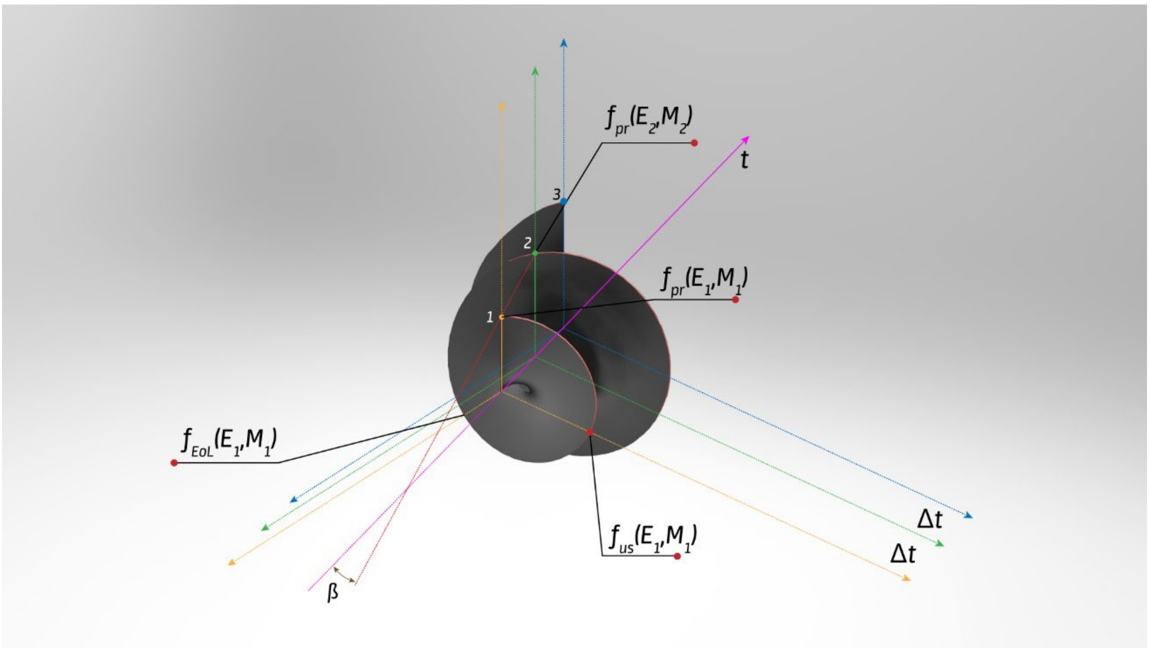


Figure 4: Angle of circularity ($\sphericalangle\beta$)

We can define a straight line that connects the value of $f_{pr}(E_n, M_n)$ and the value of $f_{pr}(E_{n+1}, M_{n+1})$ presented as Point 1 and Point 2 in Figure 4. Figure 5 presents the dependency between the $f_{pr}(E, M)$ and time in the coordination system.

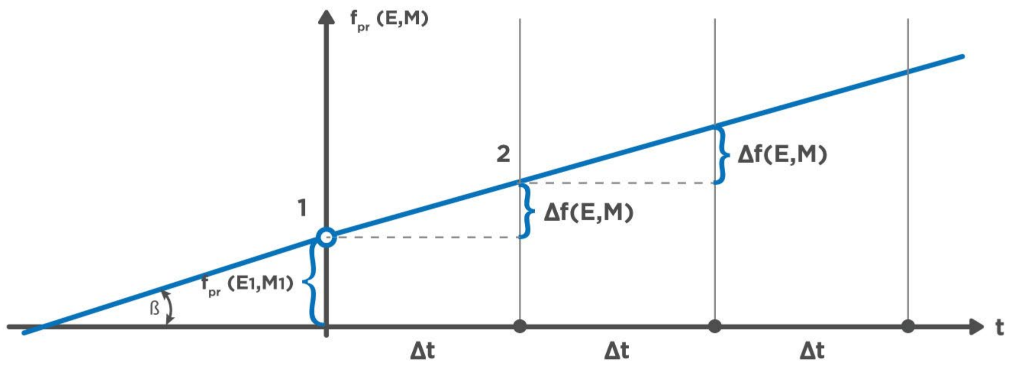


Figure 5: Angle of circularity in $f_{pr}(E_n, M_n)$ and t coordinate system

Angle β is defined as the point of intersection of the previously defined line and the axis of time *t*. This angle can be defined as an angle of circularity and helps us to observe the circularity of the material after $n + 1$ life cycles. The smaller the angle of circularity, the better the circular properties of the material. The value of $\Delta f(E, M)$ equals:

$$\Delta f(E, M) = f_{us}(E_n, M_n) + f_{EoL}(E_n, M_n) + f_{pr}(E_{n+1}, M_{n+1})$$

and $\Delta f(E, M) = f_n(E_n, M_n)$ when equal energy and material is consumed for the production of each consecutive cycle (*n* and *n+1*).

On the basis of this conclusion we can say that the angle of circularity depends on the function of the energy and material in each cycle and the time of the life cycle in the technosphere.

In an ideal situation where the material introduced in the technosphere stays there indefinitely and is reused in the consecutive life cycles, the value of the angle of circularity and the angle of circularity of production is equal to zero. This means that no additional material is added for serving the same function. No additional energy is added in the system under the analysis either. In reality, the angles however depend on the qualitative properties of the material that is recycled, as well as on the energy needed for the recycling as essential variables. Finally, the angles will depend on the real time of the life cycle, being in particularly impacted by the t of EoL.

The influence of time on angle of circularity is explained in the following section.

3.3. The relativity of time in the technosphere for packaging products

Time is a very important variable in the life cycle of packaging. The packaging production process has become simpler and faster due to the continuously expanding market and increasing demand. The maximal time of the usage phase of the life cycle is linked to the time that a product (beverage or food) is fit for consumption, hence the usage time does not depend on the packaging material, but on the packaged good, meaning the time of usage will not change if you replace the packaging for a different material with the same function.

The biggest difference occurs in the end of life stage of packaging materials. This difference comes from the varying efficiency of waste management systems, the efficiency of sorting systems, the efficiency of the recycling of the material, the recycling yields, and the location of the recycling facility. The last factor (location) is related to the time needed for transportation of the sorted and recycled material. The following equation represents the time of one life cycle of the packaging:

$$\Delta t = t_{pr} + t_{us} + t_{EoL}$$

The effect of including the real time of the life cycle in the production of packaging is presented in Figure 6.

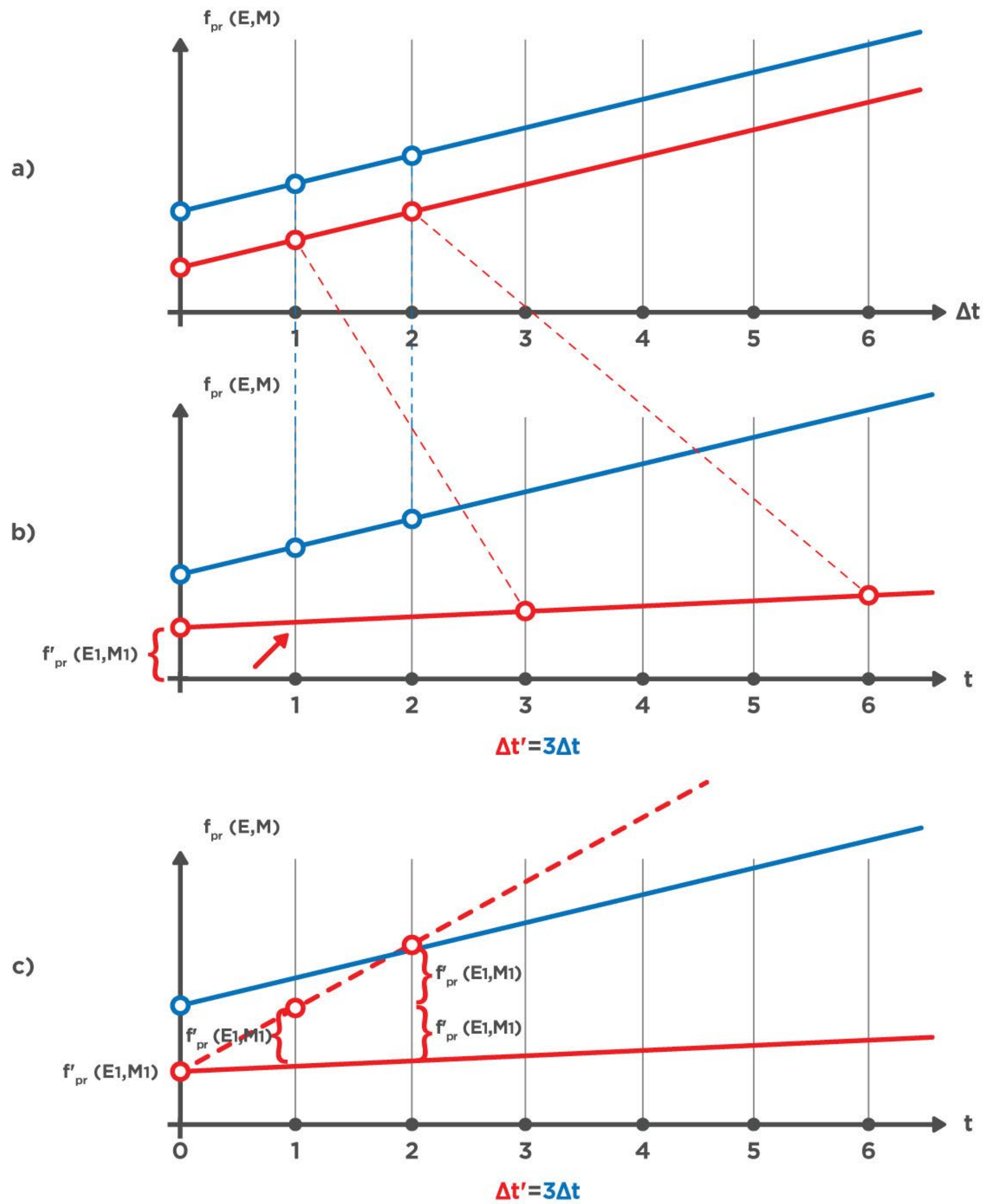


Figure 6. Relativity of time in the life cycle of two packaging systems. Difference in the function of energy and material from life cycle (6a), and from time (6b and 6c) of two systems. In the first system $\Delta t = t$ (represented in blue) and in the other system $\Delta t' = 3t$ (represented in red).

Figure 6a illustrates two different packaging systems that use the same material but with different functions of energy and material for the production of the first packaging $f_{pr}(E_1, M_1)$. The packaging represented in blue finalizes one full life cycle exactly on time for the production of new packaging from the secondary material. The life cycle of the packaging represented in red has $\Delta t'$ three times longer due to the lower efficiency of the waste management system (Figure 6b) and production of the first packaging $f'_{pr}(E_1, M_1)$.

Even though there is no difference in the relation between the $f(E, M)$ and the life cycle, a geometrical translation in time, as presented in Figure 6b (see the red arrow in the graph) shows a lack of packaging material for reproduction because the secondary material did not finalize its life cycle and therefore new additional material for the production of the packaging of the following cycle needs to be introduced into the system to serve the same function and functional unit (Figure 6c). The amount of this additional $f(E, M)$ is proportional to the relation between the time of the life cycle and the time (t_{need}) needed for the secondary material to be prepared for a new cycle (the need for a new product) of the life cycle of the packaging.

Bearing all this in mind, we can transform Equation 1 in order to present the function of the material and energy for the production of the packaging after n number of circles:

$$f_{n+1}(E_{n+1}, M_{n+1}) = f_{pr}(E_{n+1}, M_{n+1}) + \sum_{i=1}^{n} f_i(E_i, M_i) + (\frac{\Delta t}{t_{need}} - 1) f_1'(E_1, M_1)$$

(Equation 2)

where: $\Delta t, t_{need} \in N \wedge \Delta t \geq t_{need}$

Also, $\Delta t, t_{need}$ are expressed in the same time unit appropriate for the need for the production stage of packaging.

Where $\left(\frac{\Delta t}{t_{need}} - 1\right) f_{pr}'(E_1, M_1)$ in the Equation 2 is the additional number of packaging products needed for balancing the system until the end of every life cycle. Sazdovski et al. (2021) have reported that the discrepancy between the exported and imported material of the packaging is related to the fact that most plastic packaging is transported from developed countries to developing countries during the EoL. This can create a significant discrepancy in the time of the life cycle, even though it does not contribute to the circularity of the product. In addition, the time of EoL of some materials might be significantly longer than the time for production and the time of usage in the life cycle. This discrepancy in times is not taken into consideration in linear LCA calculations. As presented in *equation 2,* this discrepancy results in adding additional material and energy into the technosphere for serving the same functional unit. The longer the life cycle of the material, the more additional packaging material is needed.

The different industries producing fast moving products generally do not disclose the average time of the EoL of their products, with the aluminium industry being an exception by clamming that an aluminium can is possible to be reproduced in 60 days (3BL CSRwire, 2010; Belinda, 2006; EarthShare, 2008; Island Return It Recycling Depot, 2013; Leahy, 2019; Marck Recycling, 2015; Novelis, 2021; Recyclebank, 2012; Reyes, 2010; Richmond Steel Recycling, 2019; The Aluminum Association, 2014; Think Cans, 2017). The industry considers this as a circular property of the aluminium can. Not having information about comparative products serving similar function, we will conduct a simple comparison using two equal aluminium cans. The cans are produced under equal conditions, but they follow two different EoL scenarios: one is two times longer than the other. Therefore, we can transform the *Equation 2* to calculate the function of E and M for development of a daily production of "m"aluminium cans, with a life cycle of 60 days.

$$m f_{n+1}(E_{n+1}, M_{n+1}) = m f_{pr}(E_{n+1}, M_{n+1}) + m \sum_{i=1}^{n} f_i(E_i, M_i) + [(t_{pr} + t_{us} + 60 days)/1 day - 1]\, m f_1'(E_1, M_1)$$

(Equation 3.)

We use the same equation to calculate the function of E and M of the same production process for the aluminium cans after their use end up in a EoL that have the same function $f_{EoL}(E_n, M_n)$ but two times longer duration ($t_{EoL} = 120 days$). Having in mind that the production process is the same and assuming that the usage is the same, we can transform the equation 2 for this process.

$$mf''_{n+1}(E_{n+1}, M_{n+1}) = mf_{pr}(E_{n+1}, M_{n+1}) + m\sum_{i=1}^{n} f_i(E_i, M_i) + [(t_{pr} + t_{us} + 120days)/1day - 1]\, mf'_{pr}(E_1, M_1)$$

(Equation 4.)

Simple deduction between the Equation 4 and the Equation 3 will show us the additional material needed to serve the same function. The need for the additional material is only influenced by the length of the EoL.

$$mf''_{n+1}(E_{n+1}, M_{n+1}) - mf_{n+1}(E_{n+1}, M_{n+1}) = 60mf'_{pr}(E_1, M_1)$$

The result is 60 daily productions of the primary material $f'_{pr}(E_1, M_1)$ that are needed to be added in the technospehere to serve the same function. The linear LCAs do not calculate this additional material. This simple example illustrates the impact of time on life cycle, showing the importance of considering time when conducting life cycle analysis of packaging.

The findings provided and discussed in this section suggest that when considering the time variable in the life cycle of a packaging product, the key difference that appears between packaging materials is related to the time of the material's EoL. When comparing the life cycles of packaging made from different materials, therefore, the time of the life cycle can be equated to the time of the EoL:

$$\Delta t \cong t_{EoL} \cong t_{EoLmax}$$

In order to make a comparison of different packaging materials using the previously developed circularity indicators, we would need to define the maximal time of the EoL to be considered for all materials performing the same function. This would enable a comparison of all the materials under the same circumstances. This approach could bring improvements in the time efficiency of waste management systems and the sorting of packaging. Finally, this approach could also stimulate the creation of a local market for secondary materials.

3. Conclusions

The circular economy is a relatively new concept introduced to overcome the limitations of the traditional linear economy model that has proved to be inefficient in terms of material use and environmental protection. A growing body of scientific literature aims at providing adequate metrics in order to improve comparison between the two economic paradigms or systems serving the same function. One of the key limitations of the circular economy concept is the lack of a unique definition and of commonly accepted indicators for circularity. Moreover, there is a plethora of different approaches utilizing or introducing new variables that are not defined in previously developed conceptual frameworks of the circular economy.

Accordingly, this paper starts from the widely accepted and referenced definition of circularity in order to ascertain which key variables need to be considered. On this basis, our paper introduces for the first time a combination of the three variables that define the value creation principles developed by the Ellen MacArthur Foundation: material, energy and time. When the materials hold-up in a system is regarded as important, the time as a third variable must be taken into account.. This is especially the case for products that have a relatively short usage time in the technosphere compared to the time needed for recycling and waste management. Packaging is a perfect example of such a product.

We developed a formula for calculating the so-called "$n+1$" product that includes the time necessary for obtaining the secondary material needed for its production. According to this formula, we need to consider that the production of additional packaging products and the quantity of these products depend on the time needed for recycling in the waste management system. The t_{EoL} for different packaging materials varies, which makes LCA in circular economy difficult to compare with the tradition linear LCA method.

This is similar to the stocking of packaging in reusable packaging systems that serves the function of the system ensuring packaging availability. Traditionally, this phenomenon has not been taken into account when developing attributional LCAs between systems that serve the same function.

The representation of the life cycle of packaging proposed here addresses the problem widely discussed in scientific circles related to the allocation of credits and burdens between several consecutive life cycles. We have demonstrated this issue for the specific case in which $n \rightarrow \infty$ and applied our formula to calculate the "$(n+1)^{th}$" product.

This study showed how to improve the LCA practice by including circularity principles. While impacts from the usage of energy and material is studied in the linear LCA model, here we exposed additional considerations by adding time variable in the calculation. This is particularly obvious for fast-moving goods, such as packaging. For comparative LCAs, introduction of time as a variable can also serve for development of the circularity indicators. The presented circularity indicators can be used for the following two purposes: i) for assessing the circularity of packaging in production; and ii) for assessing the circularity of packaging during the lifetime of packaging materials. Future research should assess the application of the developed indicators in open-loop and closed-loop recycling.

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