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Research article

Comparative assessment of two circularity indicators for the case of reusable versus single-use secondary packages for fresh foods in Spain

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A R T I C L E I N F O

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A B S T R A C T

Sustainable packaging is a crucial focus in the context of circular economy efforts. This study evaluates the circularity of two secondary packaging systems used in Spanish fresh food produces: Reusable Plastic Crates and Single-use Cardboard Boxes. A Mass Flow Analysis was performed to assess the material flows in the production and use phases of both systems and two circular indicators were applied: the Material Circularity Indicator and Product Circular Indicator. While most previous studies for single-use packaging use these indicators at the product level, this study applies a system approach since the Reusable Plastic Crates can be reused 100 times. The functional unit was defined as the distribution of 1000 tonnes of fresh products, resulting in the distribution of 6,666,700 packages with 15 kg of products. The Material Circularity Indicator and Product Circular Indicator results show that Reusable Plastic Crates are more circular than Single-use Cardboard Boxes. The Product Circular Indicator provides a more comprehensive assessment of circularity by considering multiple life cycle stages, efficiency, and unrecoverable waste, resulting in a difference in circularity evaluations. The indicators used have limitations as they do not consider the resource stock. Further research is needed to explore this aspect.

1. Introduction

The linear economy follows the take-make-waste model, based on the presumption that resource availability and ecosystems regeneration are unlimited, and neglecting the existence of the planetary boundaries as a limiting factor [1]. Although some studies hold the belief that the economy only transitions from linear to circular, evidence shows that our economy has always been a mix of both. The economy's inclination toward either circular or linear models is influenced by factors such as sellers' profitability, business opportunities, and constraints like time, skills, labor, or resources [2]. Faced with the challenges of linear economies and the ongoing growth of the population, the transition towards circularity is a key step for sustainable development.

While there is a common understanding of what circular economy is, there is no unified and universal definition. In the scientific literature, there is a plethora of circularity definitions, (i.e., 95 definitions found by Kirchherr et al. (2017) [3]) and indicators [4], and

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some authors have even warned about a possible collapse of the circularity concept as a whole [5]. Of all the definitions, the most prominent one, (as highlighted by Kirchherr et al. (2017) [3]), is the one given by Ellen MacArthur's Foundation (EMF) [6]. EMF summarizes its definition in the three principles of CE: eliminating waste and pollution, regenerating nature and circulating products and materials.

Rankin (2014) [7] defined the material cycle with three components: *the resource stock* - the resources on Earth (i.e. trees)-, *the material stock* - the materials obtained from the natural resources (i.e., timber)-, and *the product stock* - the goods or products that are made from the materials and used by society-. To better adapt this framework within the circular economy, the material stock should consist of two types of materials: virgin material that comes directly from nature and recycled material that results from the technosphere. In addition, circular strategies can be incorporated into Rankin's framework. Potting et al. (2017) [8], suggested three types of circular strategies, ranked by the level of materials requirement known as 9R based on "tightness" of the material circulation. The graphical abstract shows the adaptation of the material cycle of Rankin (2014) [7] with merged circular strategies proposed by Potting et al. (2017) [8].

Having in mind this overall material cycle, the key challenge to achieve circularity is to ensure the adequate management of the three stocks (resource, material and product), meaning to close the material cycle as tight as possible to reduce the demand for virgin material and the generation of waste.

1.1. Circularity of the supply chain management

A literature review of the scientific literature was conducted in this study in October 2023 using the search string: "*circular*" AND "supply chain"* applied to titles, abstracts and keywords using the Web of Science and SCOPUS platforms, showing 3083 published studies in the English language. Most of the studies are published in the last decade, with an exponential increase in the last several years, showing a rising interest of the scientists in assessment of the circularity of supply chain management.

Measuring and improving the circular performance of supply chain management and especially supply chains in agriculture can also present a true challenge [9–11] and can provide noteworthy benefits [12]. In closed-loop supply chains (CLSC), used products are returned to the original producer for eco-friendly production, waste reduction, and resource preservation. CLSC aims to recycle and reuse all output materials, employing strategies like changing production methods or packaging. Besides environmental benefits, recycling in CLSC can positively impact a company's revenue, depending on the industry and product [13].

Vegter et al. (2021) [14] reviewed the circularity aspects of the performance measurement systems of the supply chains and concluded the scarce literature on the topic. Their conclusions state that performance measurement systems for circular supply chain management are not tested in practice and are in the early stages of development. Their previous review is based on the circularity of the processes and performance of the business models [15]. They concluded that for the improvement of circularity, some processes need to be expanded in the scope of planning of use and recovery, delivery of maintenance, and return of the products after usage. Also, they proposed a performance measurement system for circular supply chain management following the 9R framework [16].

The research developed by Alamelu et al. (2023) [17] included 486 small paper bag manufacturing units in India. They concluded that structured circular activities can improve the sustainability and circularity of the supply chain management in all segments of the system, however, there is a lack of awareness of circularity practices.

Stumpf et al. (2023) [18] used semi-structural interviews of 33 experts to identify the resources and capabilities for increasing the circularity of the plastic packaging supply chain. Collaboration capabilities between upstream and downstream actors, and design capabilities that create simpler and recyclable products were identified by the experts as the most priority aspects of improving the linearity of the plastic packaging supply system.

Carissimi et al. (2023) [19] developed an empirical analysis of circular practices of 100 Small and medium enterprises in Italy. Using the "butterfly method" developed by the EMF [6] they followed the circularity practices of the biological and technical cycles of their supply chains. The authors summarized that the companies lack knowledge of implementable circularity practices that can be implemented to achieve a circular supply chain.

To research social and cultural factors that influence circular supply chains from the perspective of the customers, Sánchez-García et al. (2023) [20] conducted a literature review. The findings of the review suggest that the involvement of multiple stakeholders, primarily final users can improve material circularity and reduce pollution.

A different approach is undertaken in the study developed by van Loon et al. (2023) [21] assessing solely the circularity of the nutrients in the agricultural food systems concluding mainly linear pathways.

The review developed by Longo et al. (2023) [22], aims to research the link between the life cycle thinking and circular strategies of 55 case studies related to the biomass supply chain worldwide. They conclude that scientific literature studies the two concepts separately recommending merged practical tools for the companies to assess the circularity and overall sustainability of bioenergy systems.

All previous literature suggests that merging social factors and primarily environmental impacts with the circularity metrics is crucial for the transition toward circular supply chains, however without adopting a universally accepted method.

1.2. Selecting appropriate circularity metrics

Merging the circularity metrics and Life Cycle Assessment (LCA) is a key to solving the sustainability assessment of the materials [23–25]. A circularity indicator based on the economic values of the product and recirculated components was developed by Linder et al. (2017) [26] and combined with the LCA results, Linder et al. (2020) [27] concluded that there is a clear correlation between circularity and relative environmental impacts. Brändström and Saidani (2022) [28] performed a comparison between circularity metrics and LCA concluding that more in-depth studies are needed in order to establish state-of-the-art circularity indicators, especially energy-focused circularity metrics. In an attempt to connect LCA and the three main variables of circularity (energy, material and time) Sazdovski et al. (2022) [29] developed two circularity indicators by defining the formula for the calculation of "n+1" product. However, all attempts to combine LCA parameters and circularity have more theoretical importance and have limited practical applicability in the circularity assessment of the systems and products. The practical implementation of circularity indicators is limited mainly to material-based circularity metrics.

Material Circularity Index (MCI) is considered the most promising material circularity metric [26] and the most used in practice [30–34]. It was developed by EMF [35] and was updated in 2019 [36] and is based on the most prominent definition of circularity of materials as indicated by some authors. MCI measures how linear flows are minimized, and the duration and intensity of using a product compared to a similar industry-average one. In the most updated version, the MCI also considers the biological cycles; meaning that those materials produced from a renewable source, once becoming waste, can regenerate by themselves.

MCI for packaging has been used mainly to assess the benefit of recycling strategies. Tashkeel et al. (2021) [37] used the MCI to evaluate the circularity of post-consumer plastic packaging waste in the Netherlands, and they incorporated the economic aspect within the MCI. Lonca et al. (2020) [32] investigated the benefits of the recycled content and closed-loop vs open-loop recycling of PET bottles in the US. However, only one article applied the MCI indicator for reusable packaging, specifically to reusable beverage cup systems in festivals [38].

Bracquené et al. (2020) [30] found certain limitations in using MCI for circular complex product supply chains. First, they argue that, even though MCI accounts for reused components, it does not displace the newly manufactured ones. Second, MCI assumes that both reuse and material recycling are 100% circular, and, therefore, MCI cannot estimate the "tightness" of the material cycles. Moreover, MCI does not take into account the source of the recycled and reused feedstock, and the final destination of the recovered components and materials. In addition, Bracquené et al. (2020) [30] highlighted that the MCI does not consider down-cycling, and, thus, it does not account for the quality preservation of the recycled materials. To overcome these limitations, Bracquené et al. (2020) [30] proposed changes to MCI and developed a new indicator, the so-called Product Circular Indicator (PCI).

1.3. Objective of the study

This article aims to analyze the circular performance of the supply chain management for fresh food products and compares the results with the Material Flow Analysis (MFA) based on the full life cycle of the systems. Specifically, two scenarios are examined by using reusable plastic crates (RPC) and single-use cardboard boxes (CBB), used in the Spanish distribution of fresh food products. While previous studies have assessed the environmental performance of this type of packaging (i.e. [39–44] this is the first one in which the inherent circularity of this type of supply system is investigated.

Hence, in this article, circularity assessment is conducted using the most frequently used and recommended circular indicator: MCI and the proposed improvement PCI. MCI is selected because it represents the most used and widely accepted circularity indicator in the scientific literature, and is frequently used by the private sector. PCI is proposed by the more recent literature that can improve the accuracy of the circularity assessment of the products and services using MCI, therefore as a comparison indicator, PCI is calculated as well in this study.

In addition, MFA is performed, to spot the differences and the accuracy of these metrics. The main objective is to give guidance on appropriate metrics depending on the accuracy and availability of the data and information of the whole supply chain.

2. Methodology

2.1. Case studies

The two most common secondary packaging systems for the distribution of fresh food products in the Spanish market are RPC and CBB. Simplicity of the design and materials used, as well as the conceptual difference of the systems: (single-use and reusable), provide a solid basis for the application of the circularity assessment and extrapolating conclusions for more complex supply chains. The LCA of the two proposed packaging solutions has been previously analyzed by Abejón et al. (2020) [39] using real-time data from the Asociación de Operadores Logísticos de Elementos Reutilizables Ecosostenibles (ARECO). The authors concluded that RPC implied significantly lower environmental impacts than CBB in almost all analyzed impact categories.

2.1.1. Reusable plastic crates

The representative RPC used in the Spanish market weighs 1.79 kg, and it has a carrying capacity of 15 kg. Its average composition is virgin material of polypropylene (PP; 43%) and high-density polyethylene (HDPE; 57%). The manufacture of RPC is based on Bala and Fullana-i-Palmer (2017) [45]. RPCs are produced from virgin material through an injection molding process and material losses from this process are granulated and reintroduced in other injection molding applications.

In the study, based on the data given from ARECO, RPCs have a lifetime of 10 years with 10 rotations per year (reused 100 times). After their lifetime, it is assumed that they are 100% collected to be recycled because the system for distribution is in a closed circuit organized by the logistics company. When RPCs are damaged, they are collected by the company and recycled. The rejected material, not suitable for reproducing from the recycling plants, is sent to an incinerator with energy recovery. It should be mentioned that from a life cycle perspective, RPCs are more sustainable. The proportion of the end-of-life stage in the carbon footprint of cardboard boxes is almost 94% higher than that of RPCs [45].

2.1.2. Cardboard boxes

The manufacture of CBB is based on Bala and Fullana-i-Palmer (2017) [45] which used data from the European Federation of Corrugated Board Manufacturers – FEFCO. CBBs are made of layers of recycled and virgin paper. For this case study, it is assumed that CBBs are manufactured from (69.1%) semi-chemical pulp (for the fluting/corrugation) and (40.9%) Kraftliner (for the liner). To produce these papers, a low amount of recycled paper was used: 10% for semi-chemical fluting and 32% for Kraftliner, the highest quality paper [46]; hence, CBB has a recycled content of 18.2%.

This CBB is representative of the specific application to distribute fresh food products. For its manufacture, the corrugated cardboard sheets are produced and cut into the required shape. In a later stage, corrugated cardboard is bent and glued into packing boxes, and they are assembled and palletized. The cardboard boxes weigh 0.807 kg and their carrying capacity is 15 kg. The CBBs are used once, and after their use, it is assumed to be 20% incinerated and 80% recycled. The quality of the recycled paper was set to be 90% of Wellenstoff quality [46], gray paper made from sorted (high quality) recycled paper [39].

2.2. Mass Flow Analysis

The material flow analysis (MFA) is a systematic assessment of the state and changes of flows and stocks of materials within a system defined in space and time [47]. MFA takes into consideration the sources of material, the pathways during the function of the material in the techno-sphere, calculating the intermediate and final sinks of a material. Based on the recommendations of the practical application of the MFA [48], LCA for Experts software (GaBi) [49] is used for the calculation of the material flow of both single-use and reusable systems.

For the calculation of the amount of material used in both systems, the functional unit defined by Abejón et al. (2020) [39] is followed for consistency of the findings between the two studies on the same systems. The LCA study refers to a functional unit: distribution of 1000 tonnes of agricultural products (fruits and vegetables) in reusable plastic crates or single-use cardboard boxes. Both types of secondary packaging can carry 15 kg of product.

To fulfill the requirements of the function and the functional unit, 66,667 units of packaging are required. The conservative scenario is calculated, assuming that the plastic crates have a 10-year lifetime and are reused in 10 rotations per year. The resulting functional unit is calculated as the distribution of 6,666,700 packages with 15 kg agricultural products with single-use CBB or RPC.

2.3. Circularity indicators

2.3.1. Material Circularity Indicator

MCI has two components: the Linear Flow Index (LFI) and the Utility factor (F(X)) (Eq.1). The LFI measures the linearity of material flows for the manufacture of a product with a mass M. Its value ranges between 0 and 1; being 1 the most linear. LFI is calculated as the division between the amounts of material with a linear flow (the amount of the virgin material (V) used in the product, and the amount of unrecoverable waste (W) generated) and the total mass flow, which is 2M for the 100% linear material flows. Nevertheless, the methodology applies a 50:50 approach for the waste generated during the processes of material recovery (W_c) and the production of recycled feedstock (W_F). This means that 50% of W_c is counted by the product and the other 50% by the next product that uses the recycled material. Also 50% of the waste derived from the production of the recycled feedstock (W_F) is counted by the product.(Eq.2).

The second key component of the MCI is the utility factor (Eq.3), calculated as a function F of the utility (X), and it defines the effect of the utility of a product (i.e., longer use) on its MCI. The utility X has two (ratio) components: the lifetime (L/L_{av}) and the use intensity (U/U_{av}) of the product (Eq.4). They reflect the higher (or lower) lifetime of the product; and therefore, the lower (or higher) amount of waste generated, and if the product has been used to its full capacity. The lower the utility, the lower the MCI score.

The MCI, calculated as in Eq. 1 (MCI_p^*), would be negative for linear flows and products that their utility is worse than average values ($X < 1$). To avoid this, MCI is calculated as presented in Eq.5.

$$MCI_p^* = 1 - LFI * F(X) \quad \text{(Eq.1)}$$

$$LFI = \frac{V + W + \frac{W_C}{2} + \frac{W_F}{2}}{2M - \frac{W_C}{2} + \frac{W_F}{2}} = \frac{V + W}{2M + \frac{W_F + W_C}{2}} \quad \text{(Eq.2)}$$

$$F(X) = \frac{0,9}{X} \quad \text{(Eq.3)}$$

$$X = \left(\frac{L}{L_{av}}\right) * \left(\frac{U}{U_{av}}\right) \quad \text{(Eq.4)}$$

$$MCI_p = \left(0, MCI_p^*\right) \quad \text{(Eq. 5)}$$

Following the MCI methodology, the amount of virgin material (V) used in the product is calculated as Eq.6:

$$V = M * (1 - F_R - F_U - F_S) \tag{Eq.6}$$

Where,

F_R is the fraction of feedstock from recycled sources;

F_U is the fraction of feedstock from reused sources;

F_S is the fraction of feedstock from biological materials; *(all dimensionless)*.

Regarding the amount of unrecoverable waste (W_0), it is calculated as presented in Eq.7:

$$W_0 = M * (1 - C_R - C_U - C_C - C_E) \tag{Eq.7}$$

Where,

C_R is the fraction of the mass of the product collected for recycling at the end of its use phase;

C_U is the fraction of the mass of the product to be reused;

C_C is the fraction of the mass of the product that is being composted;

C_E is the mass of biological matter within the product that is used for energy recovery; *(all dimensionless)*.

2.3.2. *Product circularity indicator*

The PCI is defined by Bracquené et al. (2020). To calculate the amount of virgin material (V) (Eq. (8)), PCI considers the fraction of reused components (F_U) and the amount of recycled content (F_r), as well as the efficiencies of the component and feedstock production (E_{cp}, E_{fp}). Regarding the unrecoverable waste (W; Eq. (9)), PCI considers the waste generated during material separation (W_{ms}; Eq. (10)), waste from the component production W_{cp}, waste resulting from the production of recycled feedstock (W_{frp}; Eq. (11)), and the post-use waste (uncollected products after use) (W_U; Eq. (12)) as also considered by MCI; but also waste from the feedstock production (W_{fp}; Eq. (13)) and waste from component production (W_{cp}; Eq. (14)). PCI calculates W_U and W_{ms} the same way as done by the MCI; however, they differ in the estimation of W_{rfp}.

$$V = \frac{(1 - F_u) * M}{E_{cp} * E_{fp}} * (1 - F_R) \tag{Eq. 8}$$

$$W = W_{ms} + W_{rfp} + W_U + W_{fp} + W_{cp} \tag{Eq. 9}$$

$$W_{ms} = M * (1 - E_{ms}) * C_R \tag{Eq. 10}$$

$$W_{rfp} = M * E_{ms} * C_R * \left(1 - E_{rfp}\right) \tag{Eq. 11}$$

$$W_U = M\ (1 - C_R - C_U) \tag{Eq. 12}$$

$$W_{fp} = \frac{(1 - F_U)M}{E_{fp}E_{cp}} * \left(1 - E_{fp}\right) * \left(1 - C_{fp}\right) \tag{Eq. 13}$$

$$W_{cp} = \frac{(1 - F_U)M}{E_{cp}} * \left(1 - E_{cp}\right) * \left(1 - C_{cp}\right) \tag{Eq. 14}$$

Where,

C_U is the fraction of collected end-of-use products to be reused;

C_R is the collected fraction to be recycled;

C_{fp} is the fraction of material loss that is recovered in feedstock production;

C_{cp} is the fraction of material loss that is recovered in component production; *(all dimensionless)*.

PCI estimates the recycled material exchanged outside system (R; Eq. 15) as the one entering the system for product manufacture (R_{in}; eq. (16)) minus the material leaving the system (R_{out}; Eq. (17)). R_{out} is defined as the sum of the scrap produced during the feedstock manufacture (R_{fp}; Eq. (18)) and component production (R_{cp}; Eq. (19)) and the amount of end-of-life recycled material recovered (R_{EoL}; Eq. (20)).

$$R = R_{in} - R_{out} \tag{Eq.15}$$

$$R_{in} = F_R * \frac{(1 - F_U) * M}{E_{fp} * E_{cp}} \tag{Eq. 16}$$

$$R_{out} = R_{fp} + R_{cp} + R_{EoL} \tag{Eq. 17}$$

$$R_{fp} = \left(1 - E_{fp}\right) * C_{fp} * \frac{(1 - F_U) * M}{E_{fp} * E_{cp}} \tag{Eq. 18}$$

$$R_{cp} = \left(1 - E_{cp}\right) * C_{cp} * \frac{(1 - F_U) * M}{E_{cp}} \quad \text{(Eq. 19)}$$

$$R_{EoL} = E_F * E_C * C_R * M \quad \text{(Eq. 20)}$$

PCI estimates the reused components (U) as in Eq. (21):

$$U = M * (F_U - C_U) \quad \text{(Eq. 21)}$$

Regarding the utility (X; Eq. (22)), it is defined as the ratio between available or used FUDC (Functional Usage Duty Cycles) and the expected FUDC ($FUDC_d$), meaning the amount of functional units that the product is designed for, based on the market average.

$$X = \frac{FUDC}{FUDC_d} \quad \text{(Eq. 22)}$$

PCI defines LFI as the fraction of material that follows a linear flow compared to the fully linear systems, which is considered to be the sum of V_{linear} and W_{linear}; defined in Eq. (23). Hence, PCI estimates LFI as shown in Eq. (24). However, if data on the qualities of the recycled materials are available, Eq. (25) can be used to estimate LFI. Finally, PCI is computed following Eq. (26).

$$V_{linear} = W_{linear} = \frac{M}{E_{cp} * E_{fp}} \quad \text{(Eq. 23)}$$

$$LFI = \frac{V + W + \frac{|R|}{2} + \frac{|U|}{2}}{V_{linear} + W_{linear}} \quad \text{(Eq. 24)}$$

$$LFI = \frac{V + W + Q_{in}R_{in} - Q_{out}R_{out}}{V_{linear} + W_{linear}} \quad \text{(Eq. 25)}$$

$$PCI = 1 - \frac{LFI}{X} \quad \text{(Eq. 26)}$$

Moreover, PCI allows modeling of multi-material products by applying the following mass weighting (Eq. (27)):

$$PCI_{total} = \frac{\Sigma_i M_i * PCI_i}{\Sigma_i M_i} \quad \text{(Eq. 27)}$$

Table 1
Preliminary calculation of the MCI for the product approach of the RPC.

	RPC 1	RPC (n)	RPC LAST	CBB
MCI	0.55	0.998	0.998	0.63
LFI	0.50	0.0025	0.0025	0.41
F(x)	0.90	0.90	0.90	0.90
X	**1.00**	**1.00**	**1.00**	**1.00**
L	100	100	100	1
L_{av}	100	100	100	1
L/L_{av}	1	1	1	1
U	1500	1500	1500	15
U_{av}	1500	1500	1500	15
U/U_{av}	1	1	1	1
VIRGIN MATERIAL				
Fr	0%	0%	0%	18.20%
F_U	0.0%	99.49%	99.49%	0%
M	**1.79**	**1.79**	**1.79**	**0.81**
V	**1.79**	**0.01**	**0.01**	**0.66**
UNRECOVERABLE WASTE (W)				
Product's material				
C_R			93.09%	80.00%
C_U	100%	100%		
C_C				
C_E			6.91%	20.00%
W_O	0.00	0.00	0.00	0.00
Material recovery				
E_R	100%	100%	100%	100%
W_C	0.00	0.00	0.00	0.00
Recycled feedstock production				
E_f	96.94%	96.94%	96.94%	94.74%
W_F	0.00	0.00	0.00	0.01
Total				
W	**0.00**	**0.00**	**0.00**	**0.00**

Having in mind that all of the parameters in recycling, production, quality of the recycled material, and the EoL scenario are the same per material type, a simplified formula is used, considering that the RPC is produced from a single plastic material and a single type of cardboard in the case of CBB. During the initial calculation, this approach didn't show any discrepancy in the results.

3. Results

3.1. Mass flow analysis

Fig. S1 in the Supplementary materials shows the MFAs for 6,666,700 fillings of fresh produce with RPCs and CBBs, respectively, for fulfilling the defined function. For the RPC system, the resulting product stock of 100,668 crates; of which 66,667 crates are the initial ones and 34,001 are new ones produced due to damages of the initial crates. To produce this amount of crates, 185.151 tonnes of virgin material is used, and 5.29 tonnes of material are lost, of which 4.93 tonnes are recycled and the rest are incinerated. During the use of the crates, 1.05 tonnes of material are lost due to broken crates, which are assumed to be recycled (with an efficiency of 93%), and the rest (172 tonnes) are used and recycled at the end of their lifetime. Hence, for the whole RPC system, 185.151 tonnes of virgin material are used to produce 100,668 RPCs, 12.8 tonnes are incinerated and 173 tonnes are recycled.

In the case of CBBs, 6,666,700 packages (meaning 5380.027 tonnes of material) are needed for the established function. After their use, 1100 tonnes of boxes are incinerated and the rest are recycled, with an efficiency of 95% [39]. Therefore, the CBB system uses 5380.027 tonnes of material (18.2% of recycled content) and it results in 1076 tonnes of material being incinerated and 4304 tonnes of secondary material being recycled. For the calculation of losses of quality of the recycled material, data from the European Commission [50,51] were used. According to the European Commission recommendations, the quality losses of plastic materials (HDPE and PP) at the point of the substitution is 0.9, and 0.85 for cardboard when the recycling process doesn't consider fiber losses. These parameters were used in the MFA, as well as for the circularity indicators.

3.2. Circularity indicators

3.2.1. System approach vs. individual packaging calculation

During the preliminary analysis of the case studies, accuracy test was conducted of the approaches for the calculation of the MFA and the circularity indicators. The preliminary analysis was conducted by calculating MCI on the product level and system approach. The findings of the product circularity approach calculating the MCI are presented in Table 1.

The results did not show any discrepancy in the case of single-use CBB, however in the case of reusable RPC there is a difference between the circular assessment between the first (RPC1) and all other reused plastic crates (RPC(n)). In the first crate, due to using solely virgin material, and taking into consideration that the reused fraction is zero, the MCI indicator is 0.55, and the indicator increases after the first RPC and equals 0.998. The average MCI for 100 reused RPCs was calculated as 0.993. The system approach is calculated further in the text and presents more realistic and conservative values while using the overall material needed to fulfill the function. In the case of the RPC equals 185,151 kg of plastic material, and 5,380,027 kg of cardboard for CBB.

3.2.2. Calculation of circularity indicators

The whole system has been considered to estimate the circular indicators (MCI and PCI). This means that instead of modeling 1 single box/crate for one lifetime, the circular indicators have been estimated for the 6,666,700 fillings to fulfill the functional unit. Hence, for the two indicators, the total amount of material used (M) was calculated as the amount of material needed to produce all the required RPCs and CBBs (to fulfill the FU) multiplied by their unitary weight (Table 2). To estimate the unrecoverable waste (W_0), the percentage of recycling (C_R) and incineration (C_E) of the crates and cardboard boxes were based on the MFA.

As it is shown in Table 2 both circularity indicators calculate the level of virgin material (V) differently from the MFA. The scope for the calculus of the circularity indicators is the additional material that comes to fulfill the function of the system. It is obvious from the calculations that the virgin material for MFA is the whole portion of the material that comes to serve the functional unit because the whole material that comes in the system has no recyclable content in the case of RPC. The virgin material in the case of the circularity indicators is calculated based on the proportion of material that is additionally added to replace the damaged RPC. Also, the difference in the overall material used derives from the system approach, not the product approach of the calculus. The circularity indicators calculate the portion as a sum of all material needed to fulfill the function. Without the calculation of the material needed with the overall losses from the production system. PCI calculates particular losses in the production system in the overall evaluation of the indicator, thus a lower value of the indicator, but only MFA shows the real input of material in the system under review.

Table 2
Summary of the results from the MFA, and the circularity indicators for RPC and CBB.

	RPC			CBB		
	MFA	MCI	PCI	MFA	MCI	PCI
Circularity	–	**0.85**	**0.83**	–	**0.63**	**0.58**
M	185,151	180,196	180,196	5,380,027	5,380,027	5,380,027
V	185,151	60,862	62,562	4,288,121	4,400,862	4,889,847
W	–	0.00	46.75		27,182	116,376

Calculating the circularity of the systems under review using the system approach, the MCI for the RPC system is 0.85 (Table 3). This low value is due to the non-recycled content in the crate, and in the case of CBB, calculated MCI is 0.63..

The fraction of reused materials was calculated as a ratio between the initial crates and the overall crates used due to damage during usage, resulting in a 66.22% reuse ratio of the system. The efficiency of recycled feedstock production taken from GaBi database equals 96.94% for RFC and 94.74% for CBB. The supply system is closed not allowing losses. The fraction of mass of the products collected for energy recovery is 6.91% and the remaining material is a fraction of the mass collected for recycling.

PCI is also calculated with the system approach (Table 4).

4. Discussion

The main difference between the MCI and PCI is that the latter takes material quality deterioration in consideration. This provides a quality assessment of the material going in and out in the technosphere that provides a better assessment of the linearity of the product system. Also, there is a difference in the calculation of the waste as a linearity indicator, where PCI calculates the unrecoverable waste from 5 different stages. The main difference in the calculation of our case study is waste derived from the product (component) production. PCI calculates 46 kg of waste in the case of RPC and 59 tonnes in the case of CBB, hence the difference in the overall waste, calculated using MCI and PCI. This stage takes into consideration the design phase of the products and losses during production; an important step in evaluating the efficiency of the material used in production. However, this indicator was not easy to identify. The literature does not reveal this parameter because it is case-specific, and data for the process are modeled in GaBi to provide this parameter.

Practical implications of this finding can be expected in the applicability of the circularity indicators based on the complexity of the system under observation. For assessing more complex systems using circularity indicators that consider more stages of the life cycle, due to lack of data, uncertainty, and accuracy of the obtained results might vary. In addition, evaluation of the circularity of the overall supply system can result in improved accuracy than using product-focused circularity assessment.

In the case of RPC, the slight difference in circularity calculated using MCI and PCI is mainly due to the qualitative changes of the material, and the high efficiency of manufacturing RPCs. However, this difference is higher in the case of CBB. Based on the lower quality factor of the material, as well as the less efficient production of components, there is a bigger difference in the calculated circularity of the systems with a discrepancy of 0.05 between the two circularity indicators.

The involvement of the quality degradation factors in the circularity assessment can create an even bigger discrepancy in the processes where metal products (with a quality factor equal to one, as recommended by Product Environmental Footprint (PEF) Default Parameters [50]) are compared with products made from a material having a lower quality factor. Also, MCI cannot make a

Table 3
MCI calculations based on a system approach for RPC and CBB.

	RPC	CBB
MCI	0.85	0.63
LFI	0.17	0.41
F(x)	0.90	0.90
X	**1.00**	**1.00**
L	100	1.00
L_{av}	100	1.00
L/L_{av}	1.00	1.00
U	1500	15
U_{av}	1500	15
U/U_{av}	1.00	1.00
VIRGIN MATERIAL		
Fr	0.00%	18.20%
Fs	0.00%	0.00%
F_U	66.22%	0.00%
M	**180,196**	**5,380,027**
V	**60,862**	**4,400,862**
UNRECOVERABLE WASTE (W)		
Product's material		
C_R	93.09%	80.00%
C_U	0.00%	0.00%
C_C	0.00%	0.00%
C_E	6.91%	20.00%
W_0	0.00	0.00
Material recovery		
E_R	100%	100%
Wc	0.00	0.00
Recycled feedstock production		
E_f	96.94%	94.74%
W_F	*0*	*54,364*
Total		
W	**0.00**	**27,182**

Table 4
PCI calculations based on a system approach for RPC and CBB.

	CPR	CBB
PCI	0.83	0.58
LFI	0.17	0.42
X	1	1
FUDC	100	100
FUDCd	100	100
Qin	90%	85%
Qout	90%	85%
VIRGIN MATERIAL		
F_R -fraction of recycled material content	0.00	18.20%
F_U -fraction of reused components	66.22%	0
Ecp	97.28%	90%
Efp	100%	100%
M	**180,196**	**5,380,027**
V	**62,562**	**4,889,847**
UNRECOVERABLE WASTE (W)		
Waste from feedstock production(Wfp)		
Cfp	0.00%	0.00%
Wfp	0.00	0.00
Waste from component production (Wcp)		
Ccp	97.25%	90%
Wcp	46.75	59,778
Waste during material separation (Wms)		
C_R	0.00	0.20
Ems	100%	100%
Wms	0.00	0.00
Waste generated during recycled feedstock production (WR_{FP})		
Erfp	96.94%	94.74%
Wrfp	0.00	56,598
Post-use waste (W_U)		
C_U	1.00	0.80
W_U	0.00	0.00
TOTAL		
W	**46.75**	**116,376**
RECYCLED MATERIAL EXCHANGED OUTSIDE (R)		
Entering the system for product manufacture (Rin)		
Rin	**0**	**1,087,961**
Leaving the system for product manufacture (Rout)		
Rfp	0.00	0.00
Rcp	0.00	0.00
REoL	0.00	1,019,407.50
Rout	**0.00**	**1,019,407.50**
REUSED COMPONENTS		
U		**0**

difference between the system recycling technologies. Based on the PEF method, there is a different quality factor between different recycling technologies. MCI does not make a difference between the paper-based products going through the recycling process that consider fibre losses or not, as well as PET material going through solid state polycondensation process or mechanical recycling.

The comparison between the circularity indicators with the diagram of a material cycle, provides a conclusion that both indicators cover all aspects of the material stock in the calculation of the circularity. PCI takes more detailed steps in the calculation of the circularity of the product stock than MCI. The circular strategy of reusing the product and components is covered well by both indicators. However, R_3 repair, R_4 refurbish, R_5 remanufacture and R_5 repurpose are not well presented and need additional calculations to assess the impacts of these circular strategies on the overall circularity index. This approximation can result in non-differentiation between more circular and less circular products concerning the "tightness" of the circular aspects of the material. This conclusion was highlighted in the previous scientific literature [28,32]. Also, this aspect is of the highest importance to product designers especially due to the latest changes in European legislation that require more durable products, with a possibility of easy repair, remanufacture, reusing and repurposing of the products and components and avoiding product obsolescence [52].

In addition, both circularity indicators cannot take into consideration the resource stock in their calculation methods.

Different valuations of the circular hierarchy as well as the involvement of all three stocks of material are needed for an overall assessment of the circularity of the materials in the technosphere. This approach in the scientific literature is non-existent.

5. Conclusions

Two circularity indicators have been calculated for two different packaging systems for fresh foods in Spain, namely a reusable plastic crate and a single-use cardboard box. Two known circularity indicators, MCI and PCI, are calculated based on a predefined concept of two systems for packaging for the distribution of fruits and vegetables. MFA is used as a control mechanism for the amount calculated to serve the system related to the overall material and the amount of virgin material in the system. Conclusions based on the performed calculations show that only MFA presents the real amount of the virgin material used and the overall material used by the systems.

Both indicators reveal that the reusable system using RPC is more circular than the system using CBB. This difference between the circularity evaluations is greater when using the PCI because this indicator covers more stages of the life cycle, takes into account the efficiency of more stages than MCI, and calculates the unrecoverable waste more comprehensively. However, there are difficulties in providing the data for the individual calculation of more lifecycle stages of the supply chain system. The practical implementation of the indicators shows that in a circular assessment of the system when segregated detailed data of all lifecycle stages of the system are non-existent, MCI is easier to use. Also, only MFA offers a clear picture of the overall material and the virgin material used by the system under observation.

The study showed that both indicators cover the circularity of the material stock by applying the material circulation concept and the appropriate circularity strategies. Related to the product stock, PCI can be seen as an improved version of the MCI providing more insight into the reusability of the products and components. However, PCI does not provide a significant improvement in presenting the "tightness" of the material circulation, considering the circular hierarchy of the circular strategies. Moreover, both indicators fail in the involvement of the parameters related to the resource stock in the circularity assessment. The authors believe that this might provide additional aspects of the circularity of the materials, as this will be the topic of their further research.

Data availability statement

All data used for development of the manuscript are stated in the main body of the text or in the Supplementary materials section.

CRediT authorship contribution statement

Ilija Sazdovski: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Laura Batlle-Bayer:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alba Bala:** Writing – review & editing. **Maria Margallo:** Writing – review & editing. **Sahar Azarkamand:** Writing – review & editing, Writing – original draft. **Ruben Aldaco:** Writing – review & editing. **Pere Fullana-i-Palmer:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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Appendix A. Supplementary data

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References

[1] J. Rockström, W. Steffen, K. Noone, Å. Persson, F.S. Chapin, E.F. Lambin, T.M. Lenton, M. Scheffer, C. Folke, H.J. Schellnhuber, B. Nykvist, C.A. de Wit, T. Huges, S. van der Leeuw, H. Rodhe, S. Sörlin, P.K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R.W. Corell, V.J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, J.A. Foley, A safe operating space for humanity, Nature (2009) 472–475, https://doi.org/10.1038/461472a.

[2] P. Morseletto, Sometimes linear, sometimes circular: States of the economy and transitions to the future, J. Clean. Prod. 390 (2023) 136138, https://doi.org/10.1016/j.jclepro.2023.136138.
[3] J. Kirchherr, D. Reike, M. Hekkert, Conceptualizing the circular economy: an analysis of 114 definitions, Resour. Conserv. Recycl. 127 (2017) 221–232, https://doi.org/10.1016/j.resconrec.2017.09.005.
[4] M. Saidani, B. Yannou, Y. Leroy, F. Cluzel, A. Kendall, A taxonomy of circular economy indicators, J. Clean. Prod. 207 (2019) 542–559, https://doi.org/10.1016/j.jclepro.2018.10.014.
[5] J. Kirchherr, Bullshit in the sustainability and transitions literature: a Provocation, Circ. Econ. Sustain. (2022), https://doi.org/10.1007/s43615-022-00175-9.
[6] E.M.F. Emf. Towards the Circular Economy. Economic and Business Rationale for an Accelerated Transition, 2013. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf.
[7] W.J. Rankin, Sustainability, Elsevier Ltd., 2014, https://doi.org/10.1016/B978-0-08-096988-6.00033-X.
[8] J. Potting, M. Hekkert, E. Worrell, A. Hanemaaijer, Circular Economy: Measuring innovation in the product chain - Policy report (2017). https://www.pbl.nl/sites/default/files/downloads/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf.
[9] M. Farooque, A. Zhang, M. Thürer, T. Qu, D. Huisingh, Circular supply chain management: a definition and structured literature review, J. Clean. Prod. 228 (2019) 882–900, https://doi.org/10.1016/j.jclepro.2019.04.303.
[10] S. Poponi, G. Arcese, F. Pacchera, O. Martucci, Evaluating the transition to the circular economy in the agri-food sector: selection of indicators, Resour. Conserv. Recycl. 176 (2022) 105916, https://doi.org/10.1016/j.resconrec.2021.105916.
[11] S. Poponi, G. Arcese, A. Ruggieri, F. Pacchera, Value optimisation for the agri-food sector: a circular economy approach, Bus. Strat. Environ. (2022), https://doi.org/10.1002/bse.3274.
[12] S. Lahane, R. Kant, R. Shankar, Circular supply chain management: a state-of-art review and future opportunities, J. Clean. Prod. 258 (2020) 120859, https://doi.org/10.1016/j.jclepro.2020.120859.
[13] K. Govindan, H. Soleimani, D. Kannan, Reverse logistics and closed-loop supply chain: a comprehensive review to explore the future, Eur. J. Oper. Res. 240 (2015) 603–626, https://doi.org/10.1016/j.ejor.2014.07.012.
[14] D. Vegter, J. van Hillegersberg, M. Olthaar, Performance measurement systems for circular supply chain management: Current state of development, Sustain. Times 13 (2021), https://doi.org/10.3390/su132112082.
[15] D. Vegter, J. van Hillegersberg, M. Olthaar, Supply chains in circular business models: processes and performance objectives, Resour. Conserv. Recycl. 162 (2020) 105046, https://doi.org/10.1016/j.resconrec.2020.105046.
[16] D. Vegter, J. van Hillegersberg, M. Olthaar, Performance measurement system for circular supply chain management, Sustain. Prod. Consum. 36 (2023) 171–183, https://doi.org/10.1016/j.spc.2023.01.003.
[17] R. Alamelu, M. Jayanthi, S. Dinesh, R. Nalini, N. Shobhana, R. Amudha, Sustainable supply chain and circular economy ingenuities in small manufacturing firms- a stimulus for sustainable development, Mater. Today Proc. (2023), https://doi.org/10.1016/j.matpr.2023.03.236.
[18] L. Stumpf, J.P. Schöggl, R.J. Baumgartner, Circular plastics packaging – Prioritizing resources and capabilities along the supply chain, Technol. Forecast. Soc. Change 188 (2023), https://doi.org/10.1016/j.techfore.2022.122261.
[19] M.C. Carissimi, A. Creazza, M. Fontanella Pisa, A. Urbinati, Circular economy practices enabling circular supply chains: an empirical analysis of 100 SMEs in Italy, Resour. Conserv. Recycl. 198 (2023) 107126, https://doi.org/10.1016/j.resconrec.2023.107126.
[20] E. Sánchez-García, J. Martínez-Falcó, B. Marco-Lajara, L.A. Millán-Tudela, Looking into literature in the field of circular supply chain and the subtopic from a customers' perspective: a bibliometric approach, J. Clean. Prod. 417 (2023), https://doi.org/10.1016/j.jclepro.2023.137900.
[21] M.P. van Loon, W.J. Vonk, R. Hijbeek, M.K. van Ittersum, H.F.M. ten Berge, Circularity indicators and their relation with nutrient use efficiency in agriculture and food systems, Agric. Syst. 207 (2023) 103610, https://doi.org/10.1016/j.agsy.2023.103610.
[22] S. Longo, M. Cellura, L.Q. Luu, T.Q. Nguyen, F. Guarino, Circular economy and life cycle thinking applied to the biomass supply chain: a review, Renew. Energy (2023), https://doi.org/10.1016/j.renene.2023.119598.
[23] J. Brändström, O. Eriksson, How circular is a value chain? Proposing a Material Efficiency Metric to evaluate business models, J. Clean. Prod. 342 (2022), https://doi.org/10.1016/j.jclepro.2022.130973.
[24] G. Lonca, R. Muggéo, H. Imbeault-Tétreault, S. Bernard, M. Margni, Does material circularity rhyme with environmental efficiency? Case studies on used tires, J. Clean. Prod. 183 (2018) 424–435, https://doi.org/10.1016/j.jclepro.2018.02.108.
[25] I. Sazdovski, A. Bala, P. Fullana-i-Palmer, Linking LCA literature with circular economy value creation: a review on beverage packaging, Sci. Total Environ. 771 (2021) 145322, https://doi.org/10.1016/j.scitotenv.2021.145322.
[26] M. Linder, S. Sarasini, P. van Loon, A metric for Quantifying product-level circularity, J. Ind. Ecol. 21 (2017) 545–558, https://doi.org/10.1111/jiec.12552.
[27] M. Linder, R.H.W. Boyer, L. Dahllöf, E. Vanacore, A. Hunka, Product-level inherent circularity and its relationship to environmental impact, J. Clean. Prod. 260 (2020), https://doi.org/10.1016/j.jclepro.2020.121096.
[28] J. Brändström, M. Saidani, Comparison between circularity metrics and LCA: a case study on circular economy strategies, J. Clean. Prod. 371 (2022), https://doi.org/10.1016/j.jclepro.2022.133537.
[29] I. Sazdovski, D. Bojovic, L. Batlle-Bayer, R. Aldaco, M. Margallo, P. Fullana-i-Palmer, Circular economy of packaging and Relativity of time in packaging life cycle, Resour. Conserv. Recycl. 184 (2022), https://doi.org/10.1016/j.resconrec.2022.106393.
[30] E. Bracquené, W. Dewulf, J.R. Duflou, Measuring the performance of more circular complex product supply chains, Resour. Conserv. Recycl. 154 (2020) 104608, https://doi.org/10.1016/j.resconrec.2019.104608.
[31] E. Glogic, G. Sonnemann, S.B. Young, Environmental trade-offs of downcycling in circular economy: Combining life cycle assessment and material circularity indicator to inform circularity strategies for alkaline batteries, Sustain. Times 13 (2021) 1–12, https://doi.org/10.3390/su13031040.
[32] G. Lonca, P. Lesage, G. Majeau-Bettez, S. Bernard, M. Margni, Assessing scaling effects of circular economy strategies: a case study on plastic bottle closed-loop recycling in the USA PET market, Resour. Conserv. Recycl. 162 (2020), https://doi.org/10.1016/j.resconrec.2020.105013.
[33] K. Mantalovas, G. Di Mino, Integrating circularity in the sustainability assessment of asphalt mixtures, Sustain. Times 12 (2020) 9–12, https://doi.org/10.3390/su12020594.
[34] V.G. Muñoz, L.M. Muneta, R. Carrasco-Gallego, J. de J. Marquez, D. Hidalgo-Carvajal, Evaluation of the circularity of recycled pla filaments for 3D printers, Appl. Sci. 10 (2020) 1–12, https://doi.org/10.3390/app10248967.
[35] E.M.F. Emf. Circularity Indicators, An approach to measuring circularity, 2015. Cowes, UK, https://www.ellenmacarthurfoundation.org/assets/downloads/TCE_Ellen-MacArthur-Foundation-9-Dec-2015.pdf.
[36] E.M.F. Emf, Circularity indicators. An approach to measuring circularity, Methodology (2019) 1–64. https://emf.thirdlight.com/link/3jtevhlkbukz-9of4s4/@/preview/1?o.
[37] R. Tashkeel, G.P. Rajarathnam, W. Wan, B. Soltani, A. Abbas, Cost-normalized circular economy indicator and its application to post-consumer plastic packaging waste, Polymers 13 (2021) 1–28, https://doi.org/10.3390/polym13203456.
[38] V. Šuškevičė, J. Kruopienė, Improvement of packaging circularity through the application of reusable beverage cup reuse models at outdoor festivals and events, Sustain. Times 13 (2021) 1–18, https://doi.org/10.3390/su13010247.
[39] R. Abejón, A. Bala, I. Vázquez-Rowe, R. Aldaco, P. Fullana-i-Palmer, When plastic packaging should be preferred: life cycle analysis of packages for fruit and vegetable distribution in the Spanish peninsular market, Resour. Conserv. Recycl. 155 (2020), https://doi.org/10.1016/j.resconrec.2019.104666.
[40] R. Accorsi, A. Cascini, S. Cholette, R. Manzini, C. Mora, Economic and environmental assessment of reusable plastic containers : a food catering supply chain case study, Int. J. Prod. Econ. 152 (2014) 88–101, https://doi.org/10.1016/j.ijpe.2013.12.014.
[41] S. Albrecht, T. Beck, L. Barthel, M. Fisher, Final report: the sustainability of packaging systems for fruit and vegetable transport in Europe based on Life-Cycle-Analysis, Update 2009 (2009). https://publica.fraunhofer.de/handle/publica/294710.
[42] S. Koskela, H. Dahlbo, J. Judl, M.R. Korhonen, M. Niininen, Reusable plastic crate or recyclable cardboard box? A comparison of two delivery systems, J. Clean. Prod. 69 (2014) 83–90, https://doi.org/10.1016/j.jclepro.2014.01.045.

[43] M. Levi, S. Cortesi, C. Vezzoli, G. Salvia, A Comparative life cycle assessment of Disposable and reusable packaging for the distribution of Italian fruit and vegetables, Packag. Technol. Sci. 24 (2011) 387–400, https://doi.org/10.1002/pts.946.

[44] C. Tua, L. Biganzoli, M. Grosso, L. Rigamonti, Life cycle assessment of reusable plastic crates (RPCs), Resources 8 (2019), https://doi.org/10.3390/resources8020110.

[45] A. Bala, P. Fullana-i-Palmer, Análisis comparado de diferentes opciones de distribución de frutas y hortalizas en España mediante el Análisis de Ciclo de Vida (2017). https://docplayer.es/89503778-Catedra-unesco-de-ciclo-de-vida-y-cambio-climatico.html.

[46] Stepa, Types of paper for corrugated cardboard production,. (n.d.). https://www.stepa.cz/en/technicka-data/types-of-paper-for-corrugated-cardboard-production/(accessed March 8, 2023)..

[47] P.H. Brunner, H. Rechberger. Handbook of Material Flow Analysis, Second, Taylor & Francis Group, LLC, 2017. https://books.google.es/books?hl=en&lr=&id=fGYNDgAAQBAJ&oi=fnd&pg=PP1&dq=Material+flow+analysis&ots=fi2x_F3xT0&sig=cyT-AtqOEHOlCNshdNUe8zGFAZ4#v=onepage&q=Material-flow-analysis&f=false.

[48] P.H. Brunner, H. Rechberger, Practical Handbook of Material Flow Analysis, LEWIS PUBLISHERS, 2003. https://www.taylorfrancis.com/books/mono/10.1201/9780203507209/practical-handbook-material-flow-analysis-paul-brunner-helmut-rechberger?context=ubx&refId=3d0e4b82-3419-4cb2-9bd3-d66f6e4aea14.

[49] Sphera, LCA for Experts (GaBi), 6 (n.d.). https://sphera.com/life-cycle-assessment-lca-software/..

[50] European Commission, COMMISSION RECOMMENDATION of 16.12.2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. https://environment.ec.europa.eu/publications/recommendation-use-environmental-footprint-methods_en, 2021.

[51] European Commission, COMMISSION RECOMMENDATION of 16.12.2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations - Annex I Product Environmental Footprint Method. https://environment.ec.europa.eu/publications/recommendation-use-environmental-footprint-methods_en, 2021.

[52] P. Hirsch, C. Schempp, Categorisation system for the circular economy, Eur. Community 20 (2020), https://doi.org/10.2777/172128.