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Transforming global production networks: A comprehensive approach to integrating circularity

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Abstract

The reduction of global resource consumption and the attainment of international climate goals are core issues of our time. Consequently, companies, including their global production networks, which have historically grown based on linear economic models, must undergo a transformation towards sustainability. One promising path is the concept of the circular economy, which promotes resource-efficient, closed-loop material flows. This work aims to facilitate the transformation by developing and presenting a comprehensive methodology that enables companies to analyze, evaluate, and implement measures for transitioning to a circular economy model. The approach is based on an upstream analysis of relevant (circular) influencing factors. Building on this, a maturity model is applied, which intuitively determines the current and desired state of circularity, assesses organizational readiness, and supports the identification of areas for improvement. To address these potentials, possible measures are assembled into a catalogue of measures to holistically identify circularity-promoting actions or combinations thereof. Depending on the underlying production network and its level of circular maturity, effective measures can be selected from the catalogue and proposed for implementation. Preliminary results suggest that the proposed methodology provides a comprehensive evaluation of a company's circularity potential and facilitates the integration of sustainability practices into global production networks.

Keywords: Manufacturing, Manufacturing Network, Global Production Network, Circular Production, Circular Economy, Sustainability, Remanufacturing

1. Introduction

"There is no planet B". Under this slogan climate protection organizations and their supporters globally call attention to a more sustainable future. But to which extent has this attitude also reached the commercial entities? Our economic system is still mainly characterized by the classical, linear economy model of "take-make-use-dispose" [1], which results in an enormously high creation of non-usable waste [2], and a resource consumption of 1.7 Earths [3]. The knowledge about those facts is increasingly reaching the wider world population and draws attention to this fundamental issue. Therefore, the demand for sustainable products is rising drastically and legislative measures are promoting sustainability and restricting linear economic concepts. In addition, countries are creating financial incentives to make the future more sustainable [4]. But what exactly can a more sustainable company look like? A strategic approach to addressing these issues is adopting the principles of the circular economy (CE) business model. This model is designed to be restorative and regenerative, aiming to maintain products, components, and materials at their maximum utility and value throughout the entire lifecycle [5]. It thus relates to a wide range of corporate divisions, including the global production network (GPN) of a company and has

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already begun to be implemented in practice. Nevertheless, the growth of circularity is not keeping pace with the ever-increasing demand for resources. One indicator of this is the decreasing share of secondary materials consumed globally by 21% from 2018 to 2023 [6]. It is therefore all the more important that the implementation of the CE begins immediately so it can realize its potential and ambitious climate, resource, and sustainability goals can be achieved concurrently [1]. There is hope, as the CE has reached megatrend status, with the volume of discussions, debates and articles on the concept almost tripling in the last five years [6, 7]. However, for companies, it is usually difficult to see how much has already been achieved in the course of change. For this reason, the objective of this work is to help companies with their transformation towards sustainable practices. It aims to quantify and visualize the CE status using a maturity model that enables companies to measure their current state and their desired target state towards circularity. Finally, by comparing these two, fields of action should be derived. This allows the implementation of targeted measures to ensure effective progress towards achieving a CE.

The remainder of the paper is as follows: Chapter 2 presents an excerpt of existing approaches assessing CE business models in companies and also derives the research gap. Chapter 3 details the approach to fill the identified research gap by describing the developed methodology. Chapter 4 then presents a use case with the corresponding results obtained by applying the presented approach to a company. Chapter 5 concludes the article with an outlook on the upcoming research steps.

2. State of the art

This section presents an analysis of existing approaches that have been conducted to evaluate and realize the implementation of the CE within companies. To achieve this, the following approaches try to assess circular maturity by introducing and evaluating influencing factors to provide a basis for quantifying and advancing the adoption of circular practices. An influencing factor is a condition or element that significantly determines the design, operation, and efficiency of processes either directly or indirectly [8]. In the context of circular GPNs, influencing factors are defined as conditions that significantly shape the transition from linear to circular processes. These factors include technological developments, economic incentives, regulatory requirements, and environmental and social demands. They influence the ability of companies to effectively implement circular strategies in their GPN [9]. The extant literature frequently employs terms such as *Indicator* and *Key Performance Indicator (KPI)* for interchangeably. However, these terms are intentionally not used hereafter, as they imply comparability, but their values are highly dependent on the specific definition and scope, which may lead to misinterpretations and erroneous comparisons. Therefore, the term *Influencing Factor (IF)* will be used instead. Krajnc and Glavic [10] contribute to the body of knowledge with their extensive collection of social, environmental, and economic IFs, providing a broad set aimed at reflecting and quantifying sustainability. Batableblu et al. [11] concentrate their research on the implications of the European Sustainability Reporting Standards (ESRS) for the development of sustainable production. They propose a set of 68 IFs for manufacturing companies, distributed across ten superordinate categories. Saidani et al. [12] create a taxonomy composed of ten categories to facilitate the adaptation of circularity practices. In order to assist users in selecting appropriate IFs tailored to their specific needs and requirements, the approach entails a review of 55 sets of IFs. Pauliuk [13] proposes a general system definition for deriving circular IFs, resulting in the development of a comprehensive dashboard for evaluating and quantifying circular strategies. The CE Matrix, introduced by Saari et al. [14], adopts a broad approach to assess the degree of circularity within companies and to derive suitable actions. This evaluation is based on the seven phases of the linear manufacturing value chain, ranking them from complete linearity to complete circularity. However, this approach lacks granularity, as it does not capture IFs or determine values for more detailed categories to differentiate within the seven phases. In their approach, Rossi et al. [15] evaluate 27 IFs considering three dimensions of sustainability: environmental, economic, and social. The approach aims to identify areas of high importance and potential for enhancement. Evans and Bocken [16] propose a methodology by employing a CE toolkit in workshop format to identify possible measures in companies. However, all three of the latter approaches lack certain aspects, such as network and infrastructure considerations. Nevertheless, it is evident that a comprehensive CE approach that encompasses all stages of the value chain should prioritize the circular aspects of the GPN. For example, a considerable proportion of a company's resource consumption and emissions originate within the GPN [17]. Furthermore, return systems cannot simply be appended to an extant GPN; rather, they must be thoroughly integrated into it. Regarding the subsequent processing of the data gathered by the IFs, not all of the presented approaches are comprehensive in identifying key areas and potential for integrating circularity-promoting measures to achieve a CE business model.

While circular IFs are an effective means to assess a company's current status with regard to the CE, the practical challenge of assigning values to these persists. One practical approach that addresses this challenge is the use of questionnaires on circularity. Since the previously mentioned approaches focus on the collection and categorization of the IFs, the following section will introduce approaches that follow the procedure of gathering IFs values through questionnaires. This does not only include the collection of qualitative or quantitative values through corresponding questions, but also a subsequent calculation logic to aggregate the collected data. Chen [18] introduces a comprehensive and robust sustainability assessment tool for small and medium-sized enterprises (SMEs), drawing upon a review of more than 100 works. This results in an instrument comprising 133 questions and includes a calculation logic that permits a clear quantitative aggregation of the collected data into IF values by calculating mean values for the categories of social, institutional, environmental, and economic sustainability. Utilizing the results from these IF values, areas for action are identified without further concretizing effective measures for enhancing circularity. This approach assumes complete circularity as a target state for all IFs and does not allow a definition of target states. Holly et al. [19] present a distinct evaluation approach consisting of 66 targeted questions for manufacturing companies. The methodology spans ten primary areas with 23 sub-areas, and examines not only the specific maturity level regarding circularity within the company, but also the maturity of alignment between decisions and strategic objectives. Thereby, limited focus is provided on network considerations. Additionally, the approach does not enable the establishment of precise target states, nor does it identify fields of action or present respective measures based on the findings. Amir et al. [20] strive to acquire a profound understanding of the structure and the inherent complexities of circular supply chains (CSC), aiming for the seamless forward and backward integration of the CSC into the overarching goal of a system-wide CE. Their methodology is divided into four so-called building blocks (systemic approach, main drivers, levels of decision making, and mechanisms), to which several questions are assigned in order to assess a company's circular maturity. Benfer et al. [2] adopt a somewhat distinct methodology, which is more directly oriented towards the implementation of measures. Their focus is on selecting appropriate CE strategies and designing corresponding processes through a product-centered lens. They introduce a suitability score for each product-strategy pairing, enabling targeted and efficient implementation. Nevertheless, their methodology lacks a comprehensive approach to evaluating a company, focusing on the product instead.

As demonstrated, there are numerous existing approaches for quantifying CE in companies using appropriate IFs and questionnaires. Nevertheless, when applying CE principles, companies are facing industry-specific challenges and even within a given industry, there may be discrepancies. Morseletto [21] conducts a comprehensive investigation into the efficacy of establishing targets for CE. His findings indicate that the effectiveness of target-setting is highly contingent on the specific industry and is influenced by a multitude of factors, such as pricing or the characteristics and properties of the materials used. Therefore, the presented approach should allow to individually set a company’s circular target status, which is not particularly addressed in the literature.

3. Methodology

To address the research gap identified, a methodology is presented that enables companies to holistically foster circularity. The foundation of this methodology is a circular maturity profile, which can be obtained through a procedure presented in Section 3.1. As the status of a company’s circularity degree as well as the circular target state depends on many factors, this approach considers various IFs that are assessed by a questionnaire. The results of the questionnaire’s evaluation lead to a circularity level in several circular categories summarized in the maturity profile. The circular categories comprise several subcategories to further differentiate. Clear definitions of the subcategories are provided alongside the questionnaire, ensuring that users can answer with a full understanding of their meaning and scope. Within the maturity profile, the gaps between the current and target state are identified to define the fields of action. Based on this, suitable measures for increasing circularity are selected and suggested to the company. The implementation of those should result in the attainment of the desired circular target state. The procedure and methodology are described in detail in Section 3.2.

Fig. 1. CE categories and respective subcategories.

3.1. Circular Maturity Model

To identify potential IFs, a structured literature review using the search terms *Circular (Economy), Global Production (Network), Influencing Factors, Maturity Model* and *Indicators* was conducted, resulting in a long list of IFs. This literature search considers both conventional linear and circular value chains. Moreover, the literature search incorporates all phases of a product's lifecycle, commencing with the resources, followed by the production, distribution and use phases. The final phase of the lifecycle, the end-of-life phase, is addressed by considering aspects such as reverse logistics processes and recycling. The long list of IFs was then condensed to a short list by removing duplicates, summarizing factors and selecting them based on their general relevance to the concept of CE and the characteristics of the presented approach following the approach of Peukert et al. [22]. This resulted in a short list of IFs, including examples such as *Product Design Reducing the Use of Materials* or *Optimizing Production to Recycle Waste.* This presents an initial listing that can be adjusted and expanded individually to the specific needs of the company. The IFs of the short list are mapped into a set of circular subcategories, which can be further grouped to the following four circular categories: *Corporate Strategy*, *Product, Manufacturing, and Infrastructure & Logistics*. Fig. 1 shows all the considered circular (sub)categories as part of this approach, and for better understanding, brief descriptions of the subcategories are provided in Table 1.

Table 1. Considered Subcategories with Respective Description.

Subcategory	Description
Circular Thinking	Assesses the extent to which circularity is embedded in the company culture.
Circular Finances	Represents the influence on the company's financial performance attributable to circularity.
Social Circularity	Measures the impact of circularity on social aspects, particularly on employment.
Material Usage	Assesses both the quantity of material used for the product and the selection of materials in terms of compatibility with R-strategies (reuse, repair, remanufacture) and environmental sustainability.
Product Design	Evaluates the longevity of the product and its design compatibility with R-strategies.

Resource Usage	Monitors the use of resources (such as materials, energy, information, and finances) in manufacturing processes.
Circular Processes	Tracks the reuse of recycling materials, waste, and the reintegration of defective and refurbished parts into production.
Logistic Processes	Measures the efficiency of transporting and handling goods including returning and processing returned products.
R-Strategies	Evaluates the implementation of reuse, repair, and remanufacture strategies for returned products.

To make the approach easily applicable for companies, the CE values are captured by a questionnaire. The developed questionnaire comprises 32 questions covering all four circular categories. For all questions, a rating scale with five responses is given. The exact formulation of the graduations on the scale differs between statements that should be commented and questions that ask for a percentage. Both rating scales and their selectable response levels are illustrated in Fig. 2, using the exemplary questions for the aforementioned IFs. In general, response (A) represents a fully circularly developed company and response (E) stands for a not circularly dedicated company regarding the considered IF. In order to quantify the given responses, they are matched with equidistant percentage values from 100% (A), 75% (B), 50% (C), 25% (D) to 0% (E). The presented approach is not designed to incorporate qualitative responses, such as free-text answers, in order to ensure quantitative comparability, particularly between the current and target states. Each question is matched with one certain subcategory, which is affected by the evaluated IF. Regarding the subjectivity of the self-reported data, no intentional alteration of the data by the end user is anticipated. The approach presented is entirely voluntary, and it assists companies in implementing the CE. Consequently, companies benefit from accurate information, as it enables them to make well-founded decisions based on it. Nevertheless, to avoid unintentional misrepresentations in the questionnaire, it is recommended that the questionnaire should be completed by several individuals within the company, with their answers compared against each other. This also facilitates the incorporation of diverse perspectives from various departments within the company.

SC	IF	Question	Response
Material Usage	Product Design Reducing the Use of Materials	We emphasize minimizing the use of materials in the product design process.	A Completely Agree.
			B Mostly Agree.
			C Neither Agree nor Disagree.
			D Mostly Disagree.
			E Completely Disagree.

SC	IF	Question	Response
Resource Usage	Optimizing Production to Recycle Waste	What percentage of waste from production is recycled?	A 81-100%
			B 61-80%
			C 41-60%
			D 21-40%
			E 0-20%

SC: Subcategory IF: Influencing Factor

Fig. 2. Exemplary questions with responses and affected subcategory.

To derive values for the subcategories from the provided responses, a calculation logic is employed. As previously stated, the specifications and focal points of an industry and even those of individual companies vary considerably. The presented approach aims to adapt to their specific requirements through individual customizability. It allows to weight questions of varying relevance. As a procedure for determining the weights, a pairwise comparison is proposed in which the questions assigned to a subcategory are compared with each other. Formula (1) applies to calculate the value of a subcategory k_c assigned to the circular category c. The value is calculated from the weighting factor $w_{k,q}$ of a question q for a subcategory k_c and the value of a response r_q for question q.

$$k_c = \frac{\sum_{q \in Q}\left(w_{k,q} \cdot r_q\right)}{\sum_{q \in Q}\left(w_{k,q}\right)} \quad \forall q \in Q \qquad (1)$$

Given the values of the subcategories, the cumulative value v_c of a circular category c can be calculated from the subcategories belonging to that category. In case the relevance of the subcategories to a company's overall CE goals deem to be unequal, specific subcategories can be prioritized in a manner analogous to the weighting of the questions. In order to calculate the cumulative circular category values v_c, it is necessary to apply the formula specified in (2). However, if the comparability of different companies based on the values of the subcategories and the cumulative circular category values is a primary concern, the weighting of questions and subcategories must be identical. Otherwise, the comparability between companies will be distorted.

$$v_c = \frac{\sum_{k \in K}\left(w_{c,k} \cdot k_c\right)}{\sum_{k \in K}\left(w_{c,k}\right)} \quad \forall c \in C \qquad (2)$$

Another crucial option to incorporate specific strategic targets of companies and different environments is to set a target state for achieving circular goals. In particular, this capability distinguishes the proposed approach from those found in the literature. This can be done by setting target values for each subcategory. Alternatively, the questionnaire can be filled out with target values rather than with current values. For instance, the consideration of legal requirements that must be met in the year under consideration can be used to make qualitative statements. All in all, this results in a maturity model comprising the two circular maturity states to identify the most relevant fields of action and establish the basis for implementing appropriate measures, which are detailed in the following section.

3.2. Catalogue of Measures

When it comes to actions, suitable measures building upon a company's identified gap between current and target maturity state should be derived. An extensive literature review and practical knowledge have been used, resulting in a long list of measures to integrate the CE business model into companies. Suitable measures are selected and condensed towards a catalogue of measures (short list) with a focus on CE. The following illustrates the procedure with the aid of selected measures, although it should be noted that due to space limitations, the comprehensive list of measures including the interdependencies between measures and subcategories is not

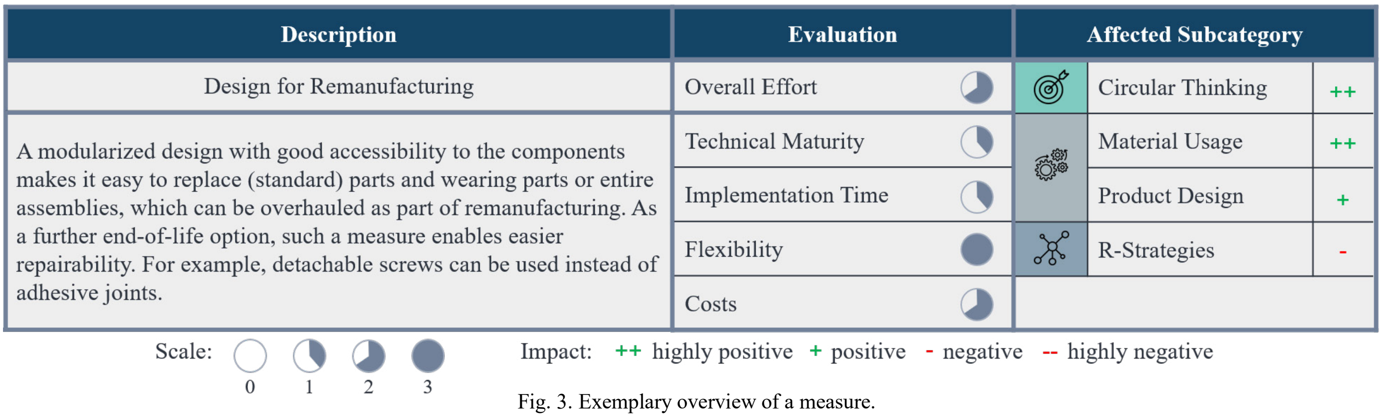

Fig. 3. Exemplary overview of a measure.

presented here. This will be explored in a future paper, with the current work focusing more on the foundational approach. Each measure is further characterized resulting in a measure overview, which is exemplarily illustrated in Fig. 3. Such a measure overview describes the measure and evaluates its applicability by a set of criteria. The measures are evaluated regarding the *Technical Maturity*, which addresses the development status of the measures and their readiness for immediate deployment. Furthermore, the *Implementation Time* assesses the time needed for planning, deploying, and integrating it into existing processes. The criterion *Flexibility* indicates the extent to which processes can maintain or enhance their adaptability when new measures are introduced, and *Costs* are assessed, with all expenses regarding the planning, deployment, and integration considered. Finally, *Overall Effort* captures the total investment of resources and time required to fully implement the circularity measures.

There is a notable deficit in the existing literature with regard to the introduction of measures based on a gap analysis on the circular maturity profile, which is crucial for the implementation of CE business models in companies. To this end, the potential for improvement in specific areas of CE is identified. In order to select and implement suitable measures for the aforementioned gaps, a mapping is conducted between the measures and the subcategories. Each measure is evaluated regarding the influence on the subcategories (whether in a positive or negative manner regarding circularity) and is incorporated into the measure overview. All subcategories that are not mentioned in a measure's overview are not affected by this measure.

4. Results

A significant element in the successful validation is the application to industrial companies, with the findings subsequently being integrated into the further development of the approach. The approach was initially validated and demonstrated in a German company, which is a leading provider of advanced and comprehensive solutions for the metallurgical industry, including the design and construction of steelmaking plants and machinery. It is currently engaged in an ongoing process of transition, with the implementation of a CE business model representing a crucial lever towards a sustainable future. The questionnaire was completed by several employees of the company, resulting in a current and target circular maturity profile, as illustrated in Fig. 4. To ensure transparency along the data processing, all questions were assigned equal weights in this example. However, as can be seen in Fig. 4, the individual subcategories were prioritized differently based on weights to reflect the specific scope of the company. For example, the aspect of reverse logistics at the end-of-life is challenging to implement for their products and thus not a primary focus for the company. Therefore, the subcategories *Logistic Processes* and *R-Strategies* are of markedly disparate importance for the company, and the weights could be adjusted accordingly.

The company's maturity profile indicates that there is still potential in all circular categories to achieve the desired target state. In particular, the discrepancy in the subcategory *Circular Thinking* highlights significant potential within the circular category *Corporate Strategy*, which should be addressed by further incorporating the CE into the company's strategy. Based on this, suitable measures can now be selected and implemented from the aforementioned catalogue of measures to enhance the value of the subcategory. One potential measure to address this gap would be the incorporation of *Design for Remanufacturing* principles, as illustrated in the example in Section 3.2. Remanufacturability involves not only the design process but also various operational aspects, and can only be implemented through a comprehensive strategic CE approach, measured by the subcategory *Circular Thinking*. Apart from this, the circular category of *Manufacturing* demonstrated addressable potential for the exemplary company, particularly within the field of *Circular Processes*. In this domain, the aforementioned procedure may be repeated in order to identify suitable measures.

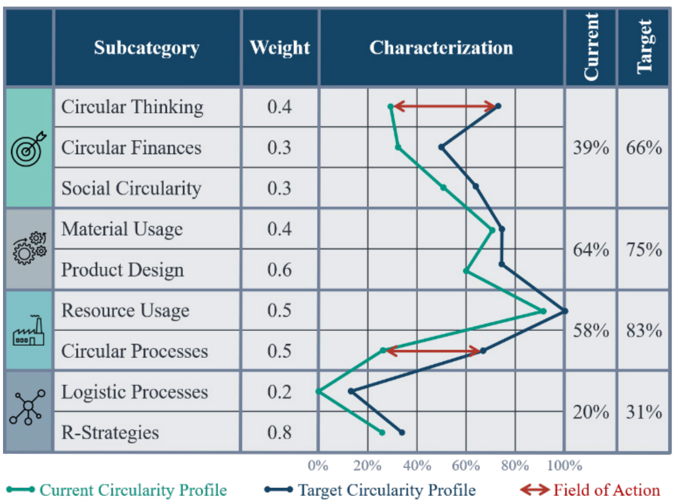

Fig. 4. Exemplary company maturity profile.

5. Summary and Outlook

The proposed approach enables a comprehensive, industry-independent assessment of a company's circularity and delivers actionable measures. Consequently, decision-makers can identify the most beneficial measures for a company based on its current circularity maturity profile and enhance its circular capabilities, particularly within the GPN. Unlike other approaches, this methodology provides a holistic perspective, offering a seamless process from assessment through questions to the derivation of measures.

The approach is based on an industry-neutral literature search, and respectively the IFs, (sub)categories, and measures proposed are also independent of industry. Although the approach meets all criteria to be considered industry-neutral, this still needs to be demonstrated. Consequently, a significant subsequent step is to apply the approach to additional companies from both the metallurgical and other industries, integrating their feedback into the ongoing methodology evolution. Moreover, the outcomes of the approach should be evaluated in comparison to existing approaches to ascertain its validity. Building on this paper, further development should be conducted to complete the mentioned list of measures. To further foster the selection of measures by evaluating the interdependencies between measures and subcategories, a simulation-based decision support system shall be developed. The approach should be easily applicable, with possible applications including a step-by-step guideline or a workshop framework for deriving circular measures. Drawing on prior experience, such as with Industry 4.0, it is anticipated that the implementation of the approach, should require 2-3 days for an expert. Once implemented, the identified measures are expected to lead to improvements in terms of processes and their efficiency.

The implementation of the presented approach on a broad scale within our economic system has the potential to reduce resource consumption, enhance sustainability, and support climate goals. The overarching objective is to transition from the linear "take-make-use-dispose" paradigm to a circular "take-make-use-reuse" model, fostering a more sustainable future.

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