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Towards Sustainable Manufacturing through Collaborative Circular Economy Strategies

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Abstract. The principles of a circular economy (CE)—social, economic and environmental—could enhance the sustainability of the manufacturing sector, but radical transitions and collaboration are required in order to fully engage with this paradigm change. This study is based on the assumption that, through collaborative strategies, a CE could transform the inefficiencies of linear value chains into novel competitive advantages for manufacturing companies. This conceptual paper presents a framework that integrates the identified inefficiencies of linear manufacturing value chains and an assessment model describing the five maturity levels of CE. At the lowest level—linearity—there is no collaboration; at the next—industrial piloting—experiments are conducted with discrete pilot projects within supply-chain partners. The third level—systemic material management—cannot be achieved without close collaboration and fair data exchange, while the next level—CE thinking—envisages a closed-loop supply chain. The highest level—full circularity—contributes not only to environmental, but also to economic and social sustainability. This paper argues that the identification of novel value circles and the co-creation of value with a variety of partners are crucial aspects for enabling the CE transition.

Keywords: circular economy, connected factories, collaboration, manufacturing companies, digitalisation, supply chain,

1 Introduction

The manufacturing industry—as, increasingly, with all industries—is faced with the challenging requirements of a transition to sustainability, which, in the literature, is discussed mainly from an environmental perspective, while the social and economic dimensions are often neglected [1]. Despite the term being widely used, the definition of CE is rather vague, and most of the literature has focused on one specific region or

on a specific CE-related application [2]. A broader formulation of consistent CE strategies therefore remains a challenge [1],[3]. In line with the collaborative networks approach, we highlight the system perspectives and use Korhonen *et al.*'s definition: '*CE is an economy constructed from societal production-consumption systems that maximizes the service produced from the linear nature-society-nature material and energy throughput flow. This is done by using cyclical materials flows, renewable energy sources and cascading type energy flows. Successful CE contributes to all the three dimensions of sustainable development. CE limits the throughput flow to a level that nature tolerates and utilises ecosystem cycles in economic cycles by respecting their natural reproduction rates*' [4].

In this paper, we present a CE matrix for the manufacturing sector, which aims to assist in i) identifying the level of CE at which a company operates and ii) the needs for improvements and collaboration that would enable the next maturity level of circularity to be achieved. The CE matrix seeks to translate the maturity levels of CE to help in conceptualising the sustainability vision of a company and to provide a conceptual framework for an elaborated roadmap to that vision's realisation.

2 Relationship with Existing Theories and Research

The principles characterising CE are a great driver for sustainable industrial systems—especially for the manufacturing sector [5], where it is called circular manufacturing [6]. In the context of the manufacturing industry, the regeneration of resources happens through different strategies, which, if adopted concurrently, support the sustainable development of manufacturing firms. Thus, there remains a clear need to identify novel, promising innovations to shift from linear business models to circular ones [7].

There are two main cycles typically identified within CE concepts: biological and technical [8]. In parallel with a sustainable transition, a digital transition disrupts ways of doing business, enabling, by the flow of information, more effective product and material circulation [9],[10]. CE implies not only decreasing one's own environmental footprint within the take–make–dispose model, but also interacting with the supply chain to optimise the entire materials loop. Thus, collaboration is a crucial enabler of sustainability [11] that can be practically implemented using Industry 4.0 technologies [12] and is necessary to enable interaction and fair data exchange between companies [13].

The CE provides opportunities to turn the inefficiencies of linear value chains (unsustainable materials, underutilised capacity, prematurely ended product lives, wasted end-of-life value and unexploited customer engagement [Fig. 1] [14]) into business value. However, due to production and consumption often taking place in different countries, supply chains may need to be reorganised to facilitate reuse and remanufacturing, and product lifetimes can be extended by upgradeability [15]. Collaborative incentives throughout the supply chain are needed for companies to actively consider sustainable materials, durability and reparability.

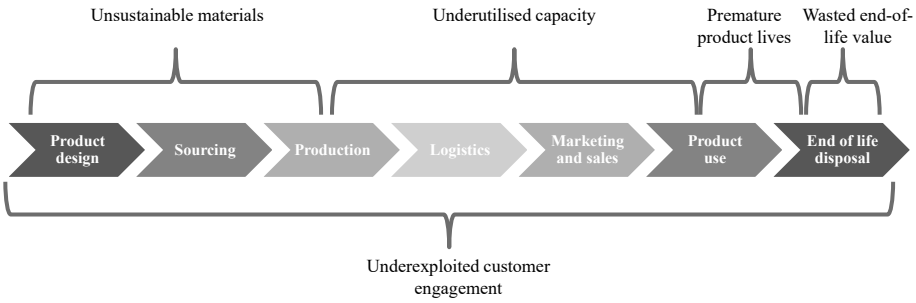

Fig. 1. Substantial inefficiencies may occur in all parts of the manufacturing value chain. Adapted from [14].

To overcome inefficiencies along the manufacturing value chain, deeper investigation is needed of the distinct points at which the different levels of CE strategies can be implemented. Collaborative strategies are needed to enable meta- and macro-level transitions [16]—that is, to broaden the approach from the concept of sustainable islands [17] towards a green transition—and the environmental challenge calls for commitment from and collaboration by companies, industries and authorities [18].

However, companies face difficulties in deciding how to examine and proceed with the sustainability transition [19], and various methods and tools have been developed to guide them in their CE transformation journeys. For example, Blomsma et al. [20] created the Circular Strategies Scanner, a tool to support the visualisation of circular-oriented innovation, to make the CE concept more tangible, to map ongoing circular initiatives and to generate new ideas for circularity. Unal and Shao [21] provided a taxonomy of strategies for CE implementation; according to the authors, despite common assumptions, companies cannot make simultaneous improvements to all CE practices simply by emphasising them equally, and need to select a CE collaboration strategy such as trade-off, cumulative model or threshold model.

Organisational sustainability readiness can be assessed with tools that are based on capability maturity models [22],[23],[24], and the ManuMaturity tool has been highlighted as an example of an implemented maturity tool that includes the sustainability dimension [25]. Its sustainability dimension has two questions: "How are resources used?" and "How are environmental impacts considered?" Applicable tools are included in the CE playbook for Finnish SMEs [14], including ecosystem partner identification and technology maturity assessment.

The CE pathway developed in the Connected Factories 2 (CF2) project raises awareness and highlights the importance of the CE paradigm for the sustainability of the manufacturing sector. The CE maturity levels are i) linearity, ii) industrial CE piloting, iii) systemic material management, iv) CE thinking and v) full circularity. Each level is described in more detail in Table 1 [26].

Table 1. CE maturity level descriptions.

Level	Description
Full circularity	Company has achieved full circularity of products, processes and operations, which are sustainable on the environmental, social and economic levels. This is accomplished by a broad understanding of value flows (such as synergies among forward and reverse logistics, local value chains and zero-waste manufacturing) and the co-creation of new value circles within manufacturing networks (such as flexible remanufacturing networks, upgrading of products and on-demand production) as a key managerial practice.
CE thinking	Eco design and circularity are an essential part of new products and the deployment of new services. The company is internally able to re-purpose industrial materials, but further opportunities are found externally. In particular, the exchange of resources with third parties is promoted through the creation of an industrial symbiosis network, and an attempt to establish a closed-loop supply chain is envisaged.
Systemic material management	The adoption of CE is extended to the whole company to identify and exploit all the emerging opportunities, at least from an internal perspective. The 'R-cycles' of industrial materials have become standard practice adopted by the company in order to systematically identify possibilities to reuse, refurbish, recycle and remanufacture materials.
Industrial CE piloting	Senior management has pushed pilot projects for some strategies that seek resource sufficiency either internally or by exchange with external industrial actors.
Linearity	Senior management of a manufacturing company is stuck in the traditional linear concept of make–take–dispose. Legal requirements for recycling, waste management and other environmental obligations are met, and the company's performance is monitored only to ensure no additional costs rather than to find new opportunities.

3 Research Methods

The aim of this paper is to identify collaborative CE strategies that can boost the transition towards a sustainable manufacturing industry. Through the lens of design science [27], the goal of exploratory researchers is to develop a 'means to an end'—an artefact to solve a practical problem. In our study, the practical managerial challenge and the research question were distilled to 'How can collaborative CE strategies enhance the transition towards sustainable manufacturing industry?' The conceptual framework for sustainable industrial systems was constructed through a literature review that combined the relevant streams of literature: circularity in value chains, collaborative (CE) strategies and CE maturity assessment. Based on this preliminary framework, a matrix combining value chain analyses and CE maturity assessments was configured.

The framework building and testing was conducted in collaboration with CF2 research practitioners [28]. The preliminary framework was presented and tested in the *Pathways to Digitalisation of Manufacturing and Associated Use Cases* webinar on Wednesday 24th March 2021, organised by the European Factories of the Future Research Association (EFFRA). Out of 77 people registered, 55 attended the webinar;

three represented associations or standardisation organisations, seven consultancies, 14 industrial companies and 31 research organisations. Feedback was collected in an interactive session via an online collaborative whiteboard platform, the Miro board. Information on the pilot projects was also gathered during the workshop, particularly case examples of the different development pilots of companies seeking to solve identified value chain inefficiencies at each CE maturity level. The input from workshop—the development pilots illustrating the CE strategies and readiness of companies in the context of the manufacturing industry [22]—was analysed, and the matrix was finalised by the researchers.

Instances of collaboration were identified in the solutions implemented in CF2 projects, see Table 2.

Table 2. Collaboration in the solutions of CF2 projects.

Level	Instance of collaboration	Projects and solutions
Linearity	No collaboration, prevalence of make–take–dispose paradigm.	No instances among CF2 projects.
Industrial CE piloting	Collaboration and experimentation with external industrial actors, with an emphasis on production and logistics.	QU4LITY: quality pilots on the reduction of unnecessary scrap material and augmented reality (AR) demos to support the maintenance. European Factory Platform: logistics traceability via blockchain.
Systemic material management	Integrated concerns with opportunities to reuse, refurbish, recycle and remanufacture materials.	Kyklos: automatic product design for a personalised 3D-printed wheelchair with AR manuals. TRICK: tracing 'from sheep to shop' via blockchain. European Factory Platform: digital marketplace with automated B2B matchmaking and new market opportunities. AI.SOV: AI-based solution to forecast and optimise spare parts production.
CE thinking	Commitment to an industrial symbiosis network in which the ultimate goal is to leverage a closed-loop supply chain.	Kyklos: in addition to the web-based configuration tool (a digital twin), the IoT is embedded in the product, enabling predictive maintenance. European Factory Platform: smart waste management with connected factories, real-time data analytics and blockchain.
Full circularity	Aspirational goals reflecting a broad understanding of value flows and the co-creation of new value circles within manufacturing networks.	None to date.

The co-development of the framework to integrate the CE maturity levels and the analysis of the value chain processes together entailed the identification—by the participating companies—of solutions to the challenges encountered at each self-assessed stage

of maturity and how they intersect with the various stages of the value chain: product design, sourcing, production, logistics, marketing & sales and product use.

4 Preliminary Conceptual Framework for a Sustainable and Circular Manufacturing Industry

Our framework combines the linear value chain [14] and the maturity levels of the CE pathway [26] into a matrix in which the value chain appears as rows and the maturity levels as columns, as shown in Table 3. The illustration of the embodiment and performance of the company in each cell guides both the assessment and identification of further steps in developing sustainable manufacturing.

5 Conclusions and Future Work

In this paper, we presented a matrix that combines the CE maturity levels defined in the CF2 project with the linear value chain. The readiness (or maturity) assessment enables capability-building and a sustainable manufacturing strategy, which is made visible via solutions and development pilots that decrease environmental impact and increase collaboration along the supply chain. The collaboration viewpoint emerges when moving from the linearity level towards full circularity. Collaboration also indicates data exchange along the supply chain, which was a key enabling element in the CE solutions presented in the webinar.

At the linearity level, no collaboration takes place, while industrial piloting indicates some goals, trials and pilots around production and logistics that remain discrete and do not flow through material management processes. Systemic material management invites R-cycles, like the reuse, refurbishment, recycling and remanufacturing of materials. The CE thinking level envisions the closed-loop supply chain, and the highest level—full circularity—contributes not only to environmental, but also to economic and social sustainability, but is not possible without collaboration.

Companies need methods and tools to guide them in their CE transformation strategy and journey. The proposed preliminary framework enables the assessment of CE maturity along the manufacturing value chain and seeks to upgrade that maturity level, contribute to the CE strategy of the company and provide options to proceed with both collaboration and digital solutions that require data exchange.

Critically, the linear model is insufficient to the transition towards a sustainable industry because it neglects the values and interests of other actors in the value chain, and sustainability needs to be approached through collaboration and jointly set goals, steps and practices. Collaboration can leverage the CE by turning the inefficiencies of linear value chains into novel competitive advantages for the manufacturing industry. Potential approaches, such as circular supply chain and product-as-a-service, require strategic collaboration within both business models and solution development.

In the next paper, we will present the results of assessments of company pilots; validation will be done with pilots from the CF2 project.

Table 3. CE maturity levels mapped with the linear value chain.

Linear value chain	Linearity	Industrial CE piloting	Systemic material management	CE thinking	Full circularity
Product design	Product design does not consider durability, upgradeability, circularity or sustainability.	Company considers transition from the use of unsustainable and hazardous substances to sustainable raw materials. Company has piloted the repair or reuse of products.	Durability and upgradeability of products is promoted and applied. Personalisation of products is driven by demand and purpose.	Environmental impact assessment is a driving force of product development (eco design). Products are designed to avoid loss and premature end-of-life.	Products are fully circular by design, enhancing purpose-based durability during the life-cycle and enabling multiple reuse, repair, remanufacturing and regenerative recycling at end-of-life.
Sourcing	No actions to reduce the consumption of energy and/or materials are being implemented. Materials are sourced based on performance and price.	Company seeks to minimise inputs of energy and materials. Material sourcing is being shifted from unsustainable to sustainable raw materials.	Sourcing is based on code of conduct guidelines for circularity and the sustainability of materials. The amount of waste is minimised and side streams are utilised.	Raw materials are sourced mainly from known and monitored secondary markets and through reverse logistics. Social impacts are considered in the sourcing process.	Full circularity is enabled by sustainable materials that have less environmental impact (on biodiversity, climate change, acidification, etc.) than traditional counterparts.
Production	Operations of the company meet environmental regulations, but R-cycles are not considered.	The minimisation of virgin raw materials, water and energy has been piloted at machine, process and company levels.	Production-on-demand allows the company to limit inputs and to reduce outputs, avoiding unnecessary use of raw materials, water and energy.	Circular production scheduling considers stocks on different levels.	Production is environmentally sound, which is enabled by close monitoring of the environmental impacts of production processes.

Linear value chain	Linearity	Industrial CE piloting	Systemic material management	CE thinking	Full circularity
Logistics	Company has no goal to optimise logistics.	Logistics optimisation pilots are taking place.	In addition to deliveries, logistics covers raw materials and waste.	Linear and reverse logistics are considered with partners. Traceability of products is implemented.	Value chains are localised, and closed loops are implemented. Transparency of products, production and logistics is enabled.
Marketing and sales	Company has not included CE sustainability views in their marketing activities.	Communication of CE piloting activities is planned as part of strengthening the company's image.	Materials origins, work force and locations are communicated transparently.	Proactive demonstrations of sustainability activities on the environmental, social and economic levels are capitalised.	Product-as-a-service and X-as-a-service approaches are implemented.
Product use	Products are not reused or repaired during their life-cycles.	Pilots are undertaken for reuse and for the recovery of materials from used products.	Production plans are based on an analysis of multisource product usage data.	Understanding customer behaviour and needs enables a prolonged life-cycle, upgrades and repairs to products.	Sharing economy business models provide novel alternatives for product usage.
End-of-life	At end-of-life, the product is treated as waste.	Pilots are undertaken that upgrade materials or products for reuse.	Reuse of products, side flows and waste is implemented.	Environmental, social and economic impacts of end-of-life products are known.	The next life-cycle of a product is known, with its environmental, social and economic impacts.

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