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Performance measurement system for circular supply chain management

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ABSTRACT

Circular supply chain management is characterized by multiple interdependencies between various performance objectives for circularity, economic, environmental and social performance. A performance measurement system which takes these interdependencies into account is currently not available, however, is needed to identify effective actions, involve stakeholders and prevent unintended consequences of actions. The objective of this paper is to develop this performance measurement system. Using a methodology of multiple case studies, we identify the interdependencies between the various performance objectives and combine these in a causal loop diagram and a system dynamics model. We then evaluate the usability of these models in two companies which are in transition to circular supply chain management. The companies confirm the relevance of performance objectives, their interdependencies and the validity of the outputs. This results in the following contributions: Service lifetime - the time period of use, recovery and reuse until incineration - is as relevant to circularity as the much-mentioned product lifetime. The maturity of circularity follows four phases: virgin materials only, combination, recovered materials only, deterioration. Shortening the supply chain leads to a rebound effect and increases the environmental impact. The circular premium can relate to shareholders as well as to customers.

1. Introduction

Circular supply chain management is characterized by a specific set of performance objectives and strives for circular, economic, environmental, and social benefits in parallel (Cagno et al., 2022; Lahane et al., 2020; Roy et al., 2022; Vegter et al., 2020). Multiple interdependencies exist between these performance objectives and insight in these interdependencies is, for multiple reasons, required to support the transition from linear supply chains to circular supply chains. Different performance objectives serve the interests of different stakeholders and insight in their interdependencies reveals over time which interests are compatible and which interests lead to conflicts (Taghikhah et al., 2019). This insight enables to improve the involvement of stakeholders to support the transition to circular supply chains. Moreover, the 9R framework is now widely used to determine a circular strategy. This framework describes a hierarchy of ten circular strategies (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover) and suggests circular strategies higher in the hierarchy lead to more sustainability (Potting et al., 2017). However, recent studies indicate that this is certainly not by definition the case and that there is a complex interdependence between circular strategies and sustainability (Blum et al., 2020). Insight in this interdependence enables to formulate circular supply chain strategies which promote sustainability (Lahane et al., 2020; Vegter et al., 2020). Finally, when interdependencies are omitted, actions to promote sustainability have undesirable consequences, the so-called rebound effects. Insight in interdependencies enables to predict the consequences of actions and prevent frustration during the transition to circular supply chains (Berkhout et al., 2000; Castro et al., 2022). However, despite its necessity, a performance measurement system which includes the interdependencies between performance objectives of circular supply chain management is currently not available. This hinders the transition from linear to circular supply chains (Lahane et al., 2020; Vegter et al., 2021).

System dynamics is a methodology which enables to identify the interdependencies between performance objectives (Oladimeji et al., 2020; Rebs et al., 2019). Currently, there are system dynamics models available which focus on reverse logistics (Kazancoglu et al., 2021), reverse supply chains (Alamerew and Brissaud, 2020) and sustainable supply chains (Oladimeji et al., 2020; Rebs et al., 2019). However, to

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the best of our knowledge there are no system dynamics models available which focus on circular supply chain management (Lahane et al., 2020; Rebs et al., 2019; Vegter et al., 2021). A system dynamics model includes interdependencies between performance objectives and recognizes the dynamic nature of causes and effects which provides several relevant benefits. Firstly, a system dynamics model is able to present how performance develops over time, on multiple dimensions. This enables to determine when an interest of a specific stakeholder is served over time and improve the involvement of stakeholders in the transition to circular supply chains. Secondly, a system dynamics model is able to determine which actions aimed at which performance objective are effective in a specific context which enables to develop a variety of possible circular transition strategies more nuanced and more effective than the currently common 9Rs (Farooque et al., 2019; Lahane et al., 2020; Potting et al., 2017). Finally, a system dynamics model is able to detect unintended consequences of actions, the rebound effects, which enables to prevent actions that frustrate the transition to circular supply chains (Castro et al., 2022). Therefore, our research objective is to develop a performance measurement system, using system dynamics, which includes interdependencies between performance objectives of circular supply chain management.

The paper is structured as follows: Section 2 presents an overview of the theoretical background. Section 3 describes the research methods and the research process. Section 4 presents the results of the study. Section 5 discusses the results and suggests directions for further research. Finally, Section 6 summarizes the knowledge contributions.

2. Theoretical background

The theoretical background presents the current state in the areas of performance measurement, circular supply chain management, barriers in the transition to circular supply chains, sustainable development and rebound effects.

2.1. Performance measurement

Performance measurement is typically used to plan, design, implement and monitor supply chains (Cagno et al., 2022; Elgazzar et al., 2019; Maestrini et al., 2017). Performance measurement has two main purposes: external reporting and internal control. External reporting provides information to various stakeholders that have an interest in the performance of the company. Internal control aims to manage the operation in a better way so the performance can improve (Cagno et al., 2022; Maestrini et al., 2017). Performance measurement requires to determine a strategy, to derive key performance objectives, to measure performance levels and to indicate necessary performance improvements (Cagno et al., 2022; Elgazzar et al., 2019; Maestrini et al., 2017).

Performance measurement systems can be classified based on their phase of development. In phase 1. Design, the performance objectives are defined and measured. In phase 2. Implementation, data is collected and analyzed. In phase 3. Use, the key dimensions of strategy are measured and in phase 4. Review, the interdependencies between performance objectives are recognized and assumptions are challenged (Maestrini et al., 2018; Vegter et al., 2021). The phase of development in current academic literature is that various performance measurement systems for circular supply chain management are in phase 1, 2 and 3. These performance measurement systems can define and measure performance objectives, collect and analyze data and measure key dimensions of strategy. However, there are no performance measurement systems in phase 4. The currently available performance measurement systems for circular supply chain management lack the ability to recognize interdependencies between performance objectives and the dynamic nature of their causes and effects (Vegter et al., 2021).

System dynamics enables to identify these interdependencies and capture the dynamic nature of causes and effects (Bassi et al., 2021; Oladimeji et al., 2020; Rebs et al., 2019; Roci et al., 2022). A system dynamics model is a representation of multiple cause-and-effect relationships and increases the understanding of the behavior of complex systems over time (Roci et al., 2022; Towill, 1996). Key elements of a system dynamics model are reinforcing feedback, balancing feedback and delay. Reinforcing feedback accelerates the growth or decline of the system. Balancing feedback reduces the gap between the current state and the goal-state of the system. Delay refers to any delay in time between action and response of the system (Towill, 1996). System dynamics has various applications in supply chain management, sustainable supply chain management, sustainable business models, circular economy and the development of performance measurement systems (Bassi et al., 2021; Oladimeji et al., 2020; Rebs et al., 2019; Roci et al., 2022).

2.2. Circular supply chain management

With circular supply chain management, the concept of circular economy is integrated in supply chain management (Farooque et al., 2019; Lahane et al., 2020; Roy et al., 2022; Vegter et al., 2021). A circular economy aims to reduce, maintain and recover resources to accomplish sustainability (Ellen Mac Arthur Foundation, 2013; Kirchherr et al., 2017). Circular supply chain management is “the design and control of a network of organizations and end-users that strives for economic, environmental, and social benefits by reducing, maintaining, and recovering resources in restorative and regenerative cycles” (Vegter et al., 2021).

Circular supply chain management differs from reverse and closed-loop supply chains in its focus on reducing, maintaining and recovering natural resources and its scope on restorative and regenerative cycles and is characterized by an interdependent set of performance objectives (Ellen Mac Arthur Foundation, 2013; Roy et al., 2022; Vegter et al., 2020; Vegter et al., 2021). In restorative and regenerative cycles, materials are extracted from the Earth, sourced and transformed into a product, used, repaired, reused and recycled and eventually discarded to the Earth through incineration or landfill (Roy et al., 2022). The duration of restorative and regenerative cycles is measured as the service lifetime, which is the period from the substance's extraction from the Earth until discard. This duration indicates how long a substance is used, recovered and reused until it is incinerated or landfilled (Cooper, 1994). Circular supply chain management is characterized by a specific set of performance objectives:

i. minimize the use of materials, water and energy (Bocken et al., 2016; Lim et al., 2022; Vegter et al., 2020)
ii. minimize inventory. Inventory has the risk of becoming obsolete which will lead to waste (Ellen Mac Arthur Foundation, 2013; Vegter et al., 2020)
iii. maximize the efficient use of Supply Chain Assets. A higher utilization of supply chain assets (such as trucks, warehouses, machines, equipment) leads to less energy use and less environmental impact (Geissdoerfer et al., 2018; Vegter et al., 2020)
iv. minimize waste. Waste is any resource disposed during or after resource extraction, production, distribution and use without being useful to the user (Bocken et al., 2016; Lim et al., 2022; Roy et al., 2022; Vegter et al., 2020)
v. maximize the availability of the product. Prolonging the product lifetime avoids the use of resources to produce a new product (Bocken et al., 2016; Bressanelli et al., 2019; Roy et al., 2022; Vegter et al., 2020)
vi. maximize the number of recovery flows. Maximizing the number of times a product is recovered in any supply chain avoids the mining of additional virgin materials to fulfill the users' need (Lahane et al., 2020; Lim et al., 2022; Roy et al., 2022; Vegter et al., 2020).

2.3. Barriers in the transition to circular supply chains

A transition from a linear supply chain to a circular supply chain faces various barriers related to new technologies, market acceptance and the involvement of stakeholders. The first barrier is the need for new technologies. Circular supply chains focus on products-as-a-service, a long product lifetime, products which are easy-to-disassemble and tracking and tracing during multiple lifecycles (Bressanelli et al., 2019; Farooque et al., 2019; Roy et al., 2022). This requires the development and adaptation of new technologies which involves substantial investments and associated risks. Products-as-a-service even has a longer payback period of these investments (Ayati et al., 2022; Roy et al., 2022). The second barrier is the market acceptance of recovered products and materials. Customers often still prefer an original product over a recovered one. A lack of market standard makes the quality of recovered products and materials more difficult to assess. The unpredictable supply of recovered products and materials makes it an unreliable source for manufacturers and a barrier for collaboration within the supply chain (Ayati et al., 2022; Lahane et al., 2020). Finally, the third barrier is the involvement of stakeholders. Circular supply chains focus on a long product lifetime. This lifetime is often longer than the lifetime of the company that produces and delivers the product. With that, company has no interest in circularity as these opportunities, its costs, revenues and risks will fall outside the company's lifetime (Lahane et al., 2020; Roy et al., 2022). This is in particular the case with electronic devices, where customers continuously and after a short time, switch to the latest high-tech product, even if they don't need or use all of its latest high-tech applications (Ellen Mac Arthur Foundation, 2018). Moreover, the circular supply chain requires additional processes for return and recovery which leads to additional costs which can be higher than the initial cost savings achieved through reuse or recycling. The resulting cost increase is not in the short-term interest of the company which can hinder the transition to circular supply chains (Ayati et al., 2022; Farooque et al., 2019; Lahane et al., 2020; Roy et al., 2022).

The evolution paths for the transition from linear to circular supply chains are described in maturity models. Maturity models enable supply chains to determine its current phase of development and also provide guidelines for subsequent steps to more advanced phases of development. Development can occur on various dimensions, such as processes, products and services, governance, business models, value creation and technologies (Sacco et al., 2021; Sehnem et al., 2019; Uhrenholt et al., 2022).

2.4. Sustainable development

The transition to a circular supply chain does not by definition lead to sustainable development (Blum et al., 2020). Although reducing waste and using recovered materials reduces the use of virgin materials, the additionally required reverse logistics and recovery processes lead to an increase of environmental impact (Taghikhah et al., 2019). Moreover, different materials, transport modalities, manufacturing processes all have different environmental impact. Different manufacturing locations, employment created and salaries paid have different societal impact. This emphasizes the importance of measuring the environmental and societal impact using the methodology of life cycle assessment, such as with eco-cost. Eco-cost is “a measure to express the amount of environmental burden of a product on the basis of prevention of that burden, and these are the costs that should be made to reduce the environmental pollution and materials depletion in our world to a level, which is in line with the carrying capacity of our Earth” (Vogtländer et al., 2001). Eco-cost is subdivided into materials, transport modalities (air, rail, road and water) and manufacturing processes, such as injection molding, coating, welding and includes sub indicators for carbon footprint, resource depletion, toxicity, fine dust and smog. S-eco-cost is “a measure to account for the unacceptable exploitation of workers” (van der Velden and Vogtländer, 2017). S-eco-cost includes sub indicators for minimum acceptable wage, child labor, extreme poverty, excessive working hours and occupational safety and health (van der Velden and Vogtländer, 2017).

Eco-cost and s-eco-cost provide insight in the prevention costs of the environmental and societal impact and represent the supply side of the supply chain. Circular premium provides insight in the consumer's willingness to pay for a certain sustainable product and represents the demand side of the supply chain. Circular premium is the difference between the circular price (= the price required for a 100 % bio-based product obtained with a sustainable approach) and the normal price (= the price consumers currently pay for fossil fuel-based products) (Appolloni et al., 2022; D'Adamo and Lupi, 2021). The circular premium can be positive and negative. A positive circular premium indicates that consumers are willing to pay more for a sustainable product. A negative circular premium indicates that consumers perceive the sustainable product as inferior to the regular product and are willing to pay less (Colasante and D'Adamo, 2021; D'Adamo and Lupi, 2021). Costs, revenues, eco-costs and circular premium are all expressed in a monetary unit which allows them to be compared relative to each other and enables to determine the feasibility of sustainable development.

The Sustainable Development Goals (SDGs) of the United Nations are the blueprint for sustainable development. These 17 goals vary from ‘no poverty’ and ‘reduced inequalities’ to ‘decent work and economic growth’ (United Nations, n.d.). Circular supply chain management, as described in Section 2.2, aims to reduce, maintain and recover natural resources (materials, water, energy) which promotes to realize SDG6 ‘Clean water and sanitation’, SDG7 ‘Affordable and clean energy’, SDG12 ‘Responsible consumption and production’ and SDG13 ‘Climate action’ (United Nations, n.d.).

2.5. Rebound effects

Circular practices can lead to rebound effects which are “divergent outcomes or effects from the intended benefits caused by a systemic response to efficiency or technical change” (Berkhout et al., 2000). The rebound effect describes a situation in which an increased efficiency in production or transport is expected to decrease environmental impact. However, due to the increased efficiency, consumption becomes cheaper which leads to an increase of consumption and, as a result, creates more environmental impact (Zink and Geyer, 2017). Although the rebound effect is often described in relation to energy efficiency, literature also describes various examples of the rebound effect in relation to material and water efficiency (Castro et al., 2022). Whether a rebound effect occurs is dependent on the complexity of the system and by adopting circular practices the complexity of the system increases (Castro et al., 2022; Zink and Geyer, 2017). This argues for a systems approach to be able to identify rebound effects and reliably assess sustainable development on multiple performance objectives over time.

3. Methods

The research objective is to develop a performance measurement system, using system dynamics, which represents the interdependencies between performance objectives of circular supply chain management. A common method to develop a performance measurement system, using system dynamics, consists of two stages. Stage 1 is to develop a qualitative model of interdependencies using causal-loop diagramming (Campuzano and Mula, 2011; Kim, 1999). Stage 2 is to translate this qualitative model into a quantified simulation model. The dynamic behavior of the quantified simulation model is tested using company data. Finally, the dynamic behavior is used to validate the performance measurement system (Towill, 1996).

In stage 1 a qualitative model of interdependencies is developed using causal loop diagramming. The causal loop diagram represents the interdependencies between performance objectives of circular supply chain management. These interdependencies are identified using a database of case studies (Ellen Mac Arthur Foundation, n.d.). This database is used because it provides a wide variety of cases of companies from various industries and various countries who all serve as a leading example for the application of circular practices. The database is developed by the Ellen Mac Arthur Foundation, which is a renowned organization, known for its extensive knowledge of the circular economy. The Ellen Mac Arthur Foundation has collected and described the cases with the aim of giving companies insight in circular practices and the performance objectives that can be achieved with these practices. These characteristics together provide a broad and varied understanding of the interdependencies between performance objectives.

The database consists of in total 164 cases which are categorized by topic. The topics 'Cities', 'Education', 'Finance' and 'Policy' are excluded from further analysis because these topics are not relevant. Some case studies are categorized in the database based on multiple topics. These case studies are selected based on the inclusion topic to ensure the widest range of case studies used for analysis. 128 case studies in the database are studied to identify cases that contain information on interdependencies between performance objectives. From these 128 case studies, in total 15 case studies contained information on interdependencies between performance objectives as described in Table 1.

The case studies used to develop the causal loop diagram are described in Table 2.

The interdependencies between performance objectives of circular supply chain management are captured in the following steps. Each case study is read to identify if the text refers to any of the performance objectives as described in Section 2.2 of this paper. If the text refers to a performance objective, it is subsequently assessed whether the text refers to another performance objective. When the text refers to another performance objective then both performance objectives are noted, together with their positive or negative relationship as described in the text. When the text doesn't refer to another performance objective, it is not included because this research explicitly focuses on relationships between performance objectives. When the text refers to a relationship with a performance objective other than those described in Section 2.2 of this paper, then this other performance objective is listed separately, together with its positive or negative relationship. Finally, the various relationships are interconnected following the methodology to develop a causal loop diagram (Campuzano and Mula, 2011; Kim, 1999).

Subsequently, two companies are selected to validate the causal loop diagram. These companies – abbreviated with company WB and company CE – are companies we have access to and were willing to participate in our research. Both companies are SMEs and are aiming to transition to circular supply chain management which makes them suitable as case studies. The companies have similarities, but also differ in various aspects. Company WB has predictable demand, low contribution margin, products with a long lifetime and a short supply chain. Company CE has unpredictable demand, high contribution margin, products with a short lifetime and a global supply chain. These differences promote a wider variation of the validation of the causal loop diagram and – at a later stage – the system dynamics model which contributes to the generalization of findings from case studies (Eisenhardt, 1989). The causal loop diagram is validated by asking two managers in both companies whether the relationships in the model are relevant to identify challenges in the transition to circular supply chain management (Barlas, 1996). The managers are selected based on their knowledge of circularity and supply chain management.

Table 1
Exclusion and inclusion criteria for case studies.

Total number of case studies in database		164
Excluded based on relevancy of topic		
- Cities	24	
- Education	1	
- Finance	2	
- Policy	9	
Total excluded based on relevancy of topic		36
Included based on relevancy of topic		
- Biodiversity	14	
- Built environment	1	
- Business	25	
- Climate	2	
- Design	20	
- Fashion	29	
- Food	22	
- Plastics	15	
Total number of relevant case studies		128
Excluded based on the absence of interdependencies between performance objectives in the case study	112	
Total number of case studies used to develop causal loop diagrams		16

Table 2
Case studies from database included in the current research.

Company number	Topic of the case study
1	A remanufacturing factory in an ecosystem
2	Reusable products for multiple brands
3	A shared system of reusable products
4	More efficient use of assets
5	A subscription model
6	Modularity, disassembly and life extension
7	Design principles for the circular economy
8	Circular supply chain management
9	Recycling for the circular economy
10	Product-as-a-service
11	Materials, recycling, product design and new business models
12	Reverse logistics
13	Cradle to Cradle
14	Product-as-a-service
15	Net zero sustainability
16	Subscription model for modular products

In stage 2 the qualitative model is translated into a quantified simulation model. More specifically, the causal loop diagram is translated into a system dynamics model, following the steps as described by Aronson and Angelakis (2018). Subsequently, the following data is collected in both companies to enable the simulation:

Demand = expected sales in number of products per time period;

Material Intensity = the amount of Kilograms materials per product;
Materials cost per Kilogram material = the average materials price per Kilogram material;
Materials eco-cost per Kilogram material = the average eco-cost per Kilogram material;
Transport cost per ton kilometer = the average amount of ton kilometers of transport multiplied with the average transport price per ton kilometer;
Transport eco-cost per ton kilometer = the average amount of ton kilometers of transport multiplied with the average eco-cost per ton kilometer of transport;
Production cost per Kilogram product = the average price of production of a Kilogram product;
Production eco-cost per Kilogram product = the average eco-cost of production of Kilogram product;
Miscellaneous = average sales price per product; service lifetime; product lifetime; supply chain lead time; return supply chain lead time; maximum capacity of assets for transport and production; maximum capacity of assets for return and recovery;

The unit 'ton kilometer' represents the movement of 1000 Kilograms material over a distance of 1 Kilometer.

In both companies, in consultation with their management, three scenarios are determined which represent increasing levels of performance improvement on the performance objectives which characterize circular supply chain management. The scenarios are described in Section 4 Results. The scenarios are simulated using the system dynamics model and the collected data. The structure and behavior of the system dynamics model are validated by the managers of both companies based on the following criteria (Barlas, 1996; Senge and Forrester, 1980):

i. direct structure test: can the managers confirm that the relationships and the parameters in the model exist in the real system
ii. structure-oriented behavior test: can the managers confirm that the model generates similar modified behavior when simulated with various scenarios
iii. behavior pattern test: can the managers confirm that the output of the model matches with the real or expected outputs.

Finally, during the development of the qualitative and quantitative model, a set of performance measures relevant for circular supply chain management is developed. This is done by developing a performance measure for each performance objective and assigning the performance measure to processes. The performance measures are based on the SCOR model (ASCM, 2022), a standard used by practitioners and academics to assign performance measures to performance objectives. In the calculation of the performance measures the unit is changed to 'Kg material' to unify the variables within the model. The definition and calculation of circularity is based on the SCOR model (ASCM, 2022) and the World Business Council for Sustainable Development (2022).

The next section presents the results: the qualitative model and the quantitative model of circular supply chain management and their evaluation, the tests of the dynamic behavior of the quantitative models, the key findings as outcome of the tests and the set of performance measures for circular supply chain management.

4. Results

The first paragraph presents the qualitative model of circular supply chain management. This model is described based on its reinforcing and balancing feedback loops. The second paragraph presents the quantitative model of circular supply chain management and is described based on its main stocks and flows. Finally, the third paragraph describes the tests of the dynamic behavior of the quantitative model of circular supply chain management.

4.1. A qualitative model of circular supply chain management

The qualitative model of circular supply chain management, derived from the various case studies in the database and represented in a causal loop diagram, is shown in Fig. 1. The qualitative model consists of four feedback loops which are motivated by a number of exemplary cause-and-effect relationships derived from the various case studies in the database.

The first feedback loop in circular supply chain management is a reinforcing feedback loop related to the demand for products. More demand leads to more sales which leads to more products at end of life. More products at end of life leads to more customers wanting to replace their product and thereby to more demand. This reinforcing feedback loop is affected by the product lifetime and service lifetime. With a longer product lifetime, it will take longer for products to be replaced which leads to less demand. If the product is at end of life and the company can recover the product, then customers will return their product and buy a new product from this company. This new product may be a reused or recycled version of the product at end of life. The case of company 1 indicates these relationships. At end of life, their products can be remanufactured multiple times during its service lifetime. These remanufactured products are resold to existing customers and by doing so the customers are retained for the company. Moreover, the case of company 6 describes how end-of-life of the product means the end of the relationship with the customer. This leads to a reconsideration by the customer whether to buy a product from this company or from a competitor. Company 16, therefore, uses durable and standardized components to be able to easily maintain and upgrade their products and form a closer, longer lasting relationship with the customer. Subscription and lease programs, as described in the cases of company 5, 10, 13 and 16, are a common way in various industries to retain customers with products with a long product lifetime.

The second feedback loop in circular supply chain management is a balancing feedback loop related to the supply of virgin or recovered materials. More material use leads to more virgin materials used. However, recovery leads to less virgin materials used. The product lifetime

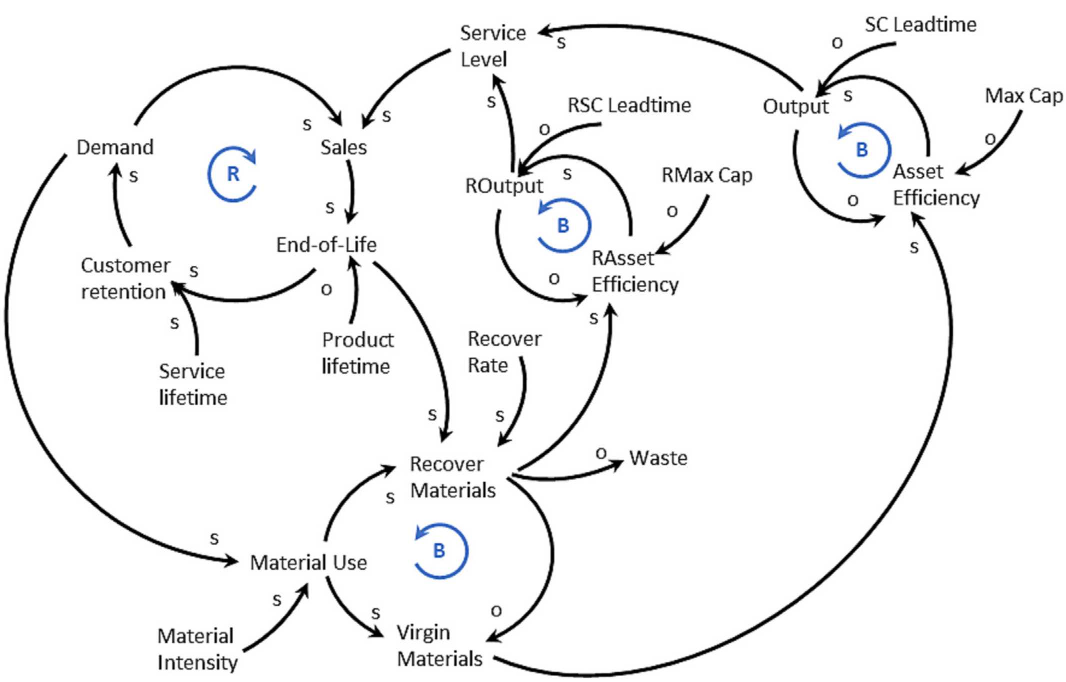

Fig. 1. Causal loop diagram of circular supply chain management.
Legend: R = Reinforcing feedback loop; B = Balancing feedback loop; s = same, a change of one variable leads to a change in the same direction for the other variable; o = opposite, a change of one variable leads to a change in the opposite direction for the other variable.

plays a key role in this balancing feedback loop. A product with a long lifetime delays this balancing effect and it also means that it takes a longer time before recovered materials are available and virgin materials can be replaced. The case of company 6 describes how their modularity and lifetime extension of components enables a longer lifetime with easy repairs. The recycled materials are used as input for manufacturing. The case of company 7 indicates the relationship between recover rates and waste. In their products, clean materials that can be easily dismantled enable reuse over recycling and these higher recover rates lead to less waste. Furthermore, the case of company 9 describes that less waste occurs by reusing the components of their products rather than recycling its materials. Finally, company 14 aims for greater control over the products they produce, enabling better maintenance and recovery which leads to less waste.

The third and fourth feedback loop in circular supply chain management are balancing feedback loops related to the use of assets for production, transport and recovery, such as machines and trucks. These assets use energy and a key characteristic of circular supply chain management is to aim for an efficient use of assets to reduce the use of energy per product. A more efficient use of assets results from a combination of availability of materials, maximum capacity, supply chain lead time and output. This balancing feedback loop occurs for the assets which produce and transport the product from virgin materials as well as the assets which handle the return and recovery. The separate loops for production from virgin materials and for return and recovery are motivated by the case of company 1 which indicates that this company has setup a separate group of assets in an eco-system of partner companies to handle the recovery flow. The case of company 11 indicates that a stable supply of recycled materials is key to fulfill its demand from customers. The case of company 8 describes the relevance of materials, capacity, lead time and output to be able to quickly respond to demand without using inventory which has the risk to become obsolete. The cases of company 2 and company 3 describe the importance of an efficient use of assets for the feasibility of a recovery flow.

4.2. A quantitative model of circular supply chain management

A quantitative model is developed based on the qualitative model presented in the previous section. A quantified model consists of the stocks and flows of the system. For circular supply chain management there are three main stocks and flows which are described below.

4.2.1. Market and Customers

The stock and flow of Markets and Customers is shown in Fig. 2.

The demand for the product is the inflow of the stock 'Market'. The demand can be fulfilled by sales, which is the outflow of the stock 'Market'. Whether sales occur depends on the service level, the extent to which demand can be met with supply. In case there is no supply available in a certain time period, this demand is considered to be lost sales and remains within the stock 'Market'. This demand will be fulfilled by competitors and can therefore not be regained in upcoming time periods. In case there is sufficient supply available, the demand leads to sales and therefore to an increase of customers. Sales is the inflow of the stock 'Customers'. The relationship with the customer ends at the end of life (EoL) of the product, which is determined by the product lifetime, and this is the outflow of the stock 'Customers'. Although the relationship with the customer ends at end of life, these customers are retained within the service lifetime, which leads to additional demand. End of life products are the secondary input for recover materials in the stock and flow described in the next paragraph. Finally, each product has a certain material intensity, the amount of materials per product, which determines how much materials are required to fulfill the demand for the product.

4.2.2. Materials, Recovered materials and Waste

The stock and flow of Materials, Recovered materials and Waste is shown in Fig. 3.

The material use is initially fulfilled with virgin materials. Virgin materials are the inflow of the stock 'Mat' which represents the amount of materials in use by customers until end of life. At end of life there is an additional availability of materials which can be recovered. Materials proceed as recover materials and are then recovered into an end product or proceed as waste, which means the materials are landfilled or incinerated. Whether materials are recovered or are waste is determined by the recover rate, the percentage of the materials in the product which can be recovered. When materials are indeed recovered, these materials are preferred over virgin materials and will replace the demand for virgin materials. Only when there are no recover materials available, virgin materials will be used.

4.2.3. Assets, Recover Assets and Supply

The stock and flow of Assets, Recover Assets and Supply is shown in Fig. 4.

The assets used for initial production and transport (Assets) are separated from the assets used for return and recover (RAssets) to enable different cost, lead times and environmental impact. The stock 'Assets' has a single inflow which are the virgin materials (= total material use minus the recover materials). The stock 'Assets' reflects the amount

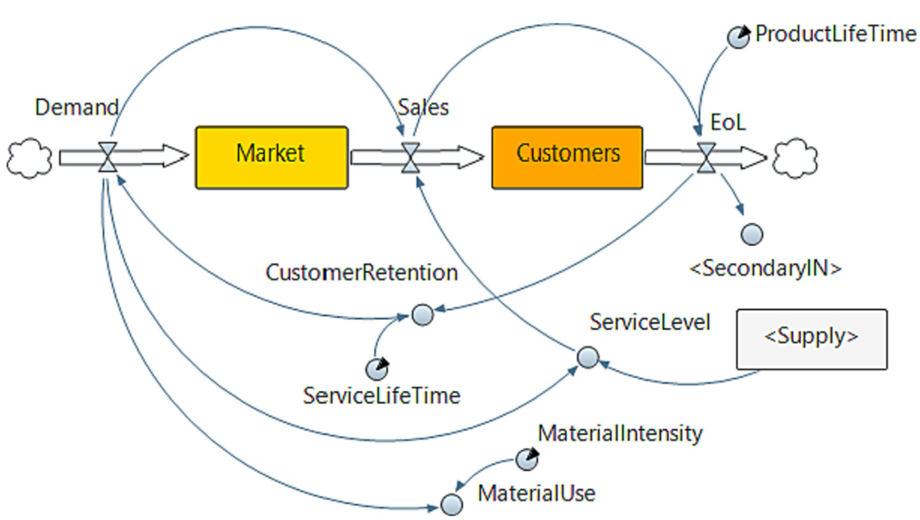

Fig. 2. Market and Customers – stock and flow.

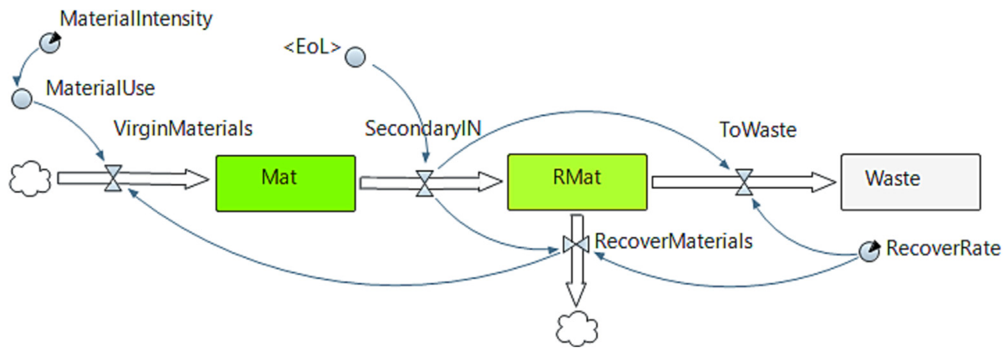

Fig. 3. Materials, Recovered materials and Waste – stock and flow.

of virgin materials which is in progress from extraction to sales (Assets). Likewise, the stock 'RAssets' has a single inflow which is the recovered materials and reflects the amount of materials in progress from end of life to sales. The stocks Assets and RAssets represent a wide variety of trucks, ships, trains, warehouses, machines and equipment and its energy use required for production, transport, return and recovery. For the assets in circular supply chain management the focus is on the most efficient use of assets (machines, trucks, equipment) to improve the efficient use of the energy these assets use. The maximum capacity of assets and the supply chain lead time are fixed. The output is adjusted to maximize asset efficiency.

The stocks and flows result in the following output measures to determine performance over time:

- Revenues = amount of Kilograms actual sales ∗ Sales Price per Kilogram
- Materials Cost = amount of Kilograms Virgin materials ∗ Materials cost per Kilogram material
- Materials Environmental impact = amount of Kilograms Virgin materials ∗ Materials eco-cost per Kilogram material
- Transport Cost = amount of ton kilometers Virgin materials ∗ Transport cost per ton kilometer
- Transport Environmental impact = amount of ton kilometers Virgin materials ∗ Transport eco-cost per ton kilometer
- Production Cost = amount of Kilograms Virgin materials ∗ Production Cost per Kilogram product
- Production Environmental impact = amount of Kilogram Virgin materials ∗ Production eco-cost per Kilogram product
- Return Cost = amount of ton kilometers Recover materials ∗ Transport cost per ton kilometer
- Return Environmental impact = amount of ton kilometers Recover materials ∗ Transport eco-cost per ton kilometer
- Recover Cost = amount of Kilogram Recover materials ∗ Recover Cost per Kilogram
- Recover Environmental impact = amount of Kilogram Recover materials ∗ Recover eco-cost per Kilogram
- Circularity % = (% Recover materials + % Recover Rate) / 2
- Miscellaneous = average sales price per product; service lifetime; product lifetime; supply chain lead time; return supply chain lead time; maximum capacity of assets for transport and production; maximum capacity of assets for return and recovery;

The metric for circularity is adapted from World Business Council for Sustainable Development (2022) for which is assumed that the recovery potential is 100 %. The unit 'ton kilometer' represents the movement of 1000 Kilograms over a distance of 1 Kilometer.

4.3. Tests of the dynamic behavior of the quantitative model

The dynamic behavior of the quantitative model for circular supply chain management is tested based on the performance objectives and the data of company WB and company CE. The companies and the tests will be subsequently described.

Company WB is a manufacturer of waste bins. Demand for the products is stable from year to year with a seasonal pattern within the year.

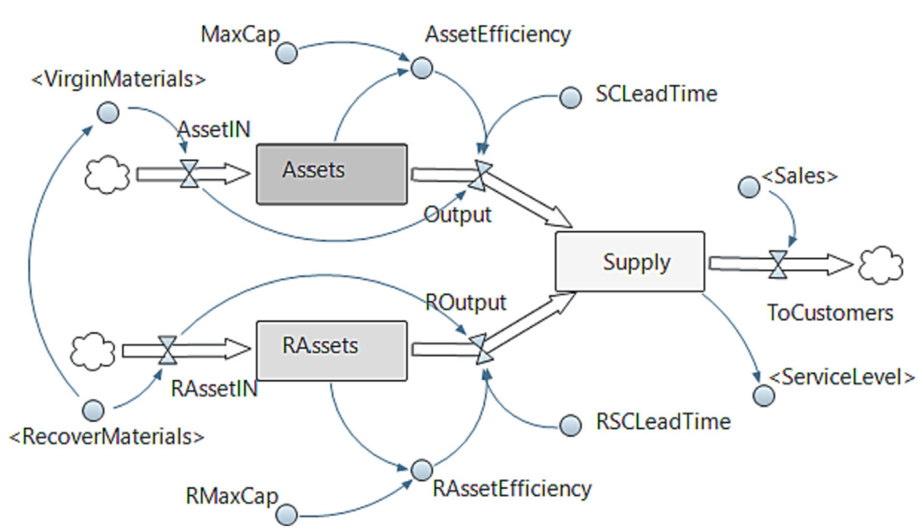

Fig. 4. Assets, Recover Assets and Supply – stock and flow.

The price and the contribution margin are low, mainly because the customer can easily choose an alternative product offered by a competitor. The company sells a product which is designed for high quality with a long lifetime and low cost of maintenance and repair. Company WB has a focus on material efficiency (plate optimization, process quality) and energy efficiency (efficient use of assets). Although its product is designed to be returned after end of life, due to its long lifetime it is still unknown how many products will actually return. After the product is returned, a quality check, cleaning and possibly some minor repairs enables that the product can be reused in a consecutive lifetime.

The performance objectives of company WB are to decrease waste in manufacturing (plate optimization, process quality) and to increase asset efficiency (more efficient energy use). This is simulated in three scenarios: current situation, minor improvement (5 % improvement on the performance objectives) and major improvement (10 % improvement on the performance objectives). These scenarios, summarized in Table 3, are determined in consultation with the management of the company WB.

Company CE is a developer of consumer electronics products. The product has a short lifetime of three years. The contribution margin is high as customers are willing to pay a higher sales price for the design and innovative applications of the product. Company CE has a focus on developing a shorter supply chain in time and in distance. Manufacturing, return and recovery will be organized in a local site closer to the customer, to build a closer relationship with the customer, better understand the use of the product and thereby enable a better response to future customer needs and demand. Finally, the company CE aims for a shorter supply chain to reduce inventory and financial liabilities before product introduction and also reduce the risk of obsolete inventory after end of life.

The performance objectives of company CE are to shorten the supply chain in distance and in time. This is simulated in three scenarios: current situation (supply chain lead time is 5 months), minor improvements (supply chain lead time is 3.5 months) and major improvements (supply chain lead time is 2 months). These scenarios, summarized in Table 4, are determined in consultation with the management of the company CE.

The identified problem for the performance measurement system is to represent the interdependencies between the performance objectives of circular supply chain management. The managers of company WB (a general manager and a process improvement manager) and of company CE (a general manager and a supply chain manager) confirm that the output measures match with expected outputs, the performance objectives are relevant and their interdependencies are as represented in the performance measurement system. The performance measurement system has led to the following key findings on the dynamic behavior of circular supply chains.

The first key finding is the relevance of service lifetime for circularity, in addition to product lifetime. See also Figs. 5 and 6. The service lifetime reflects the time period in which the product can be used, recovered and reused until it is incinerated or landfilled. The performance measurement system indicates that service lifetime plays a key role in accomplishing circularity on the long term. The service lifetime is not so much determined by the technical capabilities of the materials, but rather by the ability of the user to identify the value of the product and the company to whom the product should be returned for recovery. When the user is not able to identify value and the proper return flow, the product will very likely be offered for recycling by a general waste treatment company. This will reduce circularity on the long term as the performance measurement system indicates.

The second key finding is the maturity of circularity over time. Four phases can be distinguished in the maturity of circularity over time, as presented in Fig. 7. The first phase is 'virgin materials only'. In this phase only virgin materials are used which have a certain recovery potential. The second phase is 'combination'. Virgin and recovered materials are used in combination and its distribution varies. In this phase, circularity has an erratic progression due to varying availability of end-of-life products for recovery. The third phase is 'recovered materials only'. Only recovered materials are used and recovered for a consecutive lifetime. Finally, the fourth phase is 'deterioration'. The service lifetime has passed, materials which are multiple times recovered are now incinerated or landfilled and additional virgin materials are used to fulfill demand. Only when the service lifetime lasts indefinitely, the circularity will continue to remain at a high level.

The third key finding is the result of the test for company CE and its scenarios to shorten its supply chain. Shortening the supply chain has contradictory effects. A shorter distance decreases the cost and the environmental impact of transport. Moreover, a shorter lead time enables a better response to changes in demand, which increases sales and, as a result, increases the environmental impact of the supply chain. In other words, a shorter supply chain appears to have a rebound effect. While it may be organized with the intent to reduce environmental impact, it actually can have a contradictory effect and increase the environmental impact.

The fourth key finding is related to eco cost, cost and circular premium. The customers of company WB are mainly government institutions and larger companies which search and select their suppliers through the use of tenders. In these tenders, sustainability is a requirement that must be met in order to qualify as potential supplier. The customers are not willing to pay for sustainability and the circular premium is zero. However, in order to qualify for the tender, company WB must offer a sustainable product for the normal price and if the sustainable product requires extra costs, then the company WB bears these costs and accepts a lower margin or decides not bid for the tender.

Table 5 presents the cost and eco-cost of a normal product from company WB, made from virgin materials and incinerated after end of use. Table 6 presents the cost and eco-cost of the sustainable product, which is when the normal product is returned, recovered and reused for a consecutive lifetime. Recovery means the returned product is checked for quality and repaired. Both tables present costs and eco costs as indices, wherein the product from virgin materials is set to a total index of 100 and the product from recovered materials is expressed relative to this index.

The normal product is produced from virgin materials and delivered to the customer at total cost of 94.69 per Kg and leads to an environmental impact of 5.31 per Kg. The sustainable product is a product which is returned and recovered at total cost of 72.91 per Kg and an environmental impact of 1.17 per Kg. Both products have no societal burden. Company WB offers its employees a good salary and safe and

Table 3
Scenarios for simulation of system dynamics model – company WB.

Scenario	Decrease waste and increase asset efficiency by	Recover rate	Service lifetime (months)
Current situation	–	0 %	160
Minor improvements	5 %	40 %	160 360
Major improvements	10 %	80 %	160 360

Table 4
Scenarios for simulation of system dynamics model – company CE.

Scenario	Supply chain lead time	Recover rate	Service lifetime (months)
Current situation	5 months	0 %	48
Minor improvements	3.5 months	40 %	48 108
Major improvements	2 months	80 %	48 108

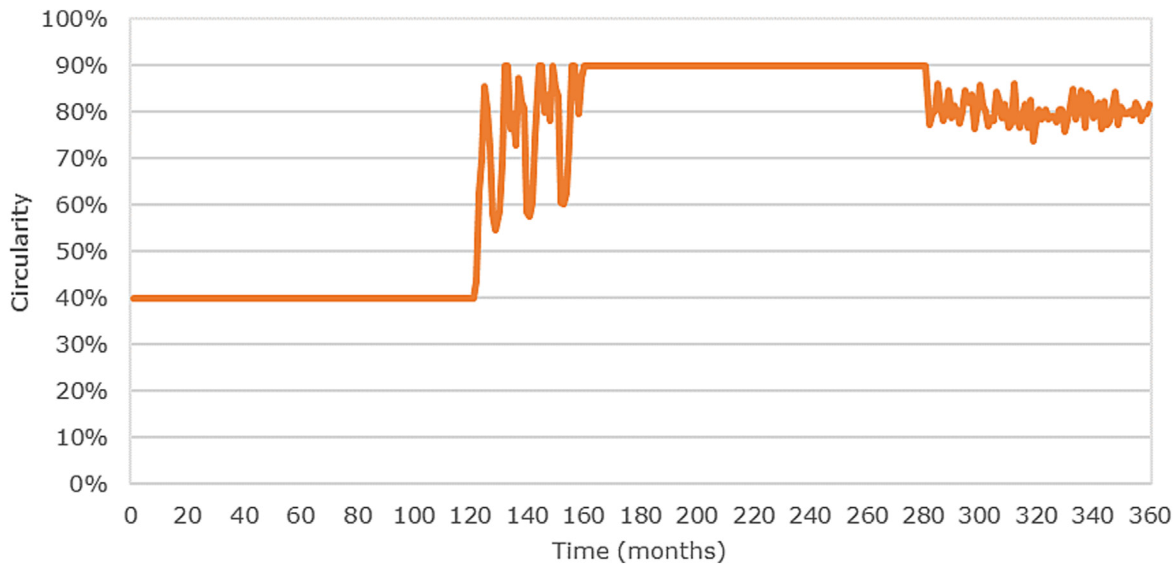

Fig. 5. Circularity over time when product lifetime = 120 months and service lifetime = 160 months.

healthy working conditions which is represented by s-eco-cost of 0.00 per Kg.

There is a difference between the circular cost (= the cost required for a sustainable product) and the normal cost (= the cost required to produce and deliver a fossil fuel-based product) which could be considered a circular premium for the shareholders of the company. In this case, the circular premium for the shareholders is positive, namely 100.00 minus 74.08 = 25.92 per Kg. Compared to the normal product, the sustainable product leads to a decrease of costs. This fits well with the requirements in the tenders that sustainability must be met in order to qualify as supplier while customers are not willing to pay for sustainability. Company WB can offer a sustainable product with less environmental impact for a normal price and accomplish a higher profit margin.

The fifth key finding is related to the factors that determine the use of energy. The use of energy occurs during transport, production, return and recover and is represented in the quantitative model by ‘asset efficiency’ and ‘recover asset efficiency’. Company CE operates a global supply chain with suppliers, manufacturing sites and customers all over the world. This supply chain uses by far the most energy for transport and returns relative to production and recovery, even in a scenario of major improvements, with 60 % reduction of distance and lead time. It is therefore that transport and returns mainly determine the use of energy and the environmental impact. Moreover, the cumulative environmental impact continues to increase during service lifetime, as presented in Fig. 8.

At the end of the product lifetime, at month 36, the cumulative environmental impact of materials and transport stabilizes and the environmental impact of the returns is introduced causing the total cumulative environmental impact to increase continuously over the service lifetime. In this supply chain, the energy use and environmental impact of returns is assumed to be equal to the energy use and environmental impact of transport. Introducing returns and recovery will therefore not lead to a reduction of energy use and environmental impact, only replace those of transport. If the energy use and environmental impact of returns are substantially lower than the energy use and environmental impact of transport, the cumulative environmental impact will stabilize more quickly in time. However, even in this situation the cumulative environmental impact is still steadily increasing. It appears that although all scenarios improve the efficient use of energy, there is

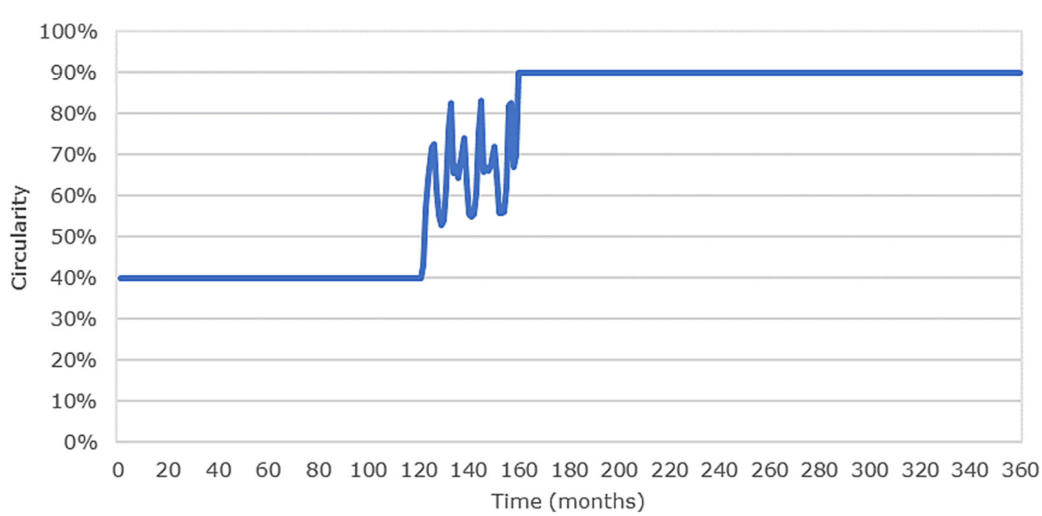

Fig. 6. Circularity over time when product lifetime = 120 months and service lifetime = 360 months.

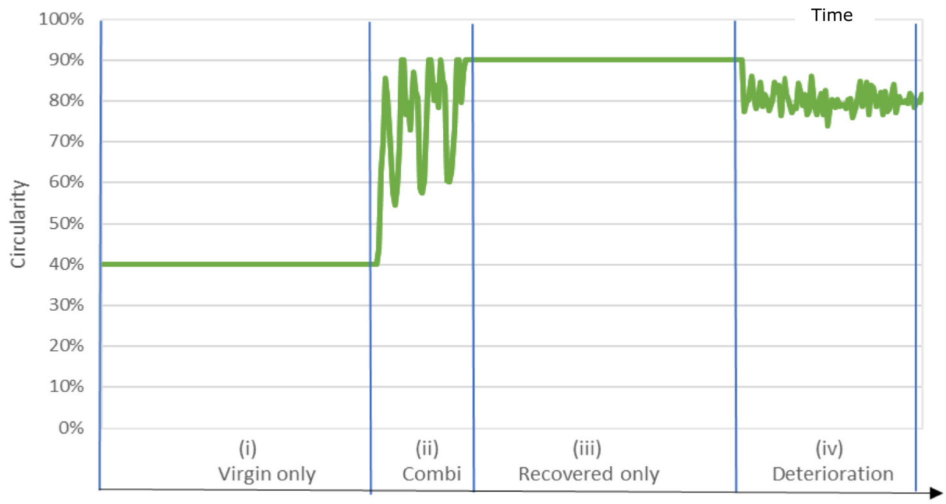

Fig. 7. Maturity of circularity over time.

only one improvement that leads to less energy used and less which is less sales of the final product.

4.4. Performance measures for circular supply chain management

For each performance objective, a performance measure is determined which is assigned to one or more processes. This results in a set of performance measures relevant for circular supply chain management as described in Table 7.

The performance objective to minimize the use of water is not explicitly assigned to a separate performance measure. In the quantitative and qualitative model, water is considered to be a material. For performance measurement, a separate performance measure for water can be included and the same performance measures can be used as is proposed for materials. Social performance is measured by 'Wage level', which is the current wage level minus the minimum acceptable wage in Int $ Purchasing Power Parity.

5. Discussion

Current literature on circular supply chain management mainly refers to closing, slowing, intensifying, narrowing and dematerializing loops (Bocken et al., 2016; Geissdoerfer et al., 2018; Lahane et al., 2020). However, these are in fact product design strategies rather than supply chain strategies. Our results clearly show the potentially large impact of a short supply chain on circularity, economic and environmental performance. This is a sound argument to expand the existing list of loops with 'shortening the loop'.

Current literature on circular supply chain management is mainly focused on the product lifetime which is the maximum period a product can function (Bocken et al., 2016; Geissdoerfer et al., 2018; Lahane et al., 2020; Roy et al., 2022). This certainly is an important variable in circular supply chain management. However, our research introduces the importance of service lifetime for circularity and sustainability. Service lifetime is the time period in which the product can be used, recovered and reused until it is incinerated or landfilled. The simulations indicate that service lifetime determines if a long product lifetime will indeed lead to long term circularity and sustainability.

A longer service lifetime increases customer retention and increases revenues. However, this customer retention and increase of revenues occurs on the long term. Most companies consider this not to be relevant as most service lifetimes will exceed the lifetime of most companies which is a barrier in the transition to circular supply chain management (Lahane et al., 2020; Roy et al., 2022). To overcome this barrier, a solution is to develop 'open source' products which composition is open and known to all. These products can be recovered by any company or consumer which will extend the service lifetime to its maximum and promote circularity. The drivers and barriers to accomplish these 'open source' products is an interesting opportunity for further research.

Sustainability is the accomplishment of economic, environmental and social benefits in parallel (Cagno et al., 2022; Roy et al., 2022; Vegter et al., 2020). This suggests that all benefits are equally important. The sustainable development goals are seventeen goals without any particular priority, suggesting that all goals are equally important. Circular practices, including several discussed in the current paper, lead to more environmental impact on the short term to possibly enable less

Table 5
Cost and eco-cost normal product.

Virgin materials	per Kg	
Materials cost	14.24	
Production cost	79.98	
Transport cost	0.47	
Total cost		94.69
Materials eco cost	4.14	
Production eco cost	1.06	
Transport eco cost	0.11	
Total eco-cost		5.31
Total s-eco-cost		0.00
Total		100.00

Table 6
Cost and eco-cost sustainable product.

Recovered materials	per Kg	
Return cost	0.46	
Recover cost	71.98	
Transport cost	0.47	
Total cost		72.91
Return eco cost	0.11	
Recover eco cost	0.95	
Transport eco-cost	0.11	
Total eco-cost		1.17
Total s-eco-cost		0.00
		74.08

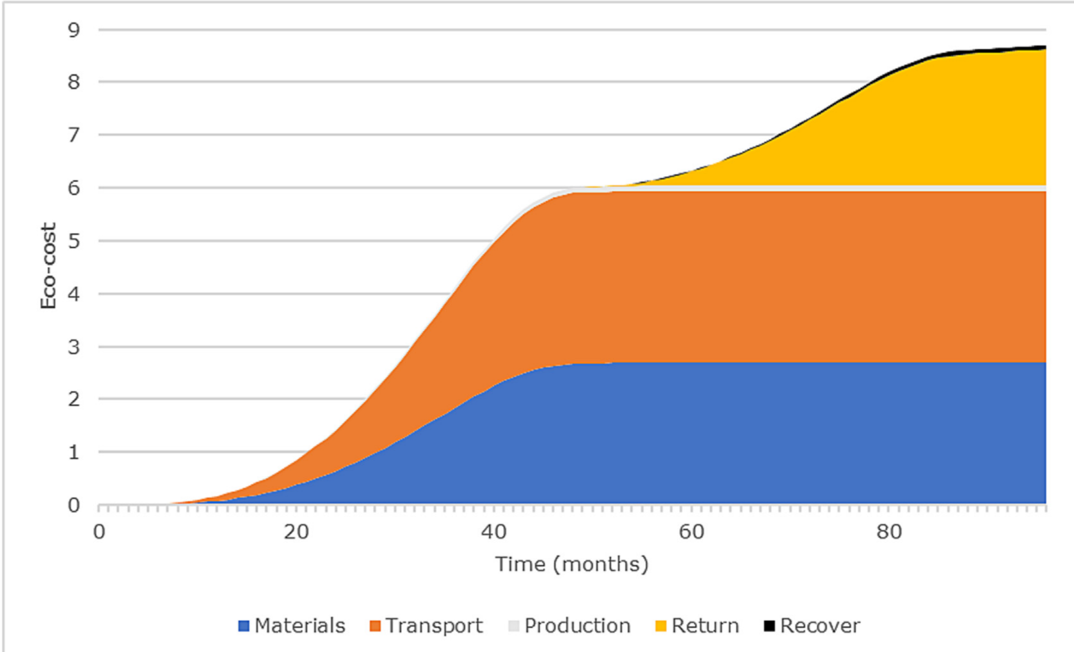

Fig. 8. Cumulative environmental impact over time for company CE in scenario 'major improvements'.

environmental impact on the longer term. The simulations in our study have shown various examples of this scenario. However, the carrying capacity of the Earth is currently already exceeded. Any increase of environmental impact, whether on the short term or on the long term, is destructive for our ecological system and thereby not sustainable. The logical consequence is that sustainability can only occur when circular supply chain management has a negative or no environmental impact and that the priority of benefits in sustainability should be changed to 1) environmental benefits 2) social benefits 3) economic benefits. The implications of a change in priority in sustainability, for research and practice, are an interesting opportunity for further research.

The most common way to determine sustainability, is to measure the economic, environmental and societal impact is using lifecycle assessment, such as eco-cost and s-eco-cost, or using reporting frameworks, such as GRI. These measurements provide a good indication of the absolute impact of a supply chain on profitability, ecology and society and the relative impact such as the energy used per Kilogram. However, these measurements provide no indication of the impact relative to the Earth's carrying capacity, climate agreements or social thresholds and the measurements provide no guidance in determining priorities between economic, environmental and social objectives. Context based sustainability seems to offer many solutions for these issues (McElroy, 2019). Connecting circular supply chain management and context-based sustainability is therefore a promising opportunity for further research.

The Sustainable Development Goals consists of goals such as SDG12 'Responsible consumption and production' and SDG8 'decent work and economic growth' (United Nations, n.d.). These goals lead to various contradictions. Our study indicates that the energy efficiency of production, transport, returns and recovery activities can be improved in various ways and this will reduce the relative impact of the supply chain. However, only less demand for the final product will reduce the absolute amount of energy used and reduce the absolute environmental impact which is required so that our economic activities return within the carrying capacity of the Earth. Less demand seems to be contradictory to the sustainable development goal of economic growth. This indicates the relevance to explore a post-growth economy and society focused on ecology and community rather than on capital accumulation (Bauwens, 2021). A promising opportunity for further research is to explore the role of circular supply chain management in a post-growth economy and society.

Maturity models describe the phases of development on various dimensions during the transition to circular supply chains. These dimensions focus on internal organizational concepts, such as processes, products and business models (Sacco et al., 2021; Sehnem et al., 2019; Uhrenholt et al., 2022). Our study indicates that also in output of circular supply chains certain phases can be distinguished. This offers the possibility to better understand the relationship between internal organizational phases and output phases of development and determine the relative importance of internal organizational concepts in the transition to circular supply chains. This insight enables companies to be more effective in their transition to circular supply chains by developing their key aspects of maturity and is therefore a promising opportunity for further research.

Rebound effects describe a situation in which an increase in resource efficiency leads to an increase of consumption and, as a result, to more resource use (Castro et al., 2022; Zink and Geyer, 2017). Our study did not find a rebound effect as a result of resource efficiency, however, did find a rebound effect as a result of resource effectiveness. The resource effectiveness is improved by a reduction in distance and lead time of the supply chain. This makes it plausible that other dimensions of effectiveness, such as an increase of reliability or agility, also lead to rebound effects. To prevent that actions lead to unintended consequences and frustrate the transition to circular supply chains, more insights in the rebound effects of effectiveness is required which is a promising opportunity for further research.

The circular premium indicates the customer's willingness to pay for a sustainable product (Appolloni et al., 2022; Colasante and D'Adamo, 2021; D'Adamo and Lupi, 2021). In one of the case studies, a sustainable product is a qualifier in order to be considered a potential supplier and the customers are not willing to pay for the sustainable product. This finding indicates that a circular premium can relate to an order qualifier and an order winner. As an order qualifier, the sustainable product is a necessary requirement in order to be considered a potential supplier. The sustainable product can be realized by an increase of efficiency which will decrease cost and increase the profit margin. The increase

Table 7
Performance measures for circular supply chain management.

	Performance objective	Performance measure	Definition and calculation	Assigned to process
i	Minimize the use of materials, water and energy	Sales	Sales in number of products per time period	Order
		Material intensity	The amount of Kilograms materials per product	Source; Transform; Fulfill; Return
		Transport	The average amount of ton kilometers of transport	Fulfill
		Materials cost	The average materials price per Kilogram material	Source; Transform; Fulfill; Return
		Transport cost	The average transport price per ton kilometer	Fulfill
		Processing cost	The average price of processing a Kilogram material	Transform; Return
		Materials environmental impact	The average eco-cost per Kilogram material	Source; Transform; Fulfill; Return
		Transport environmental impact	The average eco-cost per ton kilometer of transport	Fulfill
		Processing environmental impact	The average eco-cost of processing per Kilogram material	Transform; Return
ii	Minimize inventory	Inventory	The amount of inventory in Kilograms materials at a specific point in time	Plan; Order; Source; Transform; Fulfill; Return
iii	Maximize the efficient use of Supply Chain Assets	Capacity utilization	Output in Kilograms materials per time period / Total available capacity in Kg materials per time period	Transform; Fulfill; Return
iv	Minimize waste	Generated waste diverted from disposal	The amount of Kilograms waste diverted from disposal for reuse, recycling or other recovery options	Source; Transform; Fulfill; Return
		Generated waste directed to disposal	The amount of Kilograms waste directed to disposal for landfilling, incineration or other disposal operations	Source; Transform; Fulfill; Return
v	Maximize the availability of the product	Product lifetime	The time period the product functions as desired by the user	Plan; Order; Source; Transform; Fulfill; Return
vi	Maximize the number of recovery flows	Service lifetime	The time period of use, recovery and reuse of the product until it is incinerated or landfilled	Plan; Order; Source; Transform; Fulfill; Return
	Circularity	Circular inflow	Recovered materials used / Total Materials used	Plan; Order; Source; Transform; Fulfill; Return
		Circular outflow	Recovery potential of materials used ∗ Actual recovery of materials	Plan; Order; Source; Transform; Fulfill; Return
		Circularity	The average of Percentage of Circular inflow and Percentage of Circular outflow	Plan; Order; Source; Transform; Fulfill; Return
	Economic performance	Profit	Earnings before Interest = Revenues − Cost of Goods Sold − Operating Expenses	Plan; Order; Source; Transform; Fulfill; Return
	Environmental performance	Resource depletion	Total eco-cost of resource scarcity	Plan; Order; Source; Transform; Fulfill; Return
		Carbon footprint	Total eco-cost of carbon footprint	Plan; Order; Source; Transform; Fulfill; Return
		Toxicity	Total eco-cost of toxicity, acidification and eutrophication	Plan; Order; Source; Transform; Fulfill; Return
		Human health	Total eco-cost of fine dust and summer smog	Plan; Order; Source; Transform; Fulfill; Return
	Social performance	Wage level	Current wage level − Minimum Acceptable Wage in Int $ Purchasing Power Parity	Plan; Order; Source; Transform; Fulfill; Return

in profit margin can be considered as a positive circular premium for the shareholders. The sustainable product can also lead to an increase of cost and then the company has to accept a lower profit margin. The lower profit margin can be considered as a negative circular premium for the shareholders in order to qualify the company as potential supplier. As an order winner, the sustainability of the product is a decisive factor in the buying decision. A positive circular premium indicates that the customers are willing to pay more for the sustainable product. A negative circular premium indicates that the customers expect to pay less for the sustainable product, for example to appropriate part of its cost reduction. Expanding the circular premium to various stakeholders, such as customers and shareholders, enables to provide more insight in the involvement of various stakeholders in achieving a sustainable product. Expanding the concept of circular premium to other stakeholders, such as suppliers, would therefore be a promising opportunity for further research.

This research has limitations due to the use of secondary data in combination with the validation by two companies. Further research could test the performance measurement system in multiple companies to create a more detailed understanding of the validity of the performance measurement system under different contexts.

This performance measurement system defines the interdependencies between performance objectives of circular supply chain management. A limitation of this research is that these interdependencies can still be of very diverse nature and can be reflected in the model through very diverse formulas. The nature of the relationships has a large impact on the performance outcomes. Empirical research on the exact nature of relationships between performance objectives would be a promising opportunity for further research. This research could provide enriched insights in the dynamic behavior of circular supply chain performance over time which would support companies to transition to circular supply chains.

6. Conclusions

The contribution of this paper is a performance measurement system for circular supply chain management which represents the interdependencies between performance objectives of circular supply chain management. Including these interdependencies enables to identify effective actions, to better involve stakeholders and to prevent actions with unintended consequences.

The performance measurement system presents the performance over time on various objectives and as such reveals which interest of stakeholders are compatible and which are in conflict. In particular the interest of consumers and of the natural environment are in conflict. Efficiency improvements have a marginal influence on this conflict. Only an absolute decrease of demand can bring the environmental impact of a supply chain back to a level below the Earth's carrying capacity.

Many more circular strategies than those described in the now widely used 9R framework (reduce, reuse, recycle) are possible. The companies in the case studies determine scenarios for their specific transition to circular supply chain management and the performance measurement system enables to identify the effectiveness of actions within these scenarios. Of all possible actions, changing the service lifetime has a sound impact on circularity on the long term. The maturity of circularity follows four phases: (i) virgin materials only (ii) combination (iii) recovered materials only (iv) deterioration.

The performance measurement system prevents actions with unintended consequences, the so-called rebound effects. One of the companies in the case studies focuses in its scenario of transition to circular supply chain management on shortening the supply chain. The performance measurement system indicates that this scenario leads to a rebound effect that, to the best of our knowledge, not has been previously reported in literature. Although intended to reduce environmental impact, a shorter supply chain leads to a better ability to serve demand which increases sales and thereby increases environmental impact.

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Declaration of competing interest

The authors declare no conflict of interest.

References

Alamerew, Y.A., Brissaud, D., 2020. Modelling reverse supply chain through system dynamics for realizing the transition towards the circular economy: a case study on electric vehicle batteries. J. Clean. Prod. 254, 120025.
Appolloni, A., Jabbour, C.J.C., D'Adamo, I., Gastaldi, M., Settembre-Blundo, D., 2022. Green recovery in the mature manufacturing industry: the role of the green-circular premium and sustainability certification in innovative efforts. Ecol. Econ. 193, 107311.
Aronson, D., Angelakis, D., 2018. Step-by-step stocks and flows: converting from causal loop diagrams. Systems Thinker 10.
ASCM, 2022. Supply Chain Operations Reference Model SCOR. Version 14.0. Retrieved 21 September 2022 from https://scor.ascm.org/processes/introduction.
Ayati, M.S., Shekarian, E., Majava, J., Wæhrens, B.V., 2022. Toward a circular supply chain: understanding barriers from the perspective of recovery approaches. J. Clean. Prod. 131775.
Barlas, Y., 1996. Formal aspects of model validity and validation in system dynamics. Syst. Dyn. Rev. 12 (3), 183–210.
Bassi, A.M., Bianchi, M., Guzzetti, M., Pallaske, G., Tapia, C., 2021. Improving the understanding of circular economy potential at territorial level using systems thinking. Sustain. Prod. Consum. 27, 128–140.
Bauwens, T., 2021. Are the circular economy and economic growth compatible? A case for post-growth circularity. Resour. Conserv. Recycl. 175.
Berkhout, P.H., Muskens, J.C., Velthuijsen, J.W., 2000. Defining the rebound effect. Energy Policy 28 (6–7), 425–432.
Blum, N.U., Haupt, M., Bening, C.R., 2020. Why “Circular” doesn't always mean “Sustainable”. Resour. Conserv. Recycl. 162, 105042.
Bocken, N.M., 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 (5), 308–320.
Bressanelli, G., Perona, M., Saccani, N., 2019. Challenges in supply chain redesign for the circular economy: a literature review and a multiple case study. Int. J. Prod. Res. 57 (23), 7395–7422.
Cagno, E., Negri, M., Neri, A., Giambone, M., 2022. One Framework to Rule Them All: An Integrated, Multi-level and Scalable Performance Measurement Framework of Sustainability, Circular Economy and Industrial Symbiosis. Sustainable Production and Consumption.
Campuzano, F., Mula, J., 2011. Supply Chain Simulation: A System Dynamics Approach for Improving Performance. Springer Science & Business Media.
Castro, C.G., Trevisan, A.H., Pigosso, D.A., Mascarenhas, J., 2022. The rebound effect of circular economy: definitions, mechanisms and a research agenda. J. Clean. Prod. 131136.
Colasante, A., D'Adamo, I., 2021. The circular economy and bioeconomy in the fashion sector: emergence of a “sustainability bias”. J. Clean. Prod. 329, 129774.
Cooper, T., 1994. Beyond Recycling: The Longer Life Option. New Economics Foundation, London.
D'Adamo, I., Lupi, G., 2021. Sustainability and resilience after COVID-19: a circular premium in the fashion industry. Sustainability 13 (4), 1861.
Eisenhardt, K.M., 1989. Building theories from case study research. Acad. Manag. Rev. 14 (4), 532–550.
Elgazzar, S., Tipi, N., Jones, G., 2019. Key characteristics for designing a supply chain performance measurement system. Int. J. Product. Perform. Manag. 68 (2), 296–318.
Ellen Mac Arthur Foundation, 2013. Towards a Circular Economy—Economic and Business Rationale for an Accelerated Transition. Ellen MacArthur Foundation, Cowes, UK.
Ellen Mac Arthur Foundation, 2018. Circular Consumer Electronics. Ellen MacArthur Foundation, Cowes, UK.
Ellen Mac Arthur Foundation, n.d.Ellen Mac Arthur Foundation. (nd). Circular economy examples and case studies. Retrieved 16 August 2022 from https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/examples
Farooque, M., Zhang, A., Thürer, M., Qu, T., Huisingh, D., 2019. Circular supply chain management: a definition and structured literature review. J. Clean. Prod. 228, 882–900.
Geissdoerfer, M., Morioka, S.N., de Carvalho, M.M., Evans, S., 2018. Business models and supply chains for the circular economy. J. Clean. Prod. 190, 712–721.
Kazancoglu, Y., Ekinci, E., Mangla, S.K., Sezer, M.D., Kayikci, Y., 2021. Performance evaluation of reverse logistics in food supply chains in a circular economy using system dynamics. Bus. Strateg. Environ. 30 (1), 71–91.
Kim, D.H., 1999. Introduction to Systems ThinkingVol. 16. Pegasus Communications, Waltham, MA.
Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232.
Lahane, S., Kant, R., Shankar, R., 2020. Circular supply chain management: a state-of-art review and future opportunities. J. Clean. Prod. 258, 120859.
Lim, M.K., Lai, M., Wang, C., Lee, Y., 2022. Circular economy to ensure production operational sustainability: a green-lean approach. Sustain. Prod. Consum. 30, 130–144.
Maestrini, V., Luzzini, D., Maccarrone, P., Caniato, F., 2017. Supply chain performance measurement systems: a systematic review and research agenda. Int. J. Prod. Econ. 183, 299–315.
Maestrini, V., Luzzini, D., Caniato, F., Maccarrone, P., Ronchi, S., 2018. Measuring supply chain performance: a lifecycle framework and a case study. Int. J. Oper. Prod. Manag. 38 (4), 934–956.
McElroy, M.W., 2019. Making materiality determinations: a context-based approach (No. 2019-6). UNRISD Working Paper.
Oladimeji, O.O., Keathley-Herring, H., Cross, J.A., 2020. System dynamics applications in performance measurement research: a systematic literature review. Int. J. Product. Perform. Manag. 69 (7), 1541–1578.
Potting, J., Hekkert, M.P., Worrell, E., Hanemaaijer, A., 2017. Circular economy: measuring innovation in the product chain. Planbureau voor de Leefomgeving. 2544.
Rebs, T., Brandenburg, M., Seuring, S., 2019. System dynamics modeling for sustainable supply chain management: a literature review and systems thinking approach. J. Clean. Prod. 208, 1265–1280.
Roci, M., Salehi, N., Amir, S., Shoaib-ul-Hasan, S., Asif, F.M., Mihelič, A., Rashid, A., 2022. Towards circular manufacturing systems implementation: a complex adaptive systems perspective using modelling and simulation as a quantitative analysis tool. Sustain. Prod. Consum. 31, 97–112.
Roy, T., Garza-Reyes, J.A., Kumar, V., Kumar, A., Agrawal, R., 2022. Redesigning traditional linear supply chains into circular supply chains–A study into its challenges. Sustain. Prod. Consum. 31, 113–126.
Sacco, P., Vinante, C., Borgianni, Y., Orzes, G., 2021. Circular economy at the firm level: a new tool for assessing maturity and circularity. Sustainability 13 (9), 5288.
Sehnem, S., Vazquez-Brust, D., Pereira, S.C.F., Campos, L.M., 2019. Circular economy: benefits, impacts and overlapping. Supply Chain Manag. Int. J. 24 (6), 784–804.
Senge, P.M., Forrester, J.W., 1980. Tests for building confidence in system dynamics models. System dynamics. TIMS Studies in Management Sciences. 14, pp. 209–228.
Taghikhah, F., Voinov, A., Shukla, N., 2019. Extending the supply chain to address sustainability. J. Clean. Prod. 229, 652–666.
Towill, D.R., 1996. Industrial dynamics modelling of supply chains. Int. J. Phys. Distrib. Logist. Manag. 26 (2), 23–42.
Uhrenholt, J.N., Kristensen, J.H., Rincón, M.C., Adamsen, S., Jensen, S.F., Waehrens, B.V., 2022. Maturity model as a driver for circular economy transformation. Sustainability 14 (12), 7483.
United Nations, n.d.United Nations. (nd). Sustainable development goals. Retrieved 8 December 2022 from https://www.un.org/sustainabledevelopment/sustainable-development-goals/
van der Velden, N.M., Vogtländer, J.G., 2017. Monetisation of external socio-economic costs of industrial production: a social-LCA-based case of clothing production. J. Clean. Prod. 153, 320–330.
Vegter, D., van Hillegersberg, J., Olthaar, M., 2020. Supply chains in circular business models: processes and performance objectives. Resour. Conserv. Recycl. 162, 105046.
Vegter, D., Hillegersberg, J.V., Olthaar, M., 2021. Performance measurement Systems for Circular Supply Chain Management: current state of development. Sustainability 13 (21), 12082.
Vogtländer, J.G., Brezet, H.C., Hendriks, C.F., 2001. The virtual eco-costs '99 a single LCA-based indicator for sustainability and the eco-costs-value ratio (EVR) model for economic allocation. Int. J. Life Cycle Assess. 6 (3), 157–166.
World Business Council for Sustainable Development, 2022. Circular Transition Indicators V3.0. Metrics for Business, by Business.
Zink, T., Geyer, R., 2017. Circular economy rebound. J. Ind. Ecol. 21 (3), 593–602.