Supplemental Material

Towards achieving the Sustainable Development Goals: A collaborative action plan leveraging the circular economy potentials

Open explorations of experts in disciplines related to circular economy

1. Challenges in the transition to circular business models

While society, politics, and companies generally agree on the importance of circular business models, the actual transformation of business models is more difficult in detail. Current research attempts to identify drivers and barriers of circular business model innovation (e.g., Geissdoerfer et al., 2022). This transition usually requires more than the commitment of a single actor in the value chain. Rather, it involves multiple stakeholders in a business ecosystem such as firms or customers that may be reluctant to engage or even collaborate in the transition to circular business models (Verleye et al., 2023). Actor engagement depends on motivation, opportunity, and ability (Verleye et al., 2023) and is consequently rooted at the level of individuals operating within an ecosystem. To increase understanding of how to successfully manage the shift to circular business models, future research needs to identify and manage drivers and barriers towards circular business model transition (1) within individual firms, (2) in consumer-brand relationships (e.g., consumers demand or hesitation toward second-use products or components), (3) in inter-organizational relationships (e.g., buyer-supplier-relationships), and (4) in a wider ecosystem, involving multiple actors.

2.2 Supply-chains in Circular Economy

Against the background of resource scarcity and increasing resource consumption, businesses face various operational challenges associated with the goal of sustainable economic practices. These challenges are present both within the companies themselves and across all areas of the closed-loop supply chain. Efficient closed-loop management relies particularly on improved information processing throughout the product lifecycle, within individual companies, and across the entire closed-loop supply chain. Current research focuses especially on enhanced digitization and, as a result, notably improved acquisition, capture, and utilization of information in production and recycling processes. The aim is to simplify and target the provision, processing, and exchange of information necessary for network planning and control, and to integrate them into corresponding decision support (Scheller et al., 2021). The development of a comprehensive approach to integrating management systems and fulfillment systems, enabling coordinated decision-making in the closed-loop supply chain, is at the forefront of future research efforts. Additionally, the integration of work and organizational psychological aspects into business approaches holds great significance.

2.3 Assessment and Transformation of Value Chains in the Circular Economy

Due to the awareness of policy-makers and incoming laws such as EU Green Deal, EU CE Action Plan or the German "Lieferkettensorgfaltspflichtengesetz", the analysis and thus the assessment of value chains to foster a circular economy is of central importance (Kuci & Fogarassy, 2021). It requires the consideration of ecological, social, and economic aspects (Llorente et al., 2020). Thereby, an isolated profit maximization of single business models of individual actors along a value chain does not necessarily meet the requirements of a sustainable business. Hence, existing value chains must be transformed into circular and holistically observed ecosystems consisting of complementary value-adding actors. This construction of a circular ecosystem requires, for example, digital technologies such as platforms, but also the rethinking and understanding of the role of the individual actor in a system (Hansen et al., 2021). Therefore, approaches from the research discipline (System of) Systems Engineering may support building system understanding and creating interactions between business actors in a sustainable way (Mennenga et al., 2019). With the help of systematic and model-based approaches, business models may be analyzed and evaluated such that experiences as well as lessons learned can be shared and that a continuous learning process can lead to the promotion of innovation (Bocken et al., 2018).

2.4 Product development and dismantling in a circular automotive industry

The necessary transformation towards a circular economy by sustainable product development can only be achieved by an interdisciplinary collaboration and knowledge not only about single life phases of a product, but over the entire life cycle considering multiple requirements (Maxwell & van der Vorst, 2003). The changes of this transformation also have profound effects on working conditions in all life phases. Product development can act as a central link between all these life phases. However, in contrast to assembly, requirements resulting from disassembly or a possible reuse of the product are currently given too little consideration in product development. This particularly applies to the working conditions during the disassembly of a product which result substantially from a product's design (Vanegas et al., 2017). For this reason, a connection must be established between the working conditions of disassembly and the design of the technical product to be disassembled. For this purpose, the central requirements from disassembly must be identified and related to the associated product data from all phases of the product life cycle to, finally, provide all necessary information for the disassembly. To realize a sustainable product development, specific methods and tools for sensitizing and training product developers must be developed (e.g., through digital tools or virtual reality). Through this, the necessary competencies and knowledge can be built to anchor the minds and achieve a circular product development.

2.5 Component development for second-life applications

The transformation of the automotive industry is driven by changes in future vehicle concepts and sustainable life cycle management, covering production, operation, and component recyclability (Valiyan et al., 2022). This presents challenges, especially as a comprehensive database is currently lacking. Future vehicle usage is changing due to: a) shifting from individual vehicle use to shared fleets, b) introducing autonomous multimodal vehicles for passengers and freight, and c) growing electrified drives and advanced automation (Chen et al., 2016). These shifts alter traditional vehicle and component lifespan calculations, with increased effective operating times due to sharing and round-the-clock autonomous vehicle use. This leads to revised functional and load requirements and shorter life cycles. Reliable predictive diagnostics are crucial, using classified operating data and online monitoring to identify component loads and early damage indications, from preventing unplanned failures to maintenance planning and spotting failure indicators in critical components (Omeiza et al., 2022). Regarding life cycle considerations, focus shifts to immediate reuse, possibly after component revision (Valiyan et al., 2022). Understanding requirements, expected loads, and reuse options is vital for future developers. Knowledge transfer between academia and industry (Valiyan et al., 2022), with collaborative research, is essential for implementing findings and process changes in education and corporate practices through employee training.

2.6 Automation and robotics in the circular economy

Disassembly is an elementary process step for an efficient recycling chain (Huang et al., 2019). Disassembly operations usually include the largest number of employees and the highest complexity regarding the number of possible variants in all end-of-life treatments. Due to the small number of products that have been returned to the recycling process so far and the high variety of variants, disassembly has been carried out manually so far. But with the transformation of the industry to a circular economy, the number of products (e.g., batteries, electrical appliances) coming back from the market will increase continuously in the coming years. With higher quantities, automated disassembly solutions are becoming increasingly economical (Huang et al., 2019). However, the number of variants coming back from the market will probably remain high. Damage and dirt on the parts can additionally increase the difficulty of automation. Hence, very flexible, automated disassembly concepts will be required (Huang et al., 2019). Over the last few years, automated robotic disassembly systems have been developed (Blömeke et al., 2020; Poschmann et al., 2020b, 2021, 2020c) which are to be transferred to the working world in the next step. With the increasing spread of robot-supported automation solutions in the disassembly area, the acceptance of technology and the division of tasks between man and machine will play an important role (Poschmann et al., 2020a).

2.7 Digitization in recycling in the circular economy

The transformation from a linear to a circular economy requires efforts beyond the development of technologies or new ways of thinking. Efficient and market-dependent agile process management in a circular economy is also characterized by a massive increase in the information requirements of all actors involved (Giudice et al., 2020). More diverse product and material flows, more complex technology chains, and faster changes in market requirements lead to a work overload of employees in procurement, process planning, production, and sales. This is not only true for product manufacturing but even more in recycling. The situation is exacerbated by an increasing shortage of skilled workers. Digitalization can make a crucial contribution to counteracting this (Walden et al., 2021). It is essential to generate user-group-specific interfaces that allow the respective players to call up and enter the information that is relevant to them in a targeted manner. An approach based on the principles of System Dynamics has proven its worth, especially in the face of rapidly changing market conditions and complex process chains. Over the last few years, suitable systems and processes have been developed (Blömeke et al., 2020; Knieke et al., 2019; Lawrenz et al., 2021; Nippraschk et al., 2022) which are to be transferred to the working world in the near future.

2.8 Sustainable work design

Today, the imperative shift towards a circular economy in the field of work and economics presents four key sociological challenges. First, the transition exerts pressure on labor markets, necessitating new skill profiles across various levels, from highly qualified engineers to medium-skilled craft workers (Zamfir et al., 2017). Second, effective work organization, technology development, and workforce availability are crucial for developing, producing, and maintaining new products, services, and production processes. Making employment in the circular economy attractive while ensuring economic viability is a central concern. This entails conceptualizing, designing, and implementing mutually beneficial, decent work, a longstanding topic in work sociology (Zamfir et al., 2017). Future research must assess the applicability of existing labor knowledge to the circular economy context. Third, emerging work-related risks and health concerns, particularly in recycling jobs, need to be addressed with solutions found in work organization, process development, and labor market transitions (Panwar & Niesten, 2022). Lastly, in countries like Germany where unions and company-level co-determination remain considerably important, labor relations play a pivotal role in shaping social partner involvement in circular economy work issues and transition challenges. Understanding the future of work in a circular economy requires a comprehensive consideration of labor relations, social partners, and the dynamics of social partnership (Ghența & Matei, 2018).

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