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Manufacturing-as-a-Service (MaaS) to Increase Value Chain Resilience and Circularity: Towards a Systematic Methodology for Manufacturing Process Servitization and Value Chain Orchestration

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Abstract: In the current dynamic, volatile, and uncertain world, manufacturing companies face increasing pressure to respond efficiently and rapidly to disruptions, while at the same time adopting sustainable and circular practices. This paper focuses on Manufacturing-as-a-Service (MaaS) for enhancing resilience and promoting circularity in manufacturing value chains. Based on the limitations of existing MaaS research and scarcity of implementations, a systematic methodology is proposed for manufacturing process servitization, manufacturing process and product matching, and manufacturing process connection, collaboration and execution. This methodology supports the scaling of MaaS to a large variety of manufacturing processes, enabling dynamic distributed networks of manufacturing resources. Resiliency enhancing processes are outlined using MaaS for creating alternative value chain orchestrations, as responses to disruptions. Moreover, processes promoting circularity in relation to MaaS and resilience are outlined. This act as support for finding appropriate value chains partners to enable a circular product system and in increasing resilience and circularity simultaneously by reusing and remanufacturing critical components.

Keywords: Manufacturing-as-a-service, Resilience, Circular Economy, Servitization, Manufacturing System, Value Chain, Manufacturing Network

1. INTRODUCTION

Manufacturing companies need to adapt quickly and rapidly to changes and disruptions impacting demand and supply, as the global manufacturing environment is becoming increasingly uncertain and volatile (Romero, D., et al., 2024). At the same time, global warming and climate change forces manufacturers to lower emissions and reduce waste through circular economy principles (Acerbi, F., and Taisch, M., 2020). Traditional linear and static value chains are insufficient of handling these challenges and innovative business models, strategies, and technologies are needed to promote and enhance resilience and circularity (Eisenreich, A., et al., 2022).

Manufacturing-as-a-Service (MaaS) has attracted increasing attention in recent years (Hasan, M., and Starly, B., 2020), as it provides on-demand manufacturing value networks, where several manufacturers can form networks sharing resources and capacity in a dynamic way (Moghaddam, M., et al., 2015). Thus, MaaS can be defined as a distributed system of manufacturing, where resources, data, and software are offered as services, enabling manufacturers to access different and distributed providers to implement and execute their manufacturing processes. In this way, MaaS can enable fast and rapid orchestration and re-orchestration of value chains by combining servitized manufacturing processes on demand (Tedaldi, G., and Miragliotta, G., 2023). Despite the promising potentials of MaaS, the wide implementation in the manufacturing industry is yet to come. While many successful examples of MaaS implementation exist, these are often largely focused on one single process, e.g. additive manufacturing, and thus limited in terms of type and variety of manufacturing processes included (Tedaldi, G., and Miragliotta, G., 2023). Moreover, existing research on MaaS and other related concepts such as cloud manufacturing, platform-based manufacturing, and networked manufacturing, is largely focused on the aspects of connecting and matching the provider and customer in a servitized context through a mediation platform (Bulut, S., et al., 2021). Furthermore, existing research on MaaS cover a large variety of frameworks, technologies, and models for the MaaS concept (Kusiak, A., 2019). However, the systematic process of developing MaaS in a manufacturing context remains largely unexplored, including a lack of methods and models for manufacturing process servitization and explicit descriptions of how value chain orchestration in MaaS context can increase resilience and circularity.

Therefore, this paper presents a systematic and scalable approach for servitizing manufacturing and developing MaaS to

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increase value chain resilience and circularity. The methodology contains three distinct stages elaborated and described as a series of activities: i) manufacturing process servitization, ii) manufacturing process and product matching, and iii) manufacturing process connection, collaboration and execution. While each stage and activity need to be supported by distinct models, tools, and technologies, this paper offers a first integrated and scalable methodology for making MaaS work in the manufacturing industry and across many types of processes.

The remainder of the paper is structured as follows: Section 2 presents related research on MaaS and methodologies to support its operationalization. Section 3 presents the proposed systematic methodology for manufacturing process servitization, matching and execution, including main steps and activities for manufacturing companies as both service providers and customers. Section 4 describes how the methodology can be used to enhance value chain resilience and outlines the main activities in using manufacturing services for mitigating disruptions and promoting circular economy. Finally, Section 5 summarizes the contribution and outlines further research.

2. RELATED RESEARCH

The concept of MaaS is currently receiving increasing attention in research, reflecting a general trend towards servitization, eco-system approaches in manufacturing, and Everything-as-a-Service (XaaS) (Hasan, M., and Starly, B., 2020). MaaS encompasses platform-based manufacturing, cloud manufacturing, and software-as-a-Service, integrating these elements into a cohesive framework. Moreover, MaaS emphasizes service-oriented and networked manufacturing, facilitating collaboration and efficiency (Tedaldi, G., and Miragliotta, G., 2023). MaaS is also leveraging XaaS to transform traditional manufacturing into a more flexible, responsive, and scalable model (Bulut, S., et al., 2021). While a wide range of topics is explored within these related concepts, research is generally limited in exploring the balance between servitizing the manufacturing processes, both internally and externally, and leveraging the servitization to improve resource management and production efficiency (Bulut, S., et al., 2021). Many MaaS frameworks primarily focus on the interaction between two key actors and the mediating platform, covering both software-oriented and concept-oriented approaches (Ren, L., et al., 2017; Bulut, S., et al., 2021). Traditionally, strategic, long-term, and investment-intensive decisions, such as supplier collaborations, plant locations, and logistical setups, are now required to be made on a shorter-term, operational basis in a cost-efficient and rapid manner (Kusiak, A., 2019). This shift necessitates frequent strategic decisions with a shorter time horizon, blending strategic and operational considerations. To facilitate the transition and scale the implementation of MaaS, a comprehensive methodology is essential. This methodology should outline the critical steps and activities for servitizing manufacturing processes, connecting manufacturers based on product needs and demand, and guiding the development and execution of MaaS. A comprehensive methodology for MaaS must include structured representations of essential activities, decisions, actions, and processes (Moghaddam, M., et al., 2015). It must be versatile enough to be applied across various manufacturing contexts and processes, while also supporting a high number of manufacturers in servitizing their operations and engaging with new suppliers and customers. Additionally, it should integrate a comprehensive system of methods and models for developing and implementing MaaS, enabling various levels of digital and physical integration, real-time data exchange, tool automation, and supportive technology (Henzel, R., and Herzwurm, G., 2018; Moghaddam, M., et al., 2015). The methodology needs to capture the distinct and integrated activities and processes across both the manufacturing service provider and consumer, ensuring comprehensive coverage and integration. In the remainder of this paper, MaaS methodology is defined as a comprehensive system of methods, models, and procedures for developing, implementing, and utilizing MaaS.

3. PROPOSED MAAS METHODOLOGY

To meet the requirements elaborated in the previous section, this section describes the proposed systematic methodology for MaaS. The aim of the methodology is to support the design and implementation of MaaS by modelling the needed processes. Thus, the methodology contains an integrated representation of the essential processes and activities in MaaS, which can be used as a basis for systematizing supportive methods, models and technologies. In Figure 1, the overall process for MaaS is outlined in three stages: i) manufacturing process servitization, ii) manufacturing process and product matching, and iii) manufacturing process connection, collaboration and execution. Please note, that all figures in the remainder of the paper are original, but stored at Zenodo repository for further development. Thus, references for the specific repository are included for each figure.

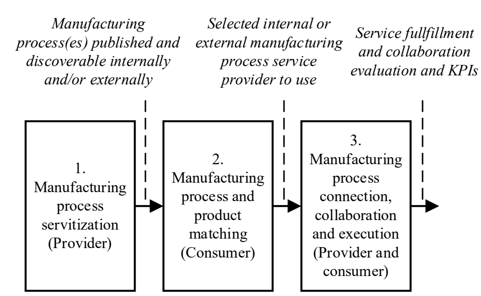

Figure 1. Overall MaaS Process (Andersen, A-L., 2024)

The overall MaaS process in Figure 1 represents the activities at highest level of aggregation. First, the manufacturers acting as providers need to servitize manufacturing processes. Second, the manufacturer that wants to use manufacturing services for a product needs to find and select a service and provider. This includes aligning specification and requirements and matching the product and the process. Last, the provider and the consumer connect, collaborate and the manufacturing processes are executed. It should be noted, that despite the linear representation, the three overall stages may be done both asynchronously and at the same time. Given that the concept of MaaS in the future is scaled and extensively used by many companies, the manufacturing process servitization (stage 1) would be done continuously and frequently by manufacturers globally whenever a potential arises, which creates a large pool and network of manufacturers that are available on-demand. Thus, the discovery, search, matching and execution of service offerings in stage 2 and 3 can be done based on this large pool of available services. Each stage and activity in the MaaS process in Figure 2-4 need to be supported by distinct methods, models, and technologies to enable MaaS at scale. However, the research presented in this paper focuses merely on outlining, describing and systematizing the needed activities and processes for making MaaS work in the manufacturing industry. Therefore, each stage of MaaS is further elaborated in the following (Figure 2-4), while the need for supportive methods, models and technologies is only described. The systematic and comparative review of these is subject to further research.

3.1 Manufacturing process servitization

Figure 2 depicts the four main activities in the first stage of MaaS, where a manufacturing company decides to offer manufacturing processes as services either in their internal production network or to external manufacturing companies.

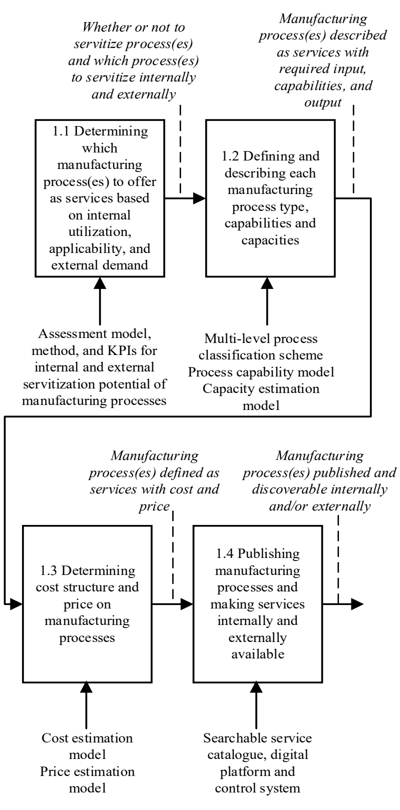

Figure 2. Manufacturing process servitization (Andersen, A-L., 2024)

All activities in this stage are completely related to the provider and can be done independently of any activities at the manufacturing company consuming the services. Essentially, stage 1 relies on the principle that all manufacturing processes can be described, documented, and published as services by defining the process types, capabilities, capacity, cost structure and price. Thus, the specific activities 1.1-1.4 and the needed supportive methods, models and technologies is a fundamental and critical aspect of being able to scale MaaS for many. In this regard, activity 1.1 should utilize specific assessment methods or frameworks for identifying potentials in offering existing manufacturing processes as services internally and externally. This could include consideration both from a resource perspective, i.e. competences, capacity utilization, financial performance, resource sharing, etc. and a market perspective, i.e. external demand, technology availability, etc. In activity 1.2, the description of manufacturing processes as services relies on standardized ways of defining type, capability, and input of manufacturing processes, so that potential customers can understand the service offering and be able to determine whether it matches their specific product to be manufactured. Thus, this stage needs to leverage multi-level classification schemes for manufacturing process types, as well as standard representations of manufacturing capabilities and capacity. After cost and price have been determined in activity 1.3, the services are published to make them discoverable for manufacturing companies that are potential customers of the service. While, cost and price estimations techniques should be adopted to the MaaS context, a digital service catalogue or platform needs to be utilized as well.

3.2 Manufacturing process and product matching

In Figure 3, the second stage of the MaaS process is outlined, defining the activities needed for a manufacturing company wanting to exploit services in a MaaS network. This may be motivated by the need to find and connect to new suppliers for a given component, manufacturers in specific locations that can produce the product or parts of it, or alternative partners to recover from a disruption.

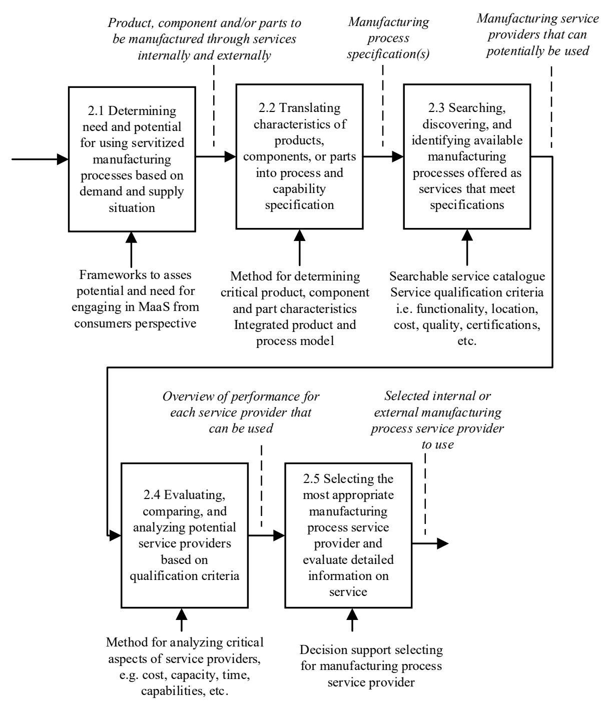

Figure 3. Manufacturing process and product matching (Andersen, A-L., 2024).

Generally, the motivations for engaging in MaaS is assessed in activity 2.1 and relate largely to the resilience aspects elaborated in Section 4. In activity 2.2, the product or part that need to be manufactured through services is considered in terms of its characteristics, which are translated into process specification. Utilizing integrated models of product characteristics and manufacturing process capabilities, enables this translation to be done in an automatic way, rather than solely assessing process compatibility in a manual way. With the required process specification as foundation, manufacturing processes offered as services can be discovered and filtered based on different potential criteria in activity 2.3. In activity 2.4, available manufacturing process service providers are analyzed and compared in terms of performance and conformance to specification and qualification criteria. Finally, the best option is selected in activity 2.5 after evaluating the detailed information on the service and provider.

Stage 1 of the MaaS methodology covers activities only for the manufacturing company offering services, and stage 2 covers only manufacturing companies using and consuming these services. However, as described in Section 2.1, MaaS can both cover i) externally connecting provider and consumers from different manufacturing companies, as well as ii) internally connecting provider and consumers from the same manufacturing company. Essentially, the concept of MaaS and the methodology proposed here is built on the principle of distributed manufacturing processes and systems, but can be applied regardless of how distributed these are in terms of both geographic distance and ownership. Thus, in large global enterprises with several plants, MaaS can be applicable between different plants, factories, or even systems within the factory.

3.3 Manufacturing process connecting, collaboration and execution

In Figure 4, the last stage of the MaaS process is elaborated.

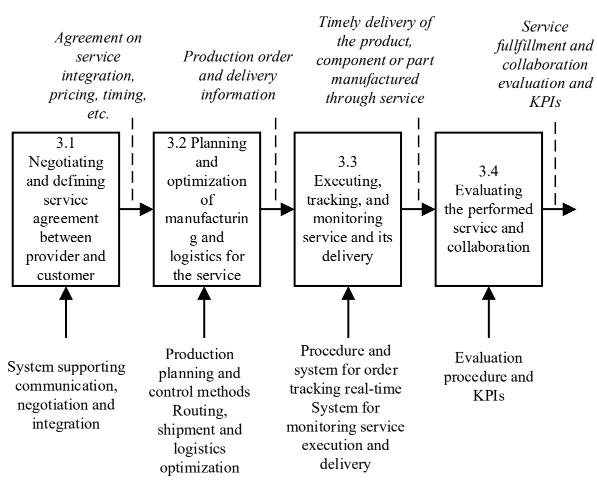

Figure 4. Manufacturing process connection, collaboration and execution (Andersen, A-L., 2024).

In contrast to the first two stages, this stage contains activities in collaboration between the manufacturing companies or entities engaging in MaaS, i.e. the manufacturer providing the service and the manufacturer using the service. In activity 3.1, the service agreement is negotiated and determined between provider and consumer. This should ideally be facilitated digitally and through a common service platform. In activity 3.2, planning and optimization of the manufacturing and logistics setup is performed, to execute the service and the delivery in the most cost-efficient and fast way possible. During manufacturing and delivery, real-time monitoring and tracking of the service progress is covered by activity 3.3, while the evaluation of MaaS collaboration and service fulfilment is covered by activity 3.4 as the final stage of the MaaS process. Evidently, the specific support and extent of automation in information exchange, machine setup, logistics planning, etc. during activity 3.2 and 3.3 depends largely on how distributed the provider and consumer is. For instance, if the MaaS process happens between two plants or entities in the same manufacturing company, it may be easier to create a more seamless integration of the digital and physical aspects of MaaS. Evidently, when MaaS happens across different manufacturing firms, the integration of data, information exchange, etc. depends heavily on legal, confidentiality, and security considerations as well.

While this section elaborated and systematized the MaaS process as a series of activities connected by input and output, the supportive models, tools and technologies were only briefly included. Evidently, these supportive elements can be traced to many different domains and theoretical areas related to manufacturing, economics, supply chain management, and operations management. Moreover, different availability and maturity exists in terms of how well the proposed MaaS stages are supported. For instance, the theoretical foundation for describing manufacturing processes as services is rather limited, as existing research provides limited procedures or models for this. Furthermore, the translation of product characteristics to process specification in stage 2 is supported to limited extent, while the role, structure and design of a mediating platform has been widely addressed in research as described in Section 2. Thus, to enable a complete methodology and system of methods to enable MaaS, extensive research and development efforts should be devoted to various critical activities in the MaaS process.

4. MAAS TO INCREASE RESILIENCE AND PROMOTE CIRCULARITY

With the proposed MaaS methodology as the foundation, procedures for enhancing resilience and promoting circularity in manufacturing can be explicitly considered. In this regard, resilience is defined as the ability to recover and continue operations efficiently, in a relatively quickly after a disruption happens (Nassehi, A., et al., 2022). Circularity is defined as the ability of the manufacturing systems and value chains to support circular economy and apply circular economy principles, such as remanufacturing, recycle, repair (Acerbi, F., and Taisch, M., 2020).

4.1 Resilience process using MaaS as a manufacturing process service consumer

In Figure 5, two overall and essential activities related to recovering and responding to a disruption are outlined. Given that a manufacturing company wants to enhance resilience, it is critical to determine not only the risk of different disruptions and external events, but also know their potential impact on demand and supply conditions in the existing value chain setup. Hereafter, different scenarios should be generated and simulated for how to respond, where MaaS can be utilized to find alternative ways for fulfilling orders and therefore contributing to different alternative value chain orchestrations. It should be noted that these activities are in the domain of the MaaS consumer and relies on the large availability of manufacturing services.

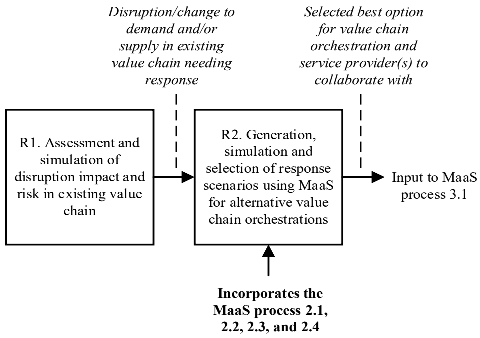

Figure 5. Resilience process as input to stage 3 and incorporating stage 2 of the MaaS process (Andersen, A.-L., 2024).

In Figure 6, the activities related to assessment and simulation of impact and risk within the existing value chain is elaborated. The output of this first part of the resilience process is the identification of disruption/external events that has high risk of severe impact on demand and/or supply in the existing value chain and therefore need mitigating measures and a response.

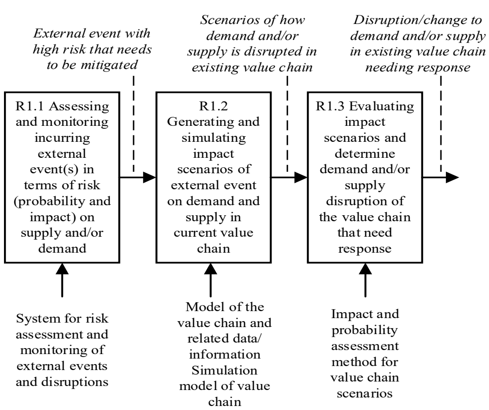

Figure 6. Resilience process (R1) for assessment and simulation of disruptions impact and risk in the existing value chain (Andersen, A-L, 2024).

In Figure 7, the integration of the resilience process and the MaaS process is detailed. The output of this process is an input to activity 3.1 in the MaaS process. Thus, after a new value chain orchestration is determined as a response to the disruption, the MaaS execution and collaboration needs to happen. Moreover, the generation of response scenarios is largely integrated with stage 2 in the MaaS process, as available services and manufacturing providers are used to form response scenarios and ultimately new value chain orchestrations on demand. The process outlined here and with MaaS as the basis, can potentially enhance the resilience and robustness of a manufacturer. Given an incurring external event, e.g. a natural disaster, trade barrier, change of regulation, the manufacturer can first assess the probability and impact of the event on the existing value chain. This could for instance lead to identified vulnerabilities in the supplying network, such as insufficient capacities in upstream supplying plants or a change in where to distribute and sell products. Responses to these disruptions can utilize MaaS and leverage a large network of available manufacturers to engage with. Therefore, MaaS can take various forms depending on the type of impact and response needed: i) engaging with a manufacturer in upstream tiers of the supply chain to secure supply of e.g. components and ii) engaging with a manufacturer at same tier the supply chain to fulfil demand, access technology, satisfy local content, etc.

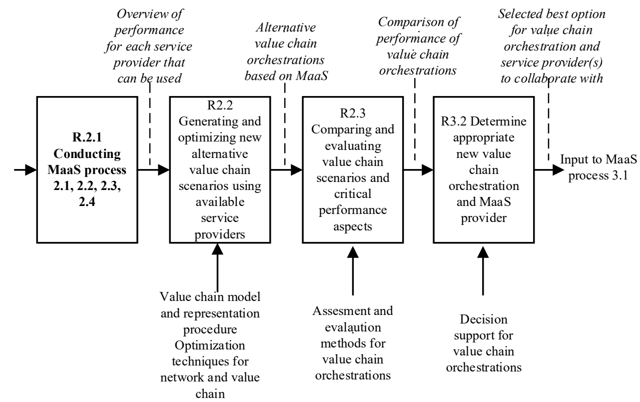

Figure 7. Resilience process (R2) integrating MaaS for generating and simulating response scenarios and alternative value chain orchestrations (Andersen, A.-L., 2024).

4.2 Circularity processes using MaaS as a manufacturing process service consumer

Extending the life of products, imply that manufacturers and value chains can handle the return of products in both logistics and manufacturing. In this regard, the MaaS process and the resilience process outlined in this paper can be envisioned to support the development of circular manufacturing value chains in two different ways; i) supporting manufacturers that wants to take-back products in finding appropriate value chains partners to enable a circular product system, and ii) supporting manufacturers in increasing resilience and circularity simultaneously by reusing and remanufacturing critical components. Thus, the first proposed approach to circularity is related to the take-back of complete products from the end-users, while the latter approach to circularity takes outset in components that are critical for the manufacturer. In Figure 8, the process of using MaaS for finding appropriate value chains partners to enable a circular product system is outlined. The process takes outset in the initial analysis and assessment of typical End-of-Life (EoL) states of products to identify products that are viable options for take-back. Various EoL strategies can be considered, e.g. recycle, repurpose, remanufacture, refurbish, repair, and reuse. Based on this knowledge, required circular processes can be specified in terms of type and capabilities, i.e. for disassembly, testing, sorting, cleaning, repair, reconditioning, reassembly, etc. This activity is largely like the specification of processes needed to manufacture a specific product in the MaaS process 2.1. Given that manufacturers have specified remanufacturing related processes as services and offered these, the network of MaaS providers can then be assessed to find the most feasible value chain setup. The potential benefits of using MaaS for developing a circular product system and value chain are for instance that manufacturers can offer disassembly and remanufacturing related processes in a broad network and build core competence and competitive advantage in the area. Moreover, manufacturers can engage with disassembly and remanufacturing processes world-wide, rather than at specific dedicated locations and can locate these close to the end-user.

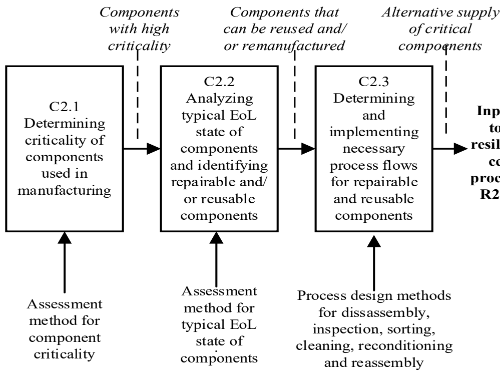

Figure 8. Circularity process (C1) using MaaS for developing a circular value chain (Andersen, A-L., 2024).

In Figure 9, the process of increasing resilience and circularity simultaneously by reusing and remanufacturing critical components is presented.

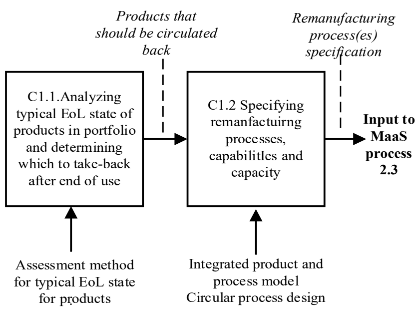

Figure 9. Circularity process (C2) enhancing resilience in manufacturing companies (Andersen, A-L., 2024).

The process takes outset in an initial assessment of the criticality of components, capturing the fundamental aspects of criticality to specific companies. In this regard, criticality can be considered broadly as being related to availability, where a critical component will significantly impair the ability to operate or fulfil orders if not available or reliable. Activity C2.2 covers the assessment of the typical EoL state of individual components, covering components fit for remanufacturing and reuse, i.e. components than can be processed, cleaned, disassembled, updated, repaired, etc., to be considered as good as new and then used in the regular manufacturing activities instead of virgin components. In case of an external event disrupting the supply of critical components, the manufacturer can instead reuse or remanufacture components from take-back products as an alternative supply stream. However, to determine whether this is a feasible and cost-efficient alternative, circular supply options should be considered in response scenario generation and simulation in the resilience process outlined in Figure 7. Thus, the process outlined in Figure 9 can enable a systematic and proactive consideration of circular supply as a resilience strategy.

5. CONCLUSIONS AND FUTURE RESEARCH

This paper presents a systematic methodology for developing and implementing MaaS. Based on the MaaS process, a resilience enhancing process is outlined for manufacturers using MaaS for creating alternative value chain orchestration as a response if a disruption occurs. Moreover, two different processes for establishing increased circularity in manufacturing are proposed. These support manufacturers in finding appropriate value chains partners to enable a circular product system and in increasing resilience and circularity simultaneously by reusing and remanufacturing critical components. While this paper offers systematic representations of activities and processes within MaaS at different levels of granularity and in connection to resilience and circularity, a complete MaaS methodology should incorporate methods, models and technologies needed for its realization. Future research should not only review available options for supporting each stage but also develop the theoretical foundation for exploiting technologies to support MaaS. Moreover, future research should aim at validating the MaaS methodology and provide case studies.

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