Journal of Cleaner Production 342 (2022) 130973

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

How circular is a value chain? Proposing a Material Efficiency Metric to evaluate business models

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ARTICLE INFO

Handling Editor: Mingzhou Jin

Keywords:
Circular economy
Circularity metric
Circular business model
Material flow visualization
System analysis
Value chain

ABSTRACT

The concept of Circular Economy is a principle aiming to improve sustainable development by reducing resource use and impact on ecological systems. An increasing number of companies are applying this theory on design strategies and business models in order to close, slow and narrow material loops. To highlight the importance, guide practitioners, and evaluate the progress of circular economy, a high number of circularity metrics (C-metrics) have been developed. However, little attention has been given to creating a connection between quantification of circularity and environmental performance. Existing metrics also do not highlight the interplay between micro (product), meso (industrial symbiosis), and macro (regional) level circularity. Moreover, existing metrics do not capture all material loops and do not adopt a value chain perspective on material flows.

To improve the connection between C-metrics and environmental performance, a framework connecting circular economy strategies and material flows was developed. Based on this framework, a material flow-based C-metric was designed aimed at converting mechanisms of closing, narrowing and slowing material loops into a single-point value. To evaluate its feasibility, the metric was tested on three circular business models that represent all three mechanisms in a value chain perspective. The results showed that the metric is feasible in more situations than existing metrics and that the circularity value is highly dependent on assumptions. In future studies, the metric should be tested and compared to Life Cycle Assessments on multiple system levels to ensure that it generates valid results. Furthermore, user input assumptions should be standardized to ensure metric reliability.

1. Introduction

In the last decade the circular economy (CE) has gained much attention from many actors including academia, public authorities and firms. It has become a promising approach to promote sustainable development by turning the linear extract-produce-use-discard approach into circular flows of resources (Korhonen et al., 2018). The CE paradigm consists of a multitude of solutions that solve environmental issues by reducing resource dependency and preventing production of waste and emissions of compounds that damage ecological systems (Alhawari et al., 2021). In a well-functioning CE, production and consumption patterns are changed in a way that economic growth is decoupled from input and output of resources (Kjaer et al., 2019).

Common strategies found in CE literature to realize such a system include smarter product use (refuse, rethink, reduce), increase product lifetime (reuse, quality, repair), and those that aim to circulate materials at end of life EOL (recycling, cascading) (Kirchherr et al., 2017). These strategies can be realized by adopting new types of business models and design strategies, which also allow materials to flow in either technical or biological resource loops (Bocken et al., 2016). Business models often linked to CE are product/service-system (PSS), which is an idea of combining resources and services to fulfill customer needs (Kjaer et al., 2019). PSS includes sharing, renting and leasing activities, which adopted correctly can be used to increase product lifetime and reduce the demand for products (Kjaer et al., 2019). A successful adoption of circular design principles and business models should close (increase circulation), slow (increase lifetime) and narrow (reduce product consumption and increase production efficiency) material loops (Bocken

Abbreviations: CE, Circular Economy; MEM, Material Efficiency Metric; MCI, Material Circularity Indicator; PCI, Product Circularity Indicator; C-metric, Circularity metric.

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https://doi.org/10.1016/j.jclepro.2022.130973
Received 10 June 2021; Received in revised form 13 January 2022; Accepted 12 February 2022
Available online 16 February 2022

et al., 2016).

Adopting circular design strategies and business models does not, however, automatically reduce environmental impact. Until now, no author has concluded that C-metrics can be used alone to choose between potential CE business models (Rigamonti and Mancini, 2021). Due to their narrow scope, trade-offs between different environmental dimensions or CE rebound effects can occur (Rigamonti and Mancini, 2021). They can also be complicated to adopt as current legislation is adapted for linear material flows, they may require high investment costs and there are few economic incentives (Govindan and Hasanagic, 2018). In public procurement, for instance, potential product providers are evaluated based on the initial purchase cost of their products, while cost on a life-cycle basis would benefit circular solutions (Sönnichsen and Clement, 2020).

To solve these problems, researchers emphasize the importance of using other indicators and to measure, monitor, benchmark and quantify the state of the CE (Kravchenko et al., 2019). For this purpose, multiple circularity metrics (C-metrics) have been developed to evaluate CE performance with different scopes (Moraga et al., 2019), focusing on different system levels (Saidani et al., 2019). At present, numerous C-metrics have been developed on all system levels, but there is a lack of consensus on what they should measure and about the connection between (micro/meso/macro) system levels (Harris et al., 2020). Relatively few of the existing metrics have been scientifically evaluated and compared with environmental performance (Harris et al., 2020). According to a restricted number of studies, those that have been tested generate results that differ from LCA results (Lonca et al., 2018). This can partly be derived from their scope being too narrow, for instance, few micro-level C-metrics consider aspects that affect the slowness of material loops (Kristensen and Mosgaard, 2020). Another missing aspect is the value chain perspective. Micro-level C-metrics are designed to assess product or company circularity, but do not consider the interplay between multiple business models throughout complete value chains. To capture sustainability aspects of CE measures, all lifecycle phases should be scrutinized (Hallstedt, 2017). Consequently, consumption patterns and longevity aspects have been marginally scrutinized (Merli et al., 2018), which makes comparison of product-oriented and service-oriented business models difficult (Linder et al., 2017).

To ensure a connection between Material Efficiency (ME) solutions and environmental sustainability, this paper adopts the position that the concept of circularity should assess both material input and material output (MIO) to evaluate how closed, slow and narrow material loops are, using a value chain perspective on material flows. Moreover, the purpose of C-metrics should be to quantify the performance of ME solutions using the same approach regardless of system level. Thus, the aim of this work is to develop a material-based C-metric that can be used as guidance for any practitioner of circular economy including designers, procurement departments, product developers and politicians. For that purpose, the following research questions are investigated:

1. How can a quantitative metric be designed to close the gap between ME solutions and sustainable development? (RQ1)
2. How feasible, reliable and valid can the metric be? (RQ2)

Section 2 contains a brief background on existing interpretations of the concept of circularity and their associated C-metrics. Section 3 describes the research methodology used in the metric development and the case study that was performed to test the metric feasibility. To describe the connection between material flows and business models, a framework that categorizes ME solutions according to how they affect material input and output is presented in section 4.1. This framework is used to answer RQ1 in section 4.2, where a new material flow–focused C-metric that can be used on all system levels is developed, aiming to capture closeness, slowness and narrowness of material loops by using a value chain perspective on material flows. The case study results are presented in section 4.3, where a tool with the developed C-metric is applied on various circular business models. In section 5, the case study results are discussed in order to answer RQ2 and in section 6 the conclusions of the contribution of this research to the field are presented.

2. Approaches to measure circularity

The concept of circularity currently has many interpretations that differ depending on system level. C-metrics sometimes measure quantitative data such as material weight or costs, sometimes qualitative attributes such as design approaches, or in some cases a combination of these (Moraga et al., 2019). On macro level (global or regional), circularity is often referred to as the ratio of cycled material at EOL, or circulation rate (Haigh et al., 2021). The system level below macro is called meso and mostly targets eco-industrial parks and industrial symbiosis (Linder et al., 2017). Metrics on this system level commonly measure recycling rates, reuse rates and maintenance aspects and generate circularity results based on multiple dimensions (Saidani et al., 2019). Existing research on micro and nano level (product or company) C-metrics shows that many metrics on this system level are either focused on economic aspects (Kristensen and Mosgaard, 2020), or that they are heavily focused on resource efficiency (de Oliveira et al., 2021). Resource efficiency C-metrics tend to focus on circulation of material, or closeness of loops, such as the ratio of circulated input (Linder et al., 2017) or material flows at EOL (Maio et al., 2015).

There are, however, those that also consider longevity aspects in the use phase (Franklin-Johnson et al., 2016). The most commonly cited metric, Material Circularity Indicator (MCI), developed by the Ellen MacArthur Foundation, is a quantitative C-metric that considers both circulation and longevity aspects by calculating the linearity of material flows over time (Goddin et al., 2019). A similar metric, Product Circularity Indictor (PCI), can be used to assess circularity on product level based on MIO throughout the product life cycle (Bracquené et al., 2020). Both MCI and PCI generate a circularity value by calculating a Linear Flow Index (LFI) and a utility factor (X) (Bracquené et al., 2020). The LFI is a factor that measures the fraction of material flowing in a linear fashion compared to a fully linear system, while the utility factor is used to calculate the expected lifetime and use rate compared to a fully linear system (Bracquené et al., 2020). The most prominent difference between these metrics is that PCI captures material losses in multiple production stages, while manufacturing production losses are summarized in one value in MCI. As both MCI and PCI are quantitative material flow-based C-metrics that can capture both closeness and slowness of loops, their design was used as inspiration for the C-metric development as described in section 3.2.

3. Research methodology

To develop a material flow-based C-metric that captures all material loops better than existing C-metrics, a framework containing existing business models and design strategies was made. Using this framework, important aspects that affect material flows can be captured. For the purpose of mapping important business models, a literature study was conducted and its process is described in Appendix A.

3.1. Strategy framework for material flows

The framework includes a concept called *circularity strategies,* which conceptualizes how different business models and design strategies reduce Material Input and Output (MIO). It also contains ME solutions, which is a more detailed description of how MIO is reduced. All these concepts can be expressed in terms of the mechanisms of narrowing, slowing and closing loops as illustrated in Fig. 1 (Bocken et al., 2016). The connection between circularity strategies, ME solutions and business models in particular was derived from Bocken et al. (2016) and a more recent review of CE business models by Lüdeke-Freund et al. (2019). This process was a means to simplify the development of a

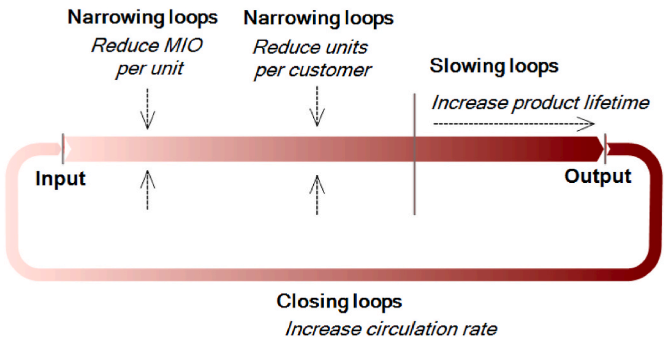

Fig. 1. Visualization of material flow mechanisms and MIO-reduction strategies.

single-point metric, which is suitable when guiding decision makers (Saidani et al., 2019).

The goal of applying the mechanisms on a given value chain could be expressed as maximizing the reduction of virgin Material Input and Output (MIO) the value chain. Thus, the scope of the framework was limited to not include energy and water use or toxicity rates. Focusing on MIO was a means to simplify calculations in the development stage. To develop a metric based on this quantification, four MIO reduction strategies were identified as illustrated in Fig. 1. In section 4.1, a more thorough description of the framework is provided.

3.2. Metric derivation and evaluation

To develop a metric that can be used regardless of system level and that captures closeness, slowness and narrowness of material flows, inspiration was taken from MCI and PCI. Similar to MCI and PCI, the perspective that a circular system should be compared to a linear system is adopted in this paper. Moreover, some components of calculating waste creation are directly taken from MCI. However, as both MCI and PCI focus on circularity rates on product level, they are not adopted for assessing the number of consumed products in a defined system. They also do not automatically consider additional material use such as packaging, which also affects the narrowness of loops and validity. To address these issues, inspiration was taken from environmental impact assessment tools such as LCA, Material Flow Analysis (MFA) and Material Input Per Service (Cahyandito, 2009). In these tools, a life cycle approach on material flows is used and the concept of function is used as a basis for comparing the efficiency of different solutions. They adopt the concept of function to ensure comparability between different solutions, which for instance is important when comparing product-focused business models with PSS.

To capture all material flows from different business models, a value chain perspective was adopted including production, retail, consumption, use phase and End of Life (EOL). The system boundary was limited to exclude extraction processes, as it requires knowledge about extraction efficiencies that highly depend on material type and require extensive data collection. The chosen unit for assessment of circularity was weight, which has the advantage of indicating resource use. Implications for the effects of all the assumptions and delimitations are further discussed in section 5.2.

To evaluate the performance of the developed metric, three desirable qualities were assessed: validity, reliability and feasibility (Linder et al., 2017). Validity concerns whether the metric reliably measures what it intends to measure (Bannigan and Watson, 2009). Reliability includes consistency and robustness of the results, meaning that a metric with high reliability delivers similar results under separate conditions (Bannigan and Watson, 2009). Feasibility refers to its usefulness (perceived economic value) and practicality (perceived cost and time to learn) (Saidani, 2019). The feasibility was tested in the case studies and its potential feasibility, reliability and validity are discussed in section 5.1.

3.3. CASE studies

The case studies were performed on three companies that have adopted different types of circular business models. They were chosen to demonstrate the feasibility in a variety of situations, including varying product types, business models and circularity mechanisms. The companies represent different sectors as their typical products include both furniture and electronics. They also represent multiple business models including PSS, sharing services and reuse, and represent all three circularity mechanisms (closing, slowing and narrowing loops). In the case studies, a value chain perspective was adopted, meaning that circularity was evaluated by calculating MIO from production to EOL. That way, a business model targeting retail potentially could be compared to a design strategy or a business model targeting production.

To calculate the MEM result, quantitative data from one company-specific product was collected in online interviews with company representatives with deep product knowledge. Two types of data were collected from the participants: quantitative data to evaluate circularity and qualitative data to understand the participants' perception of the metric. The quantitative information included product lifetime, product mass, amounts of production waste and use rate, which was also partly collected from product-specific data sheets containing the companies' product data. This data was used to calculate the MIO of the companies for a given functional unit. MEM also requires assumptions about a linear scenario (see section 4.2), for which assumptions were made based on the participants' knowledge about industry average data. To calculate MEM, the linear case was defined as follows:

- Unit demand: A high number of products are demanded, which can be calculated based on number of products consumed on average per person.
- Product lifetime: The assessed product has a short average lifetime, which can be calculated based on industry-average lifetime.
- Circulation rate: 0% recycled (or reused) material in the production and at EOL when producing and discarding a specified product.
- MIO per product: Industry-average weight of required material input and output to produce a specified product.

Data collection and metric assessment were made in less than 2 h including performing interviews, making product data assumptions and data sheet screening. Complete tables of input assumptions and underlying assumptions for the material flow visualizations are presented in Appendix B.

The first company, Varubolaget AB, is a small company with six employees that collects used furniture, refurbishes them and sells them to other companies (Varubolaget, 2022). The company works as a link between organizations that sell used products with high quality, but have no buyer that can solve the required logistics to acquire the products. This extension of product lifetime is an example of slowing loops, which the C-metric should be able to assess. Two participants working with sales and project management were interviewed, as they have profound product knowledge. The product with largest volumes and most sales by Varubolaget AB is a writing desk, which therefore was chosen for evaluation with MEM.

The second case study was made on Brighteco AB, a PSS company with five employees that provides its customers with lighting using a long-term subscription model (Brighteco, 2022). Common customers are schools, where LED TV monitors mostly produced from recycled and reused materials are installed instead of regular LED fixtures. The lifetime of the monitors is also longer than the average LED fixture. Thus, it was possible to test the metric's ability to assess both closeness and slowness of material loops. The interviews were performed with the CEO and an R&D engineer, who both have deep product knowledge and understanding of product material flows. For the case study, a regular use of LED fixtures during 45 years in a classroom suitable for 24 students was compared to the required MIO when using Brighteco's service.

The third company, Jobmeal AB, is also a PSS company, with 271 employees in different locations in Sweden (Jobmeal, 2022). The company provides its customers with coffee machines using a service that can be regarded as a sharing service. The coffee machines can provide coffee to more people than regular coffee makers, which makes it possible for Jobmeal to reduce the total material demand per customer over time. The coffee machines are also made of recyclable materials and can be used with higher intensity than regular coffee makers. This case is thus an example of closing, slowing and narrowing loops. Interviews were performed with one HR manager and one service technician, who both have long experience in the company and knowledge about their products. The metric evaluation was made on an average-sized coffee machine by comparing its resulting MIO with that from the use of regular coffee makers.

For the purpose of testing the metric and visualizing the results, the metric was incorporated in a mathematical tool. Moreover, a Sankey chart material flow visualization was made to illustrate material input and output for all linear and circular scenarios. For this purpose, the software e!Sankey was used (ifu Hamburg GmbH, 2020).

4. Results

4.1. Strategy framework

In Table 1, the connection between circularity strategies, ME solutions and business model examples is presented. Additionally, some examples of relevant value chain actors are listed.

The first strategy, reducing units per customer, includes business models and design methods that aim to reduce the demand for units, which can be described either as narrowing loops or slowing loops (Konietzko et al., 2020). This is relevant in the consumption phase, where a sufficiency business model can be applied. It includes solutions that seek to reduce (unnecessary) consumption and production rates by reducing unit and function demand. Reduced number of units per customer can be also accomplished by improving the function of products, either by increasing product functionality or use rate. Smartphones are an example of where one product supplies multiple functions and where one product can replace multiple products. Additionally, unit demand reduction can be accomplished through sharing services, where multiple people use the same product instead of owning their own, often exemplified by car sharing services (Bocken et al., 2014).

The second strategy is to increase product lifetime, which increases the time it takes for a product to reach EOL. Bocken et al. (2016) expressed this as slowing the material loops. One approach to accomplish this is to increase the utilization period of products through improved product quality. Another is to extend product use by applying upgrading, repairing and repurposing solutions, which delays the product from reaching EOL. For the latter measure, modularity is often described as an important design strategy.

The third strategy, increased circulation rate or closing loops, should be applied if the quality of a product is not sufficient for reusing without remanufacturing (Bocken et al., 2016). Closing loops can refer to materials flowing from either EOL or manufacturing processes to another manufacturing process. Industrial symbiosis is an example of where both materials and other resources flow from one manufacturing process to another (Konietzko et al., 2020).

The fourth strategy, reducing MIO per unit, includes business models that increase production efficiency in terms of resource input and output per product. These are mainly relevant in the design and production phases, where the design phase determines the prerequisites for reducing material demand. Two models that reduce unnecessary extraction are lean production and production on demand.

4.2. Metric development

To capture the circularity strategies in Table 1, the components presented in Fig. 2 are included in MEM. The MEM result is calculated by comparing the total virgin Material Input and Output (MIO) required to support a defined function in a linear case (MIO_{LIN}) and a circular case (MIO_{CIR}). The ratio between the two cases is then used to identify a single-point circularity number, where the result ranges between 0% and 100% according to Equation (1). Instructions for how the metric is best used are listed in Appendix A.

$$MEM = 100^* \left(1 - \frac{MIO_{CIR}}{MIO_{LIN}}\right) \tag{1}$$

To exemplify, if MEM were applied on a circular value chain and the result were 50%, it would mean that the total virgin material input and waste output on average are reduced by 50% compared to a linear value chain. A 100% circular value is achieved when no virgin materials are required in a defined system and no waste is created. The total MIO in either a linear or circular value chain is estimated using Equation (2):

$$MIO_x = N_{in}{}^* m_{in} + N_{out}{}^* m_{out} \tag{2}$$

Table 1
List of ME solutions, value chain actors and business model examples that affect proposed circularity strategies and mechanisms.

Circularity strategy	ME solution	Value chain actor	Business Model Examples
Reduce units per customer (Narrowing loops)	Reduce function per customer	Procurement departments	Sufficiency
	Reduce units per function by improving functionality	Designers	Combined functions
		Customers	Repurpose
	Reduce units per function by increasing use rate	Retailers	Sharing services
		Users	Product Service Systems
			Slow fashion
Increasing product lifetime (Slowing loops)	Increase lifetime	Designers	Quality products
		Manufacturers	
		Customers	
	Extend lifetime	Retailers	Reuse
		Customers	Repairing
Increase circulation rate (Closing loops)	Increase post-use circulation rates	Retail	Recycling
		Consumers	Cascading
	Increase circular input output ratio	Manufacturers	Industrial Symbiosis
			Remanufacture
Reduce MIO per unit (Narrowing loops)	Reduce input per output	Manufacturers	Production on demand
			Lean production
	Reduce product and packaging material demand	Designers	Dematerialization

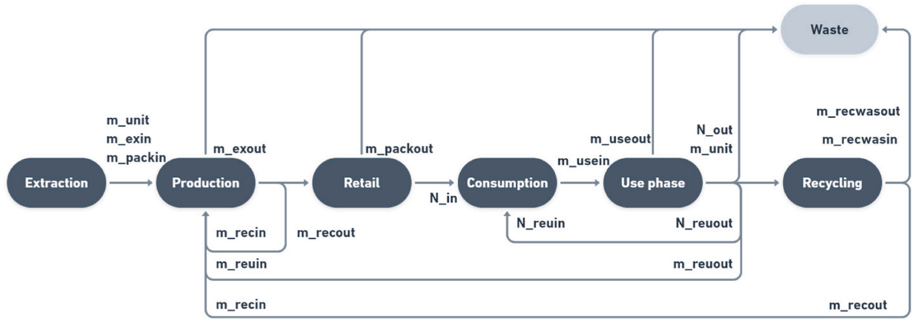

Fig. 2. Components of Material Efficiency Metric and their relevance in a product value chain.

Here (N_{in}) is the number of consumed products that require linear input with the weight (m_{in}) throughout the value chain. Similarly, (N_{out}) is the number of products that generate non-circulated material output in the value chain with the weight (m_{out}).

4.2.1. Number of products

To calculate (N_{in}) and (N_{out}), Equations (3) and (4) are used:

$$N_{in} = \frac{P_x * U_x * T * \left(1 - \frac{N_{reuin}}{N_{tot}}\right)}{L_x} \quad (3)$$

$$N_{out} = \frac{P_x * U_x * T * \left(1 - \frac{N_{reuout}}{N_{tot}}\right)}{L_x} \quad (4)$$

Here (T) defines the timeframe over which circularity is assessed and (L_x) denotes the product lifetime in terms of either uses or years[1]. The ratio T/L_x is hence the product lifetime and decides the rate at which products need to be replaced. The unit demand at a given time is denoted by (U_x* P_x), where (U_x) is the unit demand per customer and (P_x) is the number of customers provided with function.[2] Lastly, N_{reuin} is the number of products that are used to support the specified function but that do not require any virgin material input throughout the value chain. Likewise, (N_{reuout}) is the number of products that do not generate non-circulated material at End of Life (EOL).

4.2.2. Material input

The most important ME solutions to reduce (m_{in}) include *reducing material input* per *unit* and *increasing input circulation rate*. Material input per unit can be affected in the following ways:

- Reducing the unit mass (m_{unit})
- Reducing additional material input required for production (m_{exin})
- Reducing the amount of virgin material used for packaging (m_{packin})
- Reducing additional virgin material input required in the use phase (m_{usein})
- Increasing the ratio of non-linear material including reused material (m_{reuin}) and recycled material (m_{recin}), which can come from production or post-use recycling.

The total amount of input of virgin material is shown in Equation (5).

$$m_{in} = m_{unit} + m_{exin} + m_{packin} + m_{usein} - m_{reuin} - m_{recin} \quad (5)$$

4.2.3. Material output

The material output (m_{out}) is defined as the total weight of materials that due to the specified function either go to landfill or incineration in the production, retail, or use phase or at EOL. As for m_{in}, m_{out} can be reduced by reducing material output per product, which can be made in the following ways:

- Reducing production waste per unit (m_{exout})
- Reducing packaging waste ($m_{packout}$)
- Reducing waste volumes from repair and upgrade processes (m_{useout})

Moreover, increasing circulation rate throughout the value chain reduces the total material waste generation, and can be made in the following ways:

- Increasing the ratio of reused (m_{reuout}) materials post-use
- Increasing circulation of materials in production (m_{recout})
- Increasing the ratio of recycled materials (m_{recout}) post-use
- Reducing recycling waste both from input ($m_{recwasin}$) and output ($m_{recwasout}$) by increasing recycling efficiency

Equation (6) shows the resulting material output expressed in these terms:

$$m_{out} = m_{exout} + m_{packout} + m_{useout} + m_{unit} - m_{reuout} - m_{recout} + m_{recwasin} + m_{recwasout} \quad (6)$$

More specifically, ($m_{recinwas}$) and ($m_{recinwas}$) are calculated as in Equation (7) and Equation (8). These parameters are directly taken from MCI; further explanation of allocation (distribution of environmental impact between products) is listed both in Appendix A and in the MCI derivation (Ellen MacArthur Foundation, 2015).

$$m_{recwasin} = \frac{(1 - e_{rec})^* \, m_{recin}}{2^* e_{rec}} \quad (7)$$

$$m_{recwasout} = \frac{(1 - e_{rec})^* m_{recout}}{2} \quad (8)$$

4.3. CASE studies

In sections 4.3.1.-4.3.3 the results from the three case studies are presented, where data input taken from personal communication was used unless otherwise stated.

[1] For some products it is convenient to define the product lifetime by the number of uses per product (e.g. for bags, cars and packaging), while for other products, the lifetime depends less on use intensity and is defined by a set number of years (commonly for housing, electronics, and furniture). In some product categories, the circumstances decide which method is most suitable. When product lifetime is not based on use intensity, it can be defined by either technical properties, economically based on depreciation time or behavioral aspects. The lifetime for such products is estimated without quantifying use rates. Likewise, unit demand at a given time is either defined by the annual number of uses or units per customer.

[2] (U_x) and (L_x) have different units depending on how product lifetime is calculated, but the ratio U_x/L_x is the same (no. of units per customer) regardless of choice of unit.

4.3.1. Retailer of reused furniture – Varubolaget AB

For the modeling of Varubolagets' business model and a corresponding linear product, a desk called Oberon from Kinnarps was used, which has a common lifetime (L_L) of 17 years (Varubolaget AB, 2021; Personal communication, April). A desk refurbished by Varubolaget AB has similar quality as a newly produced desk, resulting in a total lifetime of 34 years (L_C). In the circular scenario, the properties of the Oberon desk were used for making assumptions about material input in loop 1 and material output after loop 2. For instance, the desk is made of 9 kg recycled material (m_{recin}) and 20 kg recyclable material (Product data sheet). When Varubolaget AB refurbishes desks, the countertop is often changed to a new one made of virgin materials. The countertop waste from loop 1 is modeled as lifetime waste (m_{use}) while the remainder of the desk circulates to retail (m_{reuse}). Moreover, no packaging is assumed to be used between the two loops, while packaging from new desks (m_{packin}) was estimated to 5 kg packaging. The resulting material flows for the two cases are shown in Fig. 3.

Using the material flow visualization in Fig. 3, the circularity value of MEM can be calculated. In the linear case, the total MIO is the sum of the total virgin material input (98 kg) and waste output (98 kg). When using the reuse service of Varubolaget, the MIO over two loops becomes 88 kg, 58 kg from input and 39 kg from output. Thus, the total MIO was reduced by 55%, which is also the MEM result.

4.3.2. Lighting as a service - brighteco AB

When assessing the circular scenario using Brighteco's business model, it was assumed that their LED monitors can be used in three 15-year intervals, making the lifetime (L_C) of the majority of the components 45 years. Using a detailed data sheet containing reuse and recycle opportunities of all LED fixture components throughout this time period, Brighteco's service was evaluated over a 45-year period (T). For the linear case, (L_L) was set to five years based on the warranty of regular LED-fixtures (Brighteco AB 2021; Personal communication, April). For a classroom with 24 students, Brighteco AB uses approximately 14 LED fixtures (U_C), while 10 are required in a linear scenario (U_L).

Every 15 years some of the components in Brighteco's LED monitors will be worn out and have to be replaced by new ones. Those parts correspond to about 11% of the weight and generate a total lifetime input (m_{use}) of 14 kg, while the rest of the LED fixtures remain in place for the whole 45-year period. Furthermore, the long lifetime of Brighteco's LED monitors is partly a result of the use of a thicker "frame," which makes the product weight (m_{unit}) heavier than regular LED monitors: 5 kg instead of 3 kg. Lastly, Brighteco avoids use of packaging by reusing packaging multiple times, almost eliminating any input or output from packaging. In Fig. 4, the material flows in the two scenarios are depicted based on these assumptions.

The relatively narrow flows of materials in the circular case is a result of the long lifetime, indicated as a bar in the use phase in Fig. 4. As some of the material input is recycled and some material output is reused, the total MIO was 51 kg in the circular value chain. As the linear value chain generates 738 kg MIO, the total MIO was reduced by 93% in the circular value chain, which is also the MEM result.

4.3.3. Coffee machine service - jobmeal AB

In this case study, the provision of one coffee machine from Jobmeal AB was compared to the provision of six linearly used coffee makers. The coffee machine can provide 36 people (P_C) with coffee, while coffee makers can support six people (P_L) with coffee. The main differences between the two scenarios included the weight of the coffee machines (m_{unit}), the number of required coffee machines (N_x), their lifetime (L_x) and the recycling rate at EOL (m_{recout}). Jobmeal's machine weighs 42 kg, while a regular coffee maker was assumed to weigh 3 kg (Jobmeal AB, 2021; Personal communication, April). Jobmeal's machines are also rented to its customers for 12 years, divided in four-year intervals. A regular coffee maker, on the other hand, will not support use for more than two years when used with the required intensity for six people (Jobmeal AB, 2021; Personal communication, April). In order for

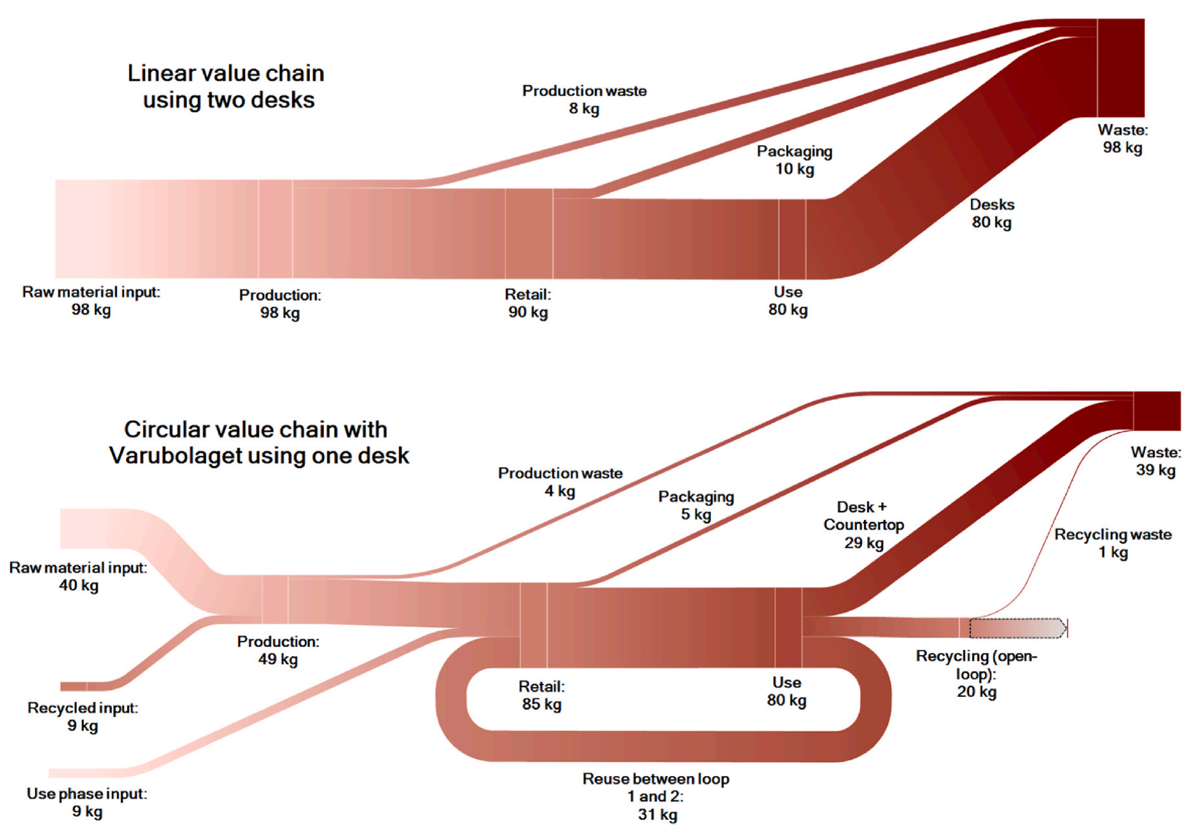

Fig. 3. Material flow of a linear desk value chain and a circular value chain using Varubolaget.

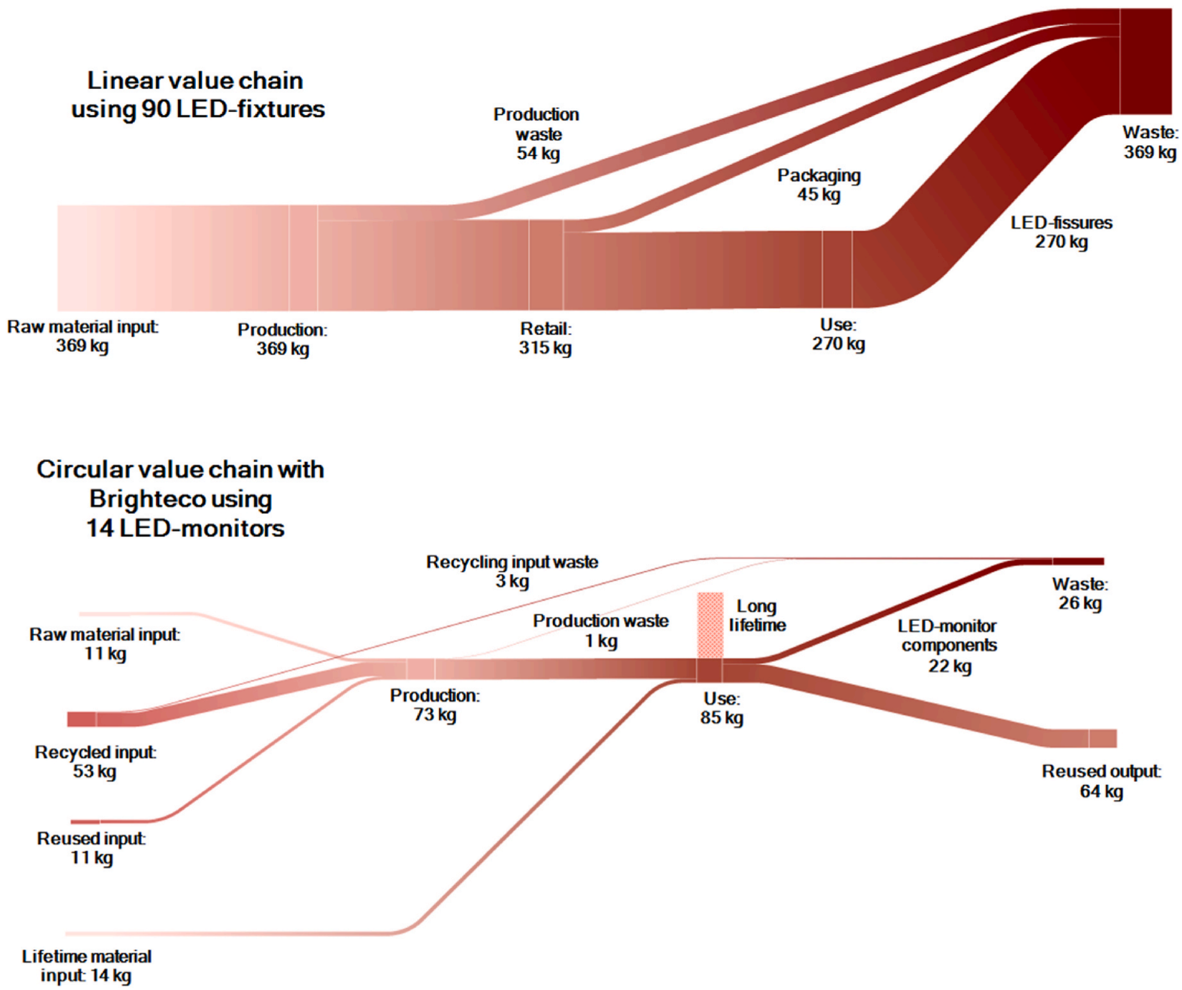

Fig. 4. Material flow of a linear LED fixture value chain and a circular value chain using lighting as a service with Brighteco.

Jobmeal's coffee machines to last for 12 years some service is required, which requires that components with an approximate weight of 13 kg (m_{use}) are substituted. Both the coffee machine and packaging are sent to recycling at EOL by Jobmeal, as opposed to the linear scenario where it was assumed that no recycling of the 0.5 kg packaging ($m_{packout}$), is made. In Fig. 5, the resulting material flows for both scenarios during 12 years is illustrated.

The material flows in the circular scenario are narrower than in the linear scenario because of longer lifetime and fewer products per person, indicated as bars in the use phase in Fig. 5. Additionally, as both the coffee machine and the packaging are sent to recycling at EOL, the total MIO was reduced from 354 kg to 93 kg when using Jobmeal's service, generating a MEM result of 77%.

5. Discussion

Based on the results from the three case studies and the literature review, the aim of this discussion is to answer RQ2 by evaluating feasibility, reliability and validity of the MEM metric. Furthermore, the implications for potential contribution to improvement of environmental sustainability are discussed.

5.1. *How feasible, reliable and valid can the metric be?*

5.1.1. *Feasibility*

The case studies showed that relatively little time was required to evaluate the MEM results compared to LCA or similar methods and that it should render a time saving. Based on the interaction with the participants, it was perceived that they understood the logic behind the metric. This can partly be derived from the metric results being presented in a single-point value, and partly by the provided material flow visualizations that further helped make the results intuitive. All participants perceived that data collection was simple in the circular cases, while it was harder to estimate use rate and lifetime in the linear cases. However, the metric in its current state requires knowledge about the underlying equations and some methodological insight. By adapting the metric for specific actors in the value chain and incorporating guidelines in future tool versions, it could be used to guide actors who do not have that insight.

Compared to the most similar metric, MCI, MEM is more data-intensive as more information about material use is required. PCI should require approximately the same amount of data, as it requires more detailed input regarding the manufacturing processes than MCI. However, as these C-metrics use a product perspective on material flows, the benefits from some business models cannot be captured. For instance, although consumption rates can be assessed to some extent with MCI and PCI with the included utility factor (X), the metrics don't specify how the use rate is increased or how many products are consumed. In MEM, it is specified if reduced product demand is a result of more intensive use (e.g. sharing services) or reduced demand for function (e.g. reduced consumption of products by applying sufficiency). Another difference compared to PCI is that the total material flow volumes are not considered in MCI and PCI. Thus, MEM should be better suited for assessing business models that reduce unit consumption

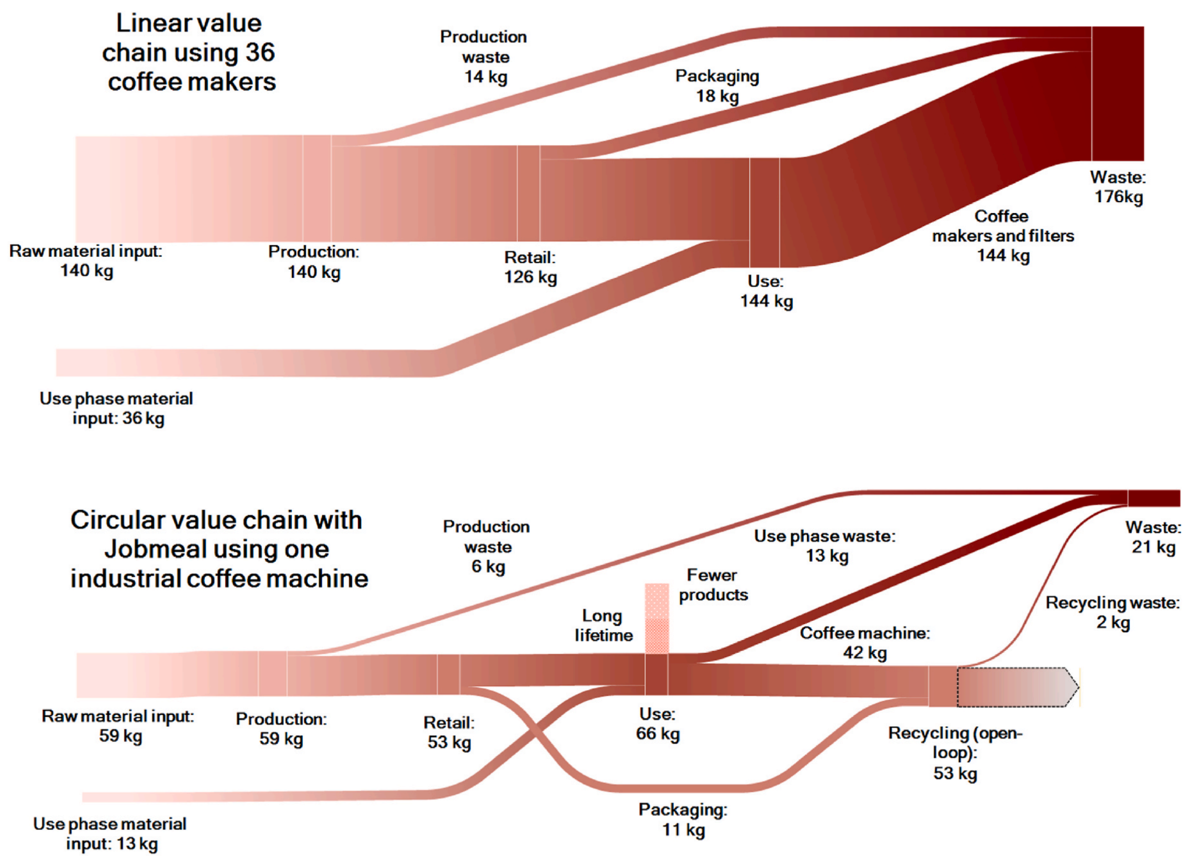

Fig. 5. Material flow of a linear consumption of coffee makers and a circular value chain using a coffee machine provision with Jobmeal.

and product weight such as PSS, sharing services, sufficiency and design for dematerialization. As the proposed C-metric is based on this framework, it enables comparability of a range of scenarios that cannot be assessed as easily using the C-metrics found in the literature review.

The feasibility of MEM was supported by the case study participants, whose aggregated perception was that the metric was relevant and applicable to their business models. Participants from Brighteco AB perceived that MEM, as opposed to other metrics they have tested, better captures their environmental performance due to the possibility to compare what function their service provides. Similar thoughts were expressed by the Jobmeal AB participants. Consequently, the case studies showed that MEM could be used to capture all four circularity strategies from Table 1 using different business models including PSS, sharing and reuse.

5.1.2. *Reliability*

The aspect that affects reliability the most is currently the inclusion of a functional unit, as it is affected by user choice. Specifically, consistency is affected by how a linear case is defined, as it depends on data that is not standardized. For instance, similar to both MCI and PCI, assumptions about industry-average lifetime and average product use rates are required. The participants from Varubolaget AB expressed a concern that their circularity value should have been higher, as they reuse most parts of their products. Even though the service itself is important, MEM generates a moderate result (55%) compared to the other case studies. This is a consequence of the business model only affecting one product loop, while MEM assesses multiple loops. If it could be ensured that the customers of Varubolaget's desks rotate multiple times, the MEM value would increase. This shows the importance of collaboration with actors along the whole value chain. If their business model would have been compared to one where the lifetime of desks is shorter, a higher circularity value would also have been generated, since the lifetime of desks most commonly may be shorter than 17 years.

Additionally, the choice of functional unit includes a specific time period, which affects the number of product loops. This is pertinent in cases where the business model is operating between two product loops. In the furniture case, the product loop both before and after the refurbishment and retail of the desk was included, while it could have been possible to make a consequential approach, in which only the second loop would have been included. Moreover, functional unit includes assumptions about the function that a product or a service provides. In a situation where one product is able to support multiple functions while another supports a single function, a subjective allocation procedure is required. To increase consistency, a third-party review of typical product lifetime, consumption rates and system boundary choices could be developed, or the data could be standardized and incorporated in a database similar to those used in LCA software. Doing so would increase reliability and avoid greenwashing due to arbitrary assumptions, as the results would depend less on the choices of the user.

5.1.3. *Validity*

When evaluating environmental performance, multiple aspects of environmental impact can be considered. Therefore, when evaluating metric validity, it is important to address which environmental impact categories the metric results should correlate with. Environmental sustainability can be evaluated based on any one of the three end-point categories biodiversity, resource scarcity and human health. It could also be evaluated based on one or more of the various midpoint impact categories that contribute to the effect on these end-point categories. In turn, the performance on mid-point categories depends on the amount of input of materials and energy, as well as type of material and how energy is generated. Resource scarcity is highly affected by the extraction of rare earth metals, while global warming is affected by the use of fossil fuels and human toxicity by emission of toxic compounds. This results in contradictory implications for environmental performance that cannot be captured in a single-point metric. As existing C-metrics tend to focus on material use while omitting energy use and toxicity rates (Elia et al., 2017), they should hence be better indicators for resource scarcity than emission-based impact categories.

To evaluate if other principles of the circular economy are followed, such as toxic-free material flows and the use of renewable energy, additional metric inputs such as energy use and toxicity rates could be incorporated in MEM. As PCI has higher resolution in the production phase than MEM, it may render results with higher correlation to resource scarcity when comparing production methods. However, when comparing business models that target stages later in the value chain, MEM is more detailed and may generate more valid results. For instance, MEM considers the total material weight, which penalizes ineffective design strategies where product weight, waste generation, use of packaging and use of material during the use phase are high. For product types where these can be reduced, material weight assessment is important for achieving correlation to environmental impact.

Limitations with MEM, MCI and PCI are the lack of distinction between different types of materials (metals/minerals/plastics/paper) and the system boundary excluding extraction processes. A potential approach to incorporate material type and extraction rates would be to make a material conversion factor based on extraction rates for a given material. This would penalize materials with high CO_2 emissions, for instance metals, as they generally require more material extraction, are more scarce and have higher embodied energy than biological materials (Cabeza et al., 2021). The limitations imply that MEM in its current version, as well as other C-metrics, could be viewed as complementary metrics to more comprehensive environmental impact assessment methods.

Summarizing the implications for validity, MEM is expected to perform best in situations where the choice of material is not a vital part of the circularity business model and where energy use or transport patterns are not significantly changed in the adopted business models. The metric is designed to provide understanding for how overall substantial MIO reduction on a large scale can be accomplished throughout value chains, a highly important step to reduce environmental impact (Liedtke et al., 2014). The metric does so by rewarding solutions where MIO is reduced over multiple life cycles and where a function can be fulfilled with the least possible material. Thus, MEM is not developed to analyze material flows in production with high resolution, unlike many life cycle assessments and existing metrics. Its strength rather comes from asking questions that highlight decisions that have higher impact on material flows. The importance of this strategy is supported by the case studies, which showed that consumption rates, product lifetime, recycling rates and use rates are aspects that have high impact on MIO and therefore resource scarcity. Solely focusing on the impact of one product, which often is the focus in LCA studies, would not reduce the total MIO by 55–93% assuming constant consumption rates.

5.2. Metric and framework contribution

The proposed framework in section 4.1 provides an understanding of how ME strategies can affect extraction rates of virgin material and how waste creation can be reduced. To capture all these, the case studies showed that a value chain perspective on material flows is required. Using the value chain perspective when assessing the impact of circular business models and design strategies can therefore support sustainable development by increasing overall circularity. The development of MEM is expected to contribute to existing research on sustainable development in the following ways:

First, MEM can be used to increase understanding about how different actors best contribute to resource-efficient value chains. When adopting one or more resource efficiency strategies, it can be complex to understand how they affect overall material flows. If applying a strict production perspective, a specific solution may seem resource efficient. However, if many units are required to fulfill a specific purpose, the environmental impact will likely be high. Using MEM, sub-optimized circularity can be detected, which can result in single actors achieving low circularity values even if it is part of a resource-efficient value chain. It is hence important to differentiate circularity of business models and value chains and to reward businesses for contributing to overall circularity.

Secondly, the metric can be used to create cross-actor collaboration opportunities. To achieve high circularity values with MEM, it is essential to collaborate over the whole value chain. For instance, the case study with Varubolaget AB exemplifies how a single actor can contribute a lot to circularity, but not create a completely circular value chain on its own. To create a circular furniture value chain, it is required to have control over, or at least have impact on, design and production strategies as well as retail and EOL processes, which determine the quality and use rate of products. The metric identifies where in the value chain better solutions are required, which highlights where collaboration is required.

Thirdly, by demonstrating how companies contribute to improved resource efficiency, the metric can foster development towards circular procurement and investments in environmental sustainability. Designing MEM as a single-point metric makes it suitable as a screening tool that highlights how unproven circular business models can contribute to resource efficiency. This could increase the chance of investors and public procurers to understand the value of their businesses. Actors interested in higher resolution in the manufacturing stages could use more detailed environmental impact assessment tools such as LCA. However, these generally require more time to execute and generate more complex results.

Lastly, MEM can help increase the interplay between micro-level and macro-level circularity, which sometimes is described as crucial to ensure a connection between circularity and sustainable development (Harris et al., 2020). The value chain perspective adopted in this study could be considered a meso level perspective, which is applicable on both product level and regional level. Using the case studies as an example, the circularity value of all lamps or desks in a specific region could be calculated and used as a baseline for improvement. To understand if a specific value chain is resource efficient, its circularity value could be compared to that of the whole industry, a nation, or a global target for circularity.

6. Conclusions

To guide practitioners of circular economy and to highlight advantages with new business models and design strategies, the use of circularity metrics (C-metrics) is investigated. Circular initiatives may gain more success if C-metrics can be used by decision-makers in e.g. investment and procurement processes. To ensure that such metrics guide its users towards sustainable solutions, it has been stressed that they should be simple to use, indicate potential environmental impact and generate consistent results. This study contributes to this research by developing a material flow-based C-metric called the Material Efficiency Metric (MEM), which can fulfill these requirements (RQ1).

This paper also emphasizes the importance of shifting focus from product circularity to value chain circularity to avoid problem shifting and rebound effects. Moreover, to find the desirable connection between micro-, meso- and macro-level circularity, the circularity concept should be consistent regardless of on which level circularity is measured. This is accomplished by designing MEM for assessing material flows on value chain level, which can be considered an example of meso level. The metric rewards business models that cause low volumes of material extraction and waste creation and evaluates circularity based on the function that products provide. Using MEM properly, it can increase the understanding of how different actors can contribute to overall material efficiency. Moreover, a common understanding of value chain circularity can increase collaboration opportunities and reward resource-efficient companies. To allow for high validity, MEM was designed based on the connection between circular practices and material loop closeness, slowness and narrowness (RQ2).

MEM was tested in three case studies, which showed that it was simple to use as it is not data intensive and can be used by a wide range of actors. For instance, it can be used to compare product-focused business models with Product Service Systems (PSS). As it has high resolution in material flows, but cannot capture the effects of energy use and high toxicity rates, it is expected to generate results that are consistent with resource efficiency, but not necessarily other impact categories. To deliver consistent results, industry standards on product lifetime and consumption rates should be used as assumptions on these data highly affect the results.

Future work should consist of testing and further improving the metric's feasibility, reliability and validity. Its feasibility could be increased by designing the metric for specific actors and sectors and by increasing the tool's user-friendliness. To ensure consistent user input and increased reliability, standardized databases should be developed for assumptions about product lifetime and average consumption rates. Increased validity can be achieved by comparing the metric results with scientifically proven methods and expanding the metric to include energy input and material type components where required. This can be executed on a variety of different business models and products, to increase sector-specific understanding for which solutions are most resource efficient. It should also be tested on additional system levels, including regional or global level and can be tested on additional business models that focus on digitalization. Such tests will highlight in which situations the metric performs well and what aspect of environmental impact it best captures.

Funding

This work received financial support from the European Regional Development Fund [grant number 20201594], Region Gävleborg, and the University of Gävle. The funding organizations have not been part of the publication process and the present work is not an official position of the supporting organizations.

CRediT authorship contribution statement

Johan Brändström: Conceptualization, Methodology, Resources, Writing – original draft, Visualization. **Ola Eriksson:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Special thanks goes to Amer Jazairy, Karl Hillman and Lucia Korbelyiova who improved the quality of the paper.

Appendix A. Metric information

Literature review process

The literature study was performed using multiple techniques, including database screening, snowball method and suggested articles from Mendeley-based library content. The most frequently used databases were Google Scholar, Elsevier, Research Gate and Scopus. Some grey literature was included, as circular economy is a relative new research area and lacks peer-reviewed research assessing the relationship between circularity and sustainability (Geissdoerfer et al., 2017). To find relevant papers, variations of the following search terms were used: "circular economy" AND "definition" OR "review", "circular economy" OR "circularity" AND "indicator" OR "measurement" OR "assessment" OR "metric" and "circular economy" AND "LCA" OR "system analysis". The reviewed articles included circular economy concept articles, systematic reviews of circularity metrics, assessments of specific metrics as well as articles focusing on system analysis and LCA. As a result, insights into current knowledge about sustainability frameworks, circularity measurements and life cycle approaches to environmental impact assessments were acquired.

CALCULATION OF RECYCLING WASTE

- $\frac{(1-e_{rec})^{*}\ m_{recin}}{2^{*}e_{rec}}$ = waste creation from recycling process - input
- $\frac{(1-e_{rec})^{*}m_{recout}}{2}$ = waste creation from recycling process - output
- e_{recin} = recycling efficiency - input
- e_{recout} = recycling efficiency - output
- $(1 - e_{recin})$ = ratio of processed material that becomes waste in recycling process - input
- $(1 - e_{recout})$ = ratio of processed material that becomes waste in recycling process - output
- $\frac{1}{e_{recin}}$ = factor to calculate the amount of material input required in recycling process to achieve a desired weight
- = factor used to divide waste allocation between two loops

How to use the metric

When using the suggested metric, the following approach is recommended:

1) **Identify purpose –** Is the metric used as a lagging or a leading indicator? This is primarily important to know which information is required and to know who can find that information.
2) **Define user –** Choose someone within a relevant organization that has a system perspective on the provided product or service. Depending on organization, identify which of the following aspects is most relevant: design, production, consumption or EOL treatment.
3) **Define functional unit –** Choose version of the metric based on if the product lifetime is determined by number of uses or by technical aspects.
4) **Define time period –** This is the time over which circularity is assessed, which should be long enough to include multiple product loops.

5) **Define a linear case –** Make assumptions on average unit lifetime and consumption rates. Assume 0% circulation.
6) **Define a circular case –** Identify the parameters that are affected as a result of actual or possible circular solutions.
7) **Calculate the material input and output –** Calculate MIO_{LIN} and MIO_{CIR} by inserting equation **(3) - (6)** into **Equation (2)**:

$$MIO_x = \frac{P_x * U_x * T^* \left(1 - \frac{N_{reuin}}{N_{tot}}\right)}{L_x} * \left(m_{unit} + m_{exin} + m_{packin} + m_{usein} - m_{reuin} - m_{recin}\right) + \frac{P_x * U_x * T^* \left(1 - \frac{N_{reuout}}{N_{tot}}\right)}{L_x} * \left(m_{exout} + m_{packout} + m_{useout} + m_{unit} - m_{reuout} - m_{recout} + m_{recwasin} + m_{recwasout}\right) \quad \text{(A1)}$$

8) **Calculate the circularity –** Insert MIO_{LIN} and MIO_{CIR} in equation (1) to calculate the MEM-result.
9) **Identify possible improvements –** By analyzing the components of the metric, consider additional possible circularity mechanisms that can increase the circularity.
10) **Complement environmental assessment –** To further capture negative environmental impact and avoid burden shifting, it is suggested to expand the analysis using additional information. The metric should primarily be complemented in situations where apparent burden shifting is caused by increased rates of **energy** use, chemical use, use of raw materials or if harvest and return procedures would deteriorate as a result of implemented circular solutions. Social aspects should also be assessed separately to complete the analysis.
11) **Complete circularity readiness –** To link environmentally focused solutions to organizational change, qualitative aspects regarding circular readiness should be assessed using a tool such as CPI or CET.

Appendix B. Case study information

The MEM equations were implemented in a tool that was used in all case studies and will appear on www.chasingcircular.com.

Case 1. Refurbishment and retail of desks with Varubolaget

Table B1
Data and assumptions used as input in the calculation the Material Efficiency Metric in case study 1

Varubolaget	Linear case		Circular case	
	Value	**Assumptions**	**Value**	**Assumptions**
Unit demand over time period (pc.)	**2**	**Generic desk**	**1**	**Kinnarp desk**
No. of people	1	Assuming same in both cases	1	Assuming same in both cases
No. of units per person	1	Assuming same in both cases	1	Assuming same in both cases
Timeframe (years)	34	Based on two loops of one typical table	34	Based on two loops of one typical table
Unit lifetime (years)	17	Based on participant experience	34	Based on two loops of one typical table
Virgin Material Input per product (kg)	**49**	**Calculation: Desk + Packaging + Production waste**	**50**	**Calculation: Desk + Packaging + Production waste + Use phase input -recycled input + recycling waste**
Unit mass (kg)	40	Assuming same weight as Kinnarp desk	40	Kinnarp data sheet
Additional production input (kg)	4	10% waste	4	10% waste
Recycled input production (kg)	0	No circulation	9	22% of unit weight - data sheet
Recycling efficiency (%)	–	N/A	90	Assumption
Reused input production (kg)	0	No circulation	0	No reuse as input in production loop 1
Reused material, closed-loop (kg)	0	No circulation	31	Whole desk minus weight of countertop
Use phase input (kg)	0	No circulation	9	Weight of one countertop
Material waste per product (kg)	**49**	**Calculation: Desk + Packaging + Production waste**	**39.5**	**Calculation: 50% of one Desk + Countertop + Packaging + Production waste + Recycling waste (input) + Recycling waste (output)**
Production waste (kg)	4	Calculation: 10% waste	4	10% waste
Recycled material EOL (kg)	0	No circulation	20	Kinnarp data sheet claims 50% recyclability of table
Recycled packaging (% of packaging weight)	0	No circulation	0	No circulation
Recycling efficiency (%)	–	N/A	90	Assumption by researcher
Reused material EOL (% of unit)	0	No circulation	0	No circulation
Material waste per product	49	Desk Packaging Production waste	39.5	50% of one Desk Countertop Packaging Production waste Recycling waste (input) Recycling waste (output)
Production waste (kg)	4	10% waste	4	10% waste
Recycled material EOL (kg)	0	No circulation	20	Kinnarp data sheet claims 50% recyclability of table

Table B2
Data and assumptions used as input in the material flow visualization in case study 1

Varubolaget	Linear case		Circular case	
Sankey chart assumptions	**Value**	**Assumptions**	**Value**	**Assumptions**
Raw material input (kg)	98	Calculation: No. of products*input per product (Material loss in extraction not regarded)	40	Calculation: Production - recycled input
Recycled input (kg)	0	No circulation	9	Data sheet
Recycling waste input (kg)	0	No circulation	0,45	Not illustrated
Reused input (kg)	0	No circulation	0	No reuse as input in production loop 1
Production (kg)	98	Calculation: No. of products*input per product	49	Desks Packaging Production waste
Production waste (kg)	8	Twice that of one product	4	Production waste loop 1
Packaging (kg)	10	Twice that of one product	5	Weight of the packaging in loop 1
Packaging to recycling (kg)	0	No circulation	0	No circulation
Use phase input (kg)	0	No refurbishing	9	Material input to refurbish desks
Retail (kg)	10	Weight of 2 desks plus 2 packaging	85	Two desks and one packaging
Use (kg)	80	Weight of 2 desks	80	Weight of 2 desks
Reuse weight (kg)	0	No circulation	31	Reuse weight between loop 1 and 2. (This was not used as input in the metric, instead the desk was assumed to have doubled lifetime)
Recycling EOL (kg)	0	No circulation	20	Kinnarp data sheet claims 50% recyclability of table
Recycling waste EOL (kg)	0	No circulation	1	20 kg to recycling, 90% efficiency in recycling, 50% of waste allocated to this desk
Reused output (kg)	0	No circulation	0	No reuse after loop 2
EOL waste (kg)	80	All goes to incineration	29	Calculation: 50% of one desk and one countertop
Waste (kg)	98	Desks Packaging Production waste	39	Calculation: 50% of desk after loop 2 + One countertop + Production waste + Packaging one table

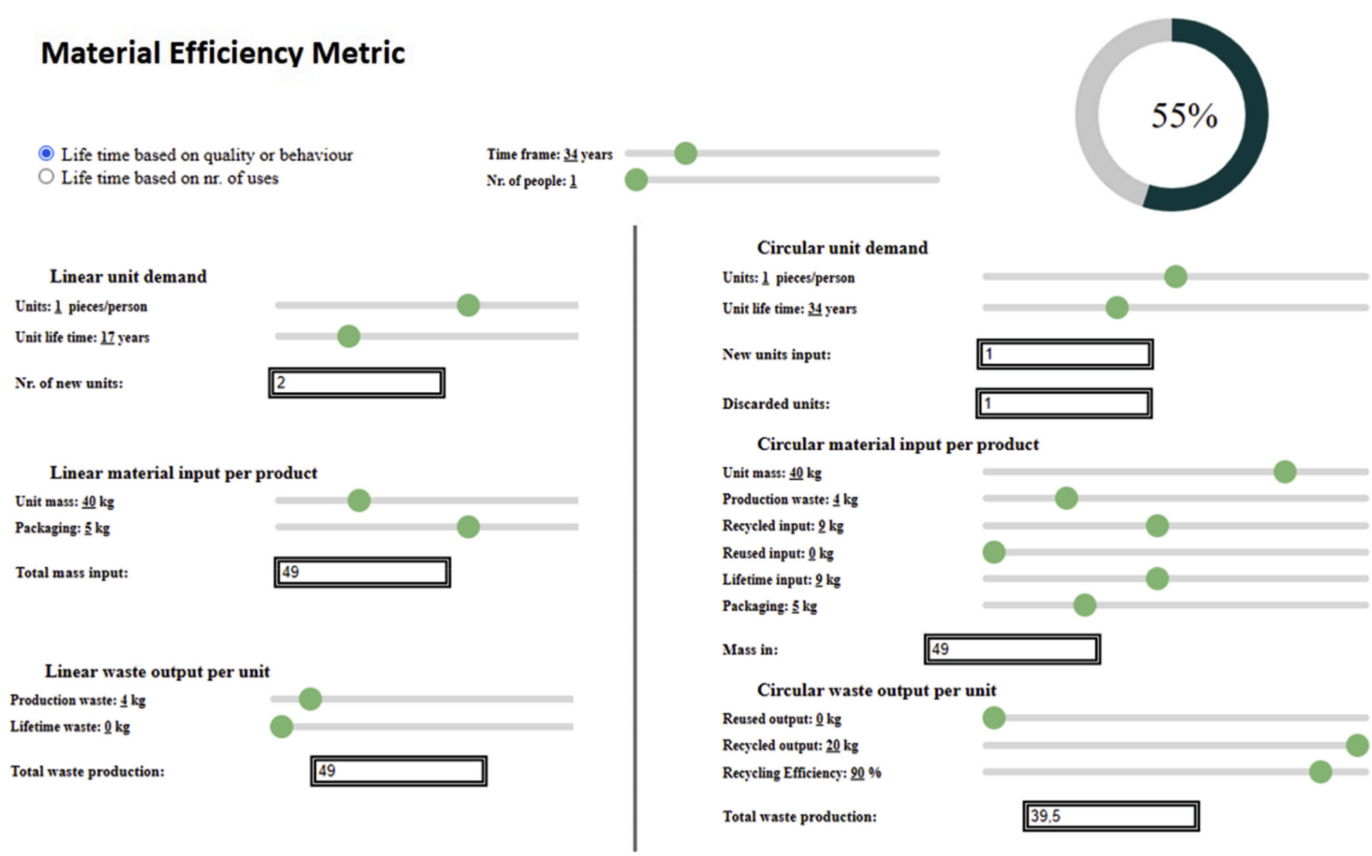

Fig. B1. Circularity result using MEM on Varubolaget.

CASE 2. LIGHTING AS A SERVICE WITH BRIGHTECO

Table B3
Data and assumptions used as input in the calculation the Material Efficiency Metric in case study 2

Brighteco	Linear case		Circular case	
	Value	**Assumptions**	**Value**	**Assumptions**
Unit demand over time period (pc.)	**90**	**Calculation: Total time period/ lifetime*units per classroom**	**14**	**Calculation: Total time period/lifetime*units per classroom**
No. of people	24	Assumption (same for both cases)	24	Assumption (same for both cases)
No. of units per person	0,42	10 lamps per classroom (Participant assumption)	0.58	14 lamps per classroom (Participant assumption)
Timeframe (years)	45	based on 3 product loops for which data sheets are available	45	based on 3 product loops for which data sheets are available
Unit lifetime (years)	5	maximum warranty according to participant	45	3 loops, 15 years each
Virgin Material Input per product (kg)	**4,1**	**Calculation: Unit mass + Additional production input + Packaging**	**1.8**	**Calculation: Virgin material input loop 1 + Lifetime use + Additional production input**
Unit mass (kg)	3	Average value of two LED-lamps found on conrad.se	5.1	Data sheet from Brighteco
Additional production input (kg)	0,6	Researcher assumption (20%)	0.1	Assumption from researcher and participant: 20% of virgin material input
Recycled input production (kg)	0	No circulation	3.6	Data sheet - 70% of mass in loop 1
Recycling efficiency (%)	–	N/A	90	Researcher assumption
Reused input production (kg)	0	No circulation	0.8	Data sheet - 16% of mass in loop 1
Reused material, closed-loop (kg)	0	No circulation	4.6	Data sheet - 90% of mass between loop 1 and 2, 2 and 3. Not illustrated, instead virgin material input during lifetime is illustrated
Use phase input (kg)	0	No circulation	1	Data sheet - 10% of mass between loop 1 and 2 plus between 2 and 3
Material waste per product (kg)	**4,1**	**Same as input due to no circulation**	**1,8**	**Calculation: Recycling waste from loop 1 input + production waste + lifetime waste + EOL waste**
Production waste (kg)	0,6	No circulation in production– > all additional input becomes waste	0,1	Assumption from researcher: same as additional production input
Recycled material EOL (kg)	0	No circulation	0	Data sheet + participant assumption
Recycled packaging (% of packaging weight)	0	No circulation	0	All packaging is reused multiple times instead
Recycling efficiency (%)	–	N/A	90	Researcher assumption
Reused material EOL (% of unit)	0	No circulation	90	Participant assumption, can possibly be done after loop 3
Material waste per product	4,1	Same as input due to no circulation	1,8	Recycling waste before loop 1 (input) + production waste + lifetime waste + EOL waste
Production waste (kg)	0,6	No circulation in production– > all additional input becomes waste	0,1	Assumption from researcher: same as additional production input
Recycled material EOL (kg)	0	No circulation	0	Data sheet + participant assumption

Table B4
Data and assumptions used as input in the material flow visualization of case study 1

Brighteco	Linear case		Circular case	
Sankey chart assumptions	**Value**	**Assumptions**	**Value**	**Assumptions**
Raw material input (kg)	369	Calculation: No. of products*input per product (Material loss in extraction not regarded)	11.3	Calculation: (virgin material input per lamp loop 1+production waste per lamp)*no. of lamps
Recycled input (kg)	0	No circulation	50.1	Calculation: No. of lamps*recycled input per lamp
Recycling waste input (kg)	0	No circulation	2.8	Calculation: (recycled input/0,9*0,1)/2
Reused input (kg)	0	No circulation	11.4	Calculation: reused material per lamp*no. of lamps
Production (kg)	369	Calculation: No. of products*input per product	72.8	Calculation: raw material input + recycled input + reused input - recycling input waste
Production waste (kg)	54	Calculation: No. of products*additional material input per product in production	1.4	Calculation: production waste per lamp*no. of lamps
Packaging (kg)	45	Calculation: Packaging per product*no. of products	0.0	Assumption: packaging can be disregarded
Packaging to recycling (kg)	0	No circulation	0.0	N/A
Use phase input (kg)	0	Researcher assumption	14.0	Calculation: input per lamp*no. of lamps
Retail (kg)	315	Calculation: Production weight - production waste	71.4	Calculation: Production - production waste
Use (kg)	270	Weight of 90 lamps	85.4	Calculation: Production - production waste + lifetime material input
Reuse weight (kg)	0	No circulation	0.0	No reuse illustration between loop 1 and 3 (as lamp remain at same location)

(*continued on next page*)

Table B4 (*continued*)

Brighteco	Linear case		Circular case	
Recycling EOL (kg)	0	No circulation	0.0	No recycling
Recycling waste EOL (kg)	0	No circulation	0.0	Participant assumption
Reused output (kg)	0	No circulation	64.3	Calculation: 90% of lamp weight*no.' of lamps
EOL waste (kg)			21.4	Calculation: Lifetime waste, 3 loops of maintenance, 10% of lamp weight
Waste (kg)	369	Equals raw material input as flow is linear	25.6	Calculation: 3*10% of product weight*no. of lamps + production waste + recycling input waste

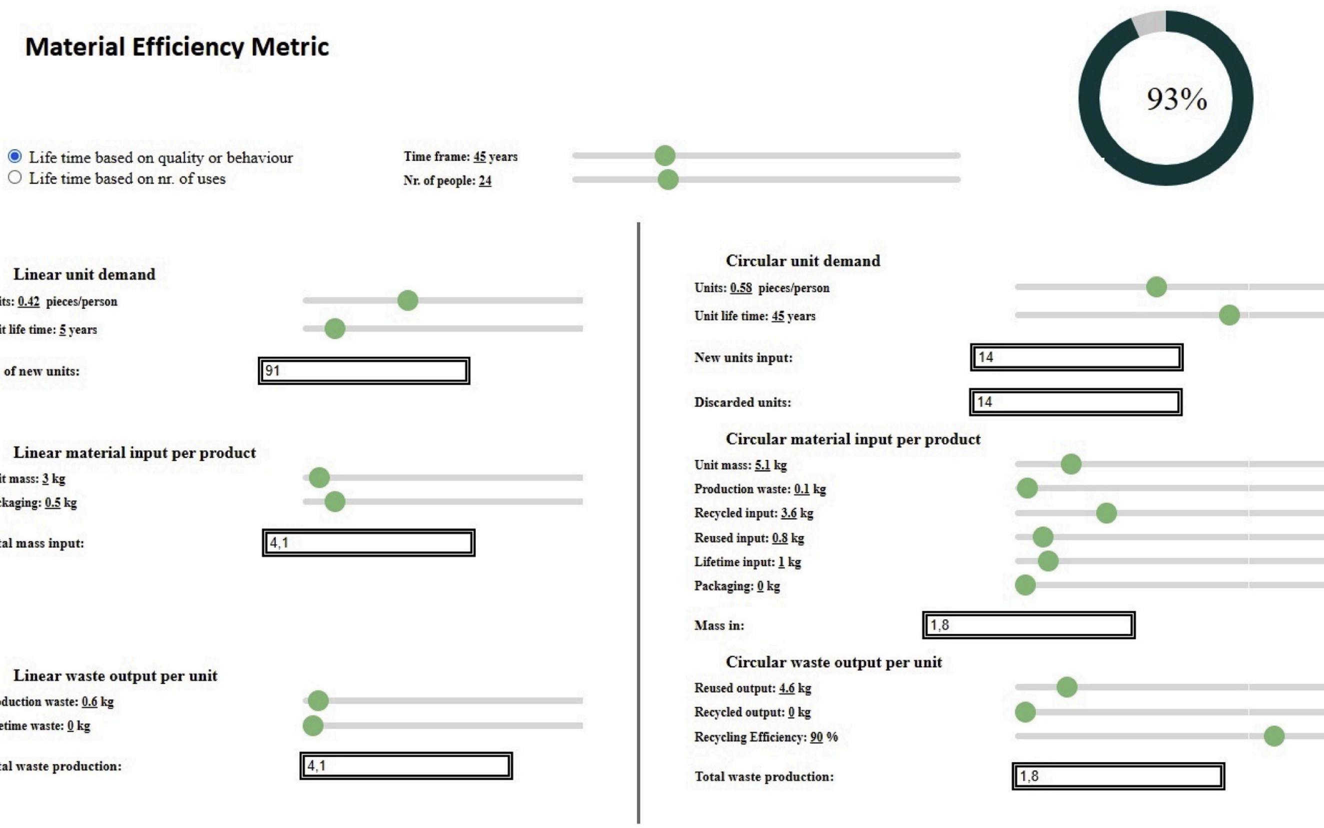

Fig. B2. Circularity result using MEM on Brighteco.

CASE 3. COFFEE MACHINES AS A SERVICE WITH JOBMEAL

Table B5
Data and assumptions used as input in the calculation of the Material Efficiency Metric in case study 3

Jobmeal	Linear case		Circular case	
	Value	**Assumptions**	**Value**	**Assumptions**
Unit demand over time period (ea.)	**36**	**Calculation: Life cycles during timeframe*no. of coffee makers at a given time = 6*6**	**1**	**The number of investigated coffee machines**
No. of people	36	Based on circular assumption	36	One Sprengler PSL50BTC can supply 36 people with coffee according to participants
No. of units per person	0.17	Calculation: no. of coffee makers at a given time/no. of people	0.03	Calculation: No. of coffee machines/no. of people
Timeframe (years)	12	Based on circular assumption	12	Based on lifetime of Sprengler machine
Unit lifetime (years)	2	Based on participants assumption. Short lifetime depends on the heavy use	12	3 retail loops, 4 years each
	4.9		**71.6**	

(*continued on next page*)

Table B5 (*continued*)

Jobmeal	Linear case		Circular case	
	Value	**Assumptions**	**Value**	**Assumptions**
Virgin Material Input per product (kg)		**Calculation: Unit mass + additional production input + packaging**		**Calculation: Unit mass + lifetime input + additional production input + packaging**
Unit mass (kg)	3	Based on participants' assumption, a common weight for coffee makers	42	Weight of Sprengler PSL50BTC, data sheet
Additional production input (kg)	0,4	Researcher assumption: 13% of initial weight	6	Researcher assumption: 14% of initial weight
Recycled input production (kg)	0	No circulation	0	No recycled input loop 1
Recycling efficiency (%)	–	N/A	–	N/A
Reused input production (kg)	0	No circulation	0	No reused input loop 1
Reused material, closed-loop (kg)	0	No circulation	90%	90% of the machine weight is used throughout the 12 years, only 10% is changed every 4 year
Use phase input (kg)	1	Weight of filters, assumption based on participants' assumption (No production waste calculated)	12.6	4.2 kg material input is required every 4 years due to wear of electronic parts and importance of hygiene
Material waste per product (kg)	**4.9**	**Same as input due to no circulation**	**22.8**	**Calculation: Production waste + lifetime waste + recycling waste**
Production waste (kg)	0,4	Assumption from researcher: same as additional production input	6	Assumption from researcher: same as additional production input
Recycled material EOL (kg)	0	No circulation	42	100% of product is sent to recycling at EOL
Recycled packaging (% of packaging weight)	0	No circulation	100	All packaging sent to recycling at EOL
Recycling efficiency (%)	–	N/A	90	Researcher assumption
Reused material EOL (% of unit)	0	No circulation	0	No reuse after 12 years
Material waste per product	4.9	Same as input due to no circulation	22.8	Calculation: Production waste + lifetime waste + recycling waste
Production waste (kg)	0.4	Assumption from researcher: same as additional production input	6	Assumption from researcher: same as additional production input
Recycled material EOL (kg)	0	No circulation	42	100% of product is sent to recycling at EOL

Table B6
Data and assumptions used as input in the material flow visualization of case study 3

Jobmeal	Linear case		Circular case	
Sankey chart assumptions	**Value**	**Assumptions**	**Value**	**Assumptions**
Raw material input (kg)	140.4	Assumption: Same as production Material loss in extraction not regarded	59	Assumption: Same as production Material loss in extraction not regarded
Recycled input (kg)	0	No circulation	0	No recycled input
Recycling waste input (kg)	–	N/A	–	N/A
Reused input (kg)	0	No circulation	0	No reused input
Production (kg)	140.4	Calculation: Production waste + packaging + weight of products	59	Calculation: Product weight + additional product input + packaging
Production waste (kg)	14.4	Calculation: Production waste per product*no. of products	6	Production waste for one product
Packaging (kg)	18	Calculation: No. of product* packaging per product	11	Packaging for one product
Packaging to recycling (kg)	0	No circulation	11	All packaging sent to recycling
Use phase input (kg)	36	Calculation: No. of products*filter weight per coffee machine	12.6	Calculation: Use phase input per product*no. of products
Retail (kg)	126	Calculation: Production - production waste	53	Calculation: Production - production waste
Use (kg)	144	Calculation: weight of all coffee machines and their filters	65.6	Calculation: Product weight + packaging + use phase input
Reuse weight (kg)	0	No circulation	–	Reuse between loop 1 and 3 not illustrated
Recycling EOL (kg)	0	No circulation	53	100% of product + packaging is sent to recycling at EOL
Recycling waste EOL (kg)	–	N/A	2.65	Calculation: 10% of 53 kg that is sent to recycling at EOL becomes waste (5.3 kg) Assumption: 50% is allocated to this case
Reused output (kg)	0	No circulation	0	no reuse after loop 3
EOL waste (kg)	144	Calculation: weight of all coffee machines and their packaging and filters	0	All sent to recycling
Waste (kg)	176,4	Calculation: Production waste + EOL waste	21,25	Calculation: Production waste + recycling waste + use phase input

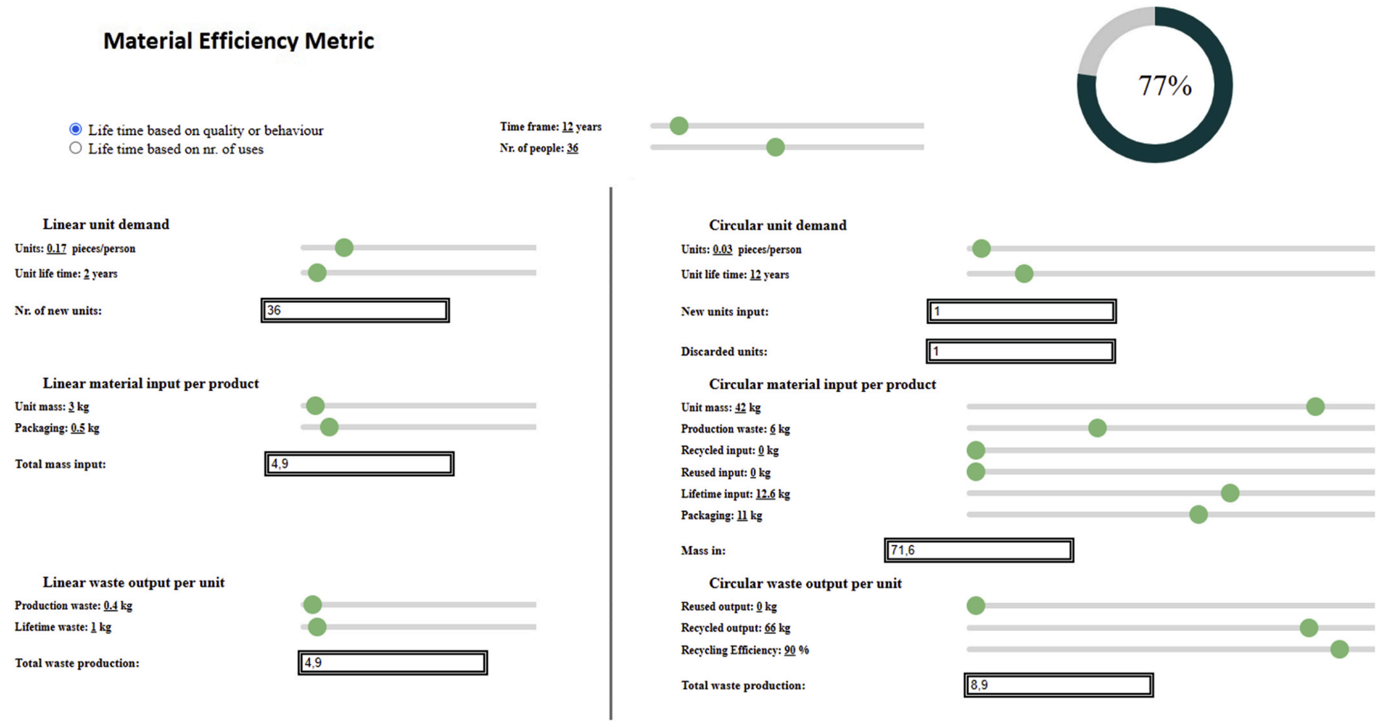

Fig. B3. Circularity result using the Material Efficiency Metric on Jobmeal.

References

Alhawari, O., Awan, U., Bhutta, M.K.S., Ali Ülkü, M., 2021. Insights from circular economy literature: a review of extant definitions and unravelling paths to future research. Sustain. Times 13, 1–22. https://doi.org/10.3390/su13020859.

Bannigan, K., Watson, R., 2009. Reliability and validity in a nutshell. J. Clin. Nurs. 18, 3237–3243. https://doi.org/10.1111/j.1365-2702.2009.02939.x.

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124.

Bocken, N.M.P., Short, S.W., Rana, P., Evans, S., 2014. A literature and practice review to develop sustainable business model archetypes. J. Clean. Prod. 65, 42–56. https://doi.org/10.1016/j.jclepro.2013.11.039.

Bracquené, E., Dewulf, W., Duflou, J.R., 2020. Measuring the performance of more circular complex product supply chains. Resour. Conserv. Recycl. 154, 104608. https://doi.org/10.1016/j.resconrec.2019.104608.

Brighteco A.B., 2022. https://www.brighteco.se/ (Accessed 17 February 2022).

Cabeza, L.F., Boquera, L., Chàfer, M., Vérez, D., 2021. Embodied energy and embodied carbon of structural building materials: worldwide progress and barriers through literature map analysis. Energy Build. 231, 110612. https://doi.org/10.1016/j.enbuild.2020.110612.

Cahyandito, M.F., 2009. The MIPS Concept (Material Input Per Unit of Service): A Measure for an Ecological Economy. Padjadjaran University.

de Oliveira, C.T., Dantas, T.E.T., Soares, S.R., 2021. Nano and micro level circular economy indicators: assisting decision-makers in circularity assessments. Sustain. Prod. Consum. 26, 455–468. https://doi.org/10.1016/j.spc.2020.11.024.

Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods : a critical analysis. J. Clean. Prod. 142, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196.

Ellen MacArthur Foundation, 2015. Circularity Indicators: an Approach to Measuring Circularity. Ellen MacArthur Found.

Franklin-Johnson, E., Figge, F., Canning, L., 2016. Resource duration as a managerial indicator for Circular Economy performance. J. Clean. Prod. 133, 589–598. https://doi.org/10.1016/j.jclepro.2016.05.023.

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – a new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048.

Goddin, J., Marshall, K., Pereira, A., Design, G., Herrmann, S., Ds, S., Sam, J., Dupont, T., Krieger, C., Lenges, E., Ben, C., Pierce, J., Susan, E., Gispen, I.-J., Veenendaal, R., Per, I., Natureworks, S., Ford, L., Goodman, T., Vetere, M., Graichen, F., Anu, S., Tetrapak, N., Cockburn, D., 2019. An Approach to Measuring Circularity.

Govindan, K., Hasanagic, M., 2018. A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective. Int. J. Prod. Res. 56, 278–311. https://doi.org/10.1080/00207543.2017.1402141.

Haigh, L., Wit, M. de, Daniels, C. von, Colloricchio, A., Hoogzaad, J., Fraser, M., Sutherland, A.B., McClelland, J., Morgenroth, N., Heidtmann, A., 2021. The Circularity Gap Report 2021, 71. Circ. Econ.

Hallstedt, S.I., 2017. Sustainability criteria and sustainability compliance index for decision support in product development. J. Clean. Prod. 140, 251–266. https://doi.org/10.1016/j.jclepro.2015.06.068.

Harris, S., Martin, M., Diener, D., 2020. Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. Sustain. Prod. Consum. 26, 172–186. https://doi.org/10.1016/j.spc.2020.09.018.

Hamburg GmbH, ifu, 2020. e! Sankey.

Jobmeal A.B., 2022. https://www.jobmeal.se/ (Accessed 17 February 2022).

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2017.09.005.

Kjaer, L.L., Pigosso, D.C.A., Niero, M., Bech, N.M., McAloone, T.C., 2019. Product/service-systems for a circular economy: the route to decoupling economic growth from resource consumption? J. Ind. Ecol. 23, 22–35. https://doi.org/10.1111/jiec.12747.

Konietzko, J., Bocken, N., Hultink, E.J., 2020. A tool to analyze, ideate and develop circular innovation ecosystems. Sustain. Times 12, 14–17. https://doi.org/10.3390/SU12010417.

Korhonen, J., Honkasalo, A., Seppälä, J., 2018. Circular economy : the concept and its limitations. Ecol. Econ. 143, 37–46. https://doi.org/10.1016/j.ecolecon.2017.06.041.

Kravchenko, M., Tim, C., Daniela, C., Pigosso, A., Stief, P., Dantan, J., Etienne, A., Siadat, A., 2019. Implications of developing a tool for sustainability screening of circular economy initiatives. In: Procedia CIRP. Elsevier B.V., pp. 625–630. https://doi.org/10.1016/j.procir.2019.01.044

Kristensen, H.S., Mosgaard, M.A., 2020. A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? J. Clean. Prod. 243, 118531. https://doi.org/10.1016/j.jclepro.2019.118531.

Liedtke, C., Bienge, K., Wiesen, K., Teubler, J., Greiff, K., Lettenmeier, M., Rohn, H., 2014. Resource use in the production and consumption system-the MIPS approach. Resources 3, 544–574. https://doi.org/10.3390/resources3030544.

Linder, M., Sarasini, S., van Loon, P., 2017. A metric for quantifying product-level circularity. J. Ind. Ecol. 21, 545–558. https://doi.org/10.1111/jiec.12552.

Lonca, G., Muggéo, R., Imbeault-Tétreault, H., Bernard, S., Margni, M., 2018. Does material circularity rhyme with environmental efficiency? Case studies on used tires. J. Clean. Prod. 183, 424–435. https://doi.org/10.1016/j.jclepro.2018.02.108.

Lüdeke-Freund, F., Gold, S., Bocken, N.M.P., 2019. A review and typology of circular economy business model patterns. J. Ind. Ecol. 23, 36–61. https://doi.org/10.1111/jiec.12763.

Maio, D., Maio, F., Di Rem, P.C., 2015. A robust indicator for promoting circular economy through recycling. J. Environ. Protect. 6, 1095–1104. https://doi.org/10.4236/jep.2015.610096.

Merli, R., Preziosi, M., Acampora, A., 2018. How do scholars approach the circular economy? A systematic literature review. J. Clean. Prod. 178, 703–722. https://doi.org/10.1016/j.jclepro.2017.12.112.

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Acker, K., de Meester, S., Dewulf, J., 2019. Circular economy indicators: what do they measure? Resour. Conserv. Recycl. 146, 452–461. https://doi.org/10.1016/j.resconrec.2019.03.045.

Rigamonti, L., Mancini, E., 2021. Life cycle assessment and circularity indicators. Int. J. Life Cycle Assess. 26, 1937–1942. https://doi.org/10.1007/s11367-021-01966-2.

Saidani, M., 2019. Monitoring and advancing the circular economy transition. In: Piloter et catalyser la transition vers une économie circulaire – Outils et indicateurs de circularité appliqués. https://doi.org/10.13140/RG.2.2.10123.34084/1.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A taxonomy of circular economy indicators. J. Clean. Prod. 207, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014.

Sönnichsen, S.D., Clement, J., 2020. Review of green and sustainable public procurement: towards circular public procurement. J. Clean. Prod. 245 https://doi.org/10.1016/j.jclepro.2019.118901.

Varubolaget A.B., 2022. https://rp.se/ (Accessed 17 February 2022). Varubolaget will cease to exist, but the interviewees can now reached at Research Partner, a company applying the same business model.