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ALIGNING MASS CUSTOMIZATION WITH CIRCULAR ECONOMY

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Abstract: *Impelled by the advent of the Industry 4.0 transition, Mass Customization (MC) is gaining momentum to better align the products, services, and systems provided by manufacturers with the needs and expectations of their customers. Due to the recent mega-trends affecting society, users are always more demanding for sustainable products. Circular Economy (CE) is considered the most promising and impactful paradigm to address sustainable development. In this context, MC can support the implementation of CE-based dynamics and, for this reason, synergies, opportunities, and challenges among these two paradigms were analysed and defined. However, how to fully align MC with CE to minimize the related negative effects deriving from the adoption of each of them has still to be explored. Therefore, the aim of this paper is to deepen the analysis of the contact points among the two paradigms and to provide a deep analysis of the common opportunities and challenges. Results highlight that the role of digital technologies in their common adoption and alignment is pivotal.*

Key Words: ***Mass Customization, Circular Economy, Industry 4.0, Digital Transformation, customer involvement, Manufacturing***

1. INTRODUCTION

In the current era, consumer preferences have changed from mass-produced standardised goods to customised made-to-order ones that may meet each customer's unique intrinsic needs (Sassanelli et al., 2023b). Low-cost mass customisation (MC), that combines efficiency and diversity, is required (Piller and Kumar, 2006). Many industrial sectors have noticed this shift in customer needs, most notably the car market, which offers tens of thousands of varieties, as well as firms in the electronics or fashion industries (Piller and Stotko, 2002). In addition, impelled by the advent of the Industry 4.0 (I4.0) transition (Quadrini et al., 2022; Rüßmann et al., 2015), MC is progressively gaining momentum to support a better alignment of the products, services, and systems provided by manufacturers to the needs and expectations of customers (Franco et al., 2020; Genest and Gamache, 2020). However, the globe is going through an epochal moment marked by profound, worldwide, and constantly changing developments that affect all economic players (Vitti et al., 2024), including countries and businesses, as well as all of humanity. Humanity need to learn how to read these "mega-trends" (i.e., increasing urbanisation, mass migration in quest of a better life, population expansion, the careless use of limited natural resources, and pollution from unrestrained human activity) and take advantage of them to know what the industry's potential future holds (Garetti and Taisch, 2012).

Due to these recent mega-trends affecting society, users are always more demanding for sustainable products (Appolloni et al., 2022). Circular Economy (CE) is considered the most promising and impactful paradigm to address sustainable development (Sassanelli et al., 2023a), strongly impacting the manufacturing industry (Acerbi et al., 2022). MC can enhance the implementation of CE-based dynamics and, for this reason, synergies, opportunities, and challenges between the two paradigms were analysed and defined (Bertassini et al., 2023). However, how to fully align MC with CE to minimize the related negative effects deriving from the adoption of each of them has still to be explored. Therefore, the aim of this paper is to deepen the analysis of the contact points among the two paradigms and to provide a deep analysis of the common opportunities and challenges. Results highlight that the role of digital technologies in their common adoption and alignment is pivotal.

The paper is structured as follows. Section 2 introduces the paradigms of CE and MC, also listing the opportunties and challengesof MC for CE. Section 3 shows the research method adopted and Section 4 presents the results. Section 5 discusses them and Section 6 concludes the paper, also opening rooms for further investigations.

2. RESEARCH CONTEXT

2.1 Mass customization (MC)

MC is defined as the concept bonding a low costs mass production with flexible individual customization (Pine II, 1992). Company delivering individualized goods according to MC need to: develop the solution space (detect the needs of their potential customers, find out where needs diverge most and develop a customisable product offering) (Salvador et al., 2009), design a robust and flexible process design to produce solutions at reasonable costs (Duray et al., 2000; Feitzinger and Lee, 1997; Salvador et al., 2009), support the customer in the choice navigation (communicate the offer to potential customers who need to be aided to implement their co-creation task (Salvador et al., 2009).

Gilmore and Pine II (1997) categorized four types of MC approaches based on the occurrence of changes in the product or in its representation. The four types are: (1) “Collaborative Customisation” (both product and its representation change through the dialogue among designers and customers on product/packaging), (2) “Adaptive Customisation” (no change is implemented by the provider, so the standard product is modified by the customer to satisfy its individual needs), (3) “Cosmetic Customisation” (the provider changes only the representation of the product to each customer), (4) “Transparent Customisation” (customers are provided with customized products often without even knowing it). Similarly, based on the degree of interaction required and the degree of digitizability, Müller and Piller (2004) detected other 4 types of strategies of MC, as follows: “Add-on” (very small or no degree of digitizability and interaction), “Attract attention” (low level of customer integration and high degree of digitizability), “Product Configuration” (low level of digitizability and high level of customer integration), “E-Service-Innovations” (high level of both digitizability and customer integration).

They also detected specific methods for achieving mass customization: soft customization (i.e., Self customization, Point-of-delivery customization, Service customization) and hard customization (i.e., Customization-standardization-mix, Modular product architectures, Flexible customization). Soft customization implies a fixed set of solutions. Thus, all modules are designed and customization is based on the combination of modules. Whatever combination the customer chooses, the company has previously designed that part and generally fully controls the number of possible variants. Hard customization implies that, upon customer request, some parts are manufactured only for them or even designed only for them. Here, parts and components, that could not have anticipated in advance and which will surely hardly suit any other use, may appear. Many people are interested in the possibilities that come with MC. Numerous businesses have already adopted this new business model and are running profitably. However, the majority are relatively modest start-ups that penetrate mature industries by taking advantage of the novelty impact of mass customisation (Piller, 2005).

2.2 Circular Economy (CE)

In an effort to improve the resource efficiency of material assets while minimising emissions, resource usage, pollution, and waste, the CE paradigm was introduced towards the end of the 1980s (Stahel and Reday-Mulvey, 1981) and is progressively gaining momentum in manufacturing (Acerbi et al., 2024) and througout society (Sassanelli et al., 2023a). Circular Business Models (CBMs) are a new class of business models (BMs) whose value creation is based on preserving the economic value that items have after they are used and using it to create new kinds of market offers. Often, digital technologies are demanded to fully embrace and exploit the potential of the CE paradigm, from a company perspective (Rosa et al., 2020) through circular supply chains (Chiappetta Jabbour et al., 2020; Taddei et al., 2024) up to the so called CE ecosystems (Trevisan et al., 2021).

Being start-ups those more inclined to implement MC business models, it could be useful to start to analyse the linke between MC and CE on this kind of companies. Henry et al. (2020) found five different kinds of circular start-ups: design-based (innovating in areas such as product design and source material), waste-based (deriving value from underutilised external waste sources, such as excess food), platform-based (often concentrating on enabling technology to enable marketplaces that are B2B, B2C, and C2C), service-based (typically integrating their products into a service system, keeping ownership of the tangible product with them), and nature-based (revitalising the socio-ecological system by providing goods or services).

These circular companies can move from the start-up to the scale-up stage using three distinct types of strategies: 1) commercial, 2) phased and 3) synced (Han et al., 2023). "Commercial" scaling is the first strategy, characterising new businesses that emphasise investing time and money to expand their operations to maximise profits. The majority of service- and platform-based start-ups who consider themselves to be "grown circular" employ this growth strategy. These service-based startups often provide subscription mobility services. In the second strategy, “Phased”, circular start-ups go through "phases" where they scale first on the commercial side and subsequently their circular effect. This growth strategy has been seen in service- and design-based circular start-ups. Scaling tactics centred on product development, with resources allocated to a more effective system and expanding transaction kinds and sales channels, predominate this first commercial period. "Synced" scaling is the third strategy in which circular start-ups aim to expand their effect and their business at the same time, provided that increasing their business does not conflict with increasing their impact. This growth strategy was employed by platform-, waste-, service-, and design-based circular start-ups. These start-ups have one thing in common: their unconventional business plans, which frequently go against the accepted norms in the sector and the prevailing consumer patterns. These startups must actively develop new "rules" while operating outside of an established framework to continue operating as for-profit companies and addressing the significant societal issues for which they were created.

2.3 Opportunities and challenges of MC for CE

MC, being applied with sustainability goals, can be a valuable means to implement CE (Piller, 2005). Bertassini et al. (2023) summed up the synergies between CE and MC concepts in Table 1, even though so far it seems that they have been studied together in a very limited way, and they have been analysed and implemented as completely different domains.

Table 1. Synergies between MC and CE (adopted by Bertassini et al. (2023))

Mass customization	Circular economy
Co-creation (co-design) with customers	Co-creation with stakeholders
Interaction/communication with customers	Interaction/communication with stakeholders
Modular design & Design for X	Eco design
	Value optimization
	Material and energy efficiency
	Life cycle thinking
Build-to-order & postponement	Material and energy efficiency
Platform	Dematerialization
	Service nature (product-as-a-service)
	Closed-loop supply chains
Digital technologies	Digital technologies

The synergies defined in Table 1 were useful to uncover the opportunities and challenges of the joint implementation of the two domain, that however deserve to be further analysed and detailed.

3. RESEARCH METHODOLOGY

The analysis proposed has been conducted using as baseline the work by Bertassini et al. (2023). Two experts with more than 10 years of experience respectively on MC and CE were involved to focus on the challenges and opportunities in this twofold domain. They used as main drivers for the analysis of such joint opportunities and challenges on one side the type of CE start-ups (and more in general companies) involved (design-, waste-, platform-, service-, and nature-based (Henry et al., 2020)) and their related scale-up phase (commercial (C); Phased (P); Synced (S) (Han et al., 2023)), and on the other one the type of MC (soft or hard) (Müller and Piller, 2004).

4. RESULTS

This section is dedicated to elaborating on each of the identified opportunities for integrating CE principles with MC concepts, providing a clearer understanding of their potential impacts and applications. In the following sub-sections, an elaboration on each opportunity is provided, followed by a deep analysis based on both the CE and MC classifications presented in Section 3.

4.1 Opportunities (O)

O#1: Design and Development of Products More Aligned with Customers' Needs

By integrating MC into product design and development, companies can create solutions that are more closely aligned with individual customer preferences and needs. This approach not only enhances customer satisfaction but also reduces waste generated from products that do not meet market demands. This approach can reduce overproduction and the consumption of unnecessary resources and aligns closely with CE principles by ensuring products are used longer and more thoroughly.

Most directly, it impacts customer satisfaction and economic sustainability through the waste reduction and resource efficiency by ensuring products are valued and used longer. Properties as modularity to support customization should not compromise the overall product function, enabling the product to be more consistent with the customer requirements and needs, and avoiding making the product acquirable only by the targeted single customer for whom it has been realized (otherwise it could easily become a waste).

O#2: Increasing Awareness of Environmental, Social, and Economic Impacts of the selected features of a given product/solution

Educating customers and stakeholders about the impacts of their choices can influence purchasing decisions towards more sustainable options. Providing information about the lifecycle impacts of products encourages more responsible consumption patterns. This transparency can motivate consumers to choose products that are more sustainable, supporting broader environmental and social goals. While more indirect, raising awareness is crucial for driving behavioural change among consumers and stakeholders. Critical for changing consumer behaviours but depends on effective communication strategies. Also in this case, the role of digital technologies to monitor systems during their lifecycle and gather data and information to the provider (when possible), allows to give back to the users a customized solution. Dedicated and customized information could support customers not only in the choice of the product but also in using it in a sustainable way up to its disposal. In this case, the product itself could be customized by the manufacturer to enable the provision in the product of the customized function. Otherwise, customers could be called to exploit supportive physical evidence (digital devices external to the product) to obtain their awareness of environmental. Social and economic impacts of selected features of a given product/solution.

O#3: Potential to Introduce Multiple-Life Cycles, Eco-Design, and Extended Product Lifetime

Customized products are often designed to better fit the specific needs and contexts of their users, which can lead to longer product lifetimes. Modular designs enable easier upgrades, repairs and repurpose thus supporting multiple-life cycles and reducing the need for full product replacements. This not only enhances the product's value over its lifecycle but also reduces waste and encourages a more sustainable management of materials that are easier to disassemble and recycle. It also supports sustainability through design principles that extend product life and facilitate material reuse and is pivotal for reducing waste and maximizing resource use.

This opportunity can be supported by the adoption of design practices that are also supporting the provision of servitized solutions. Approaches like design for reliability, modularity, customizability, maintainability/serviceability, assembly and disassembly, but also design for inspectability and testability can support the provision of a less expensive solution, fostering the provision of services throughout its entire lifecycle and enabling to slow and close resource loops and narrow resource flows through resource efficiency.

O#4: Introduction of Closed-Loop Supply Chains to support multiple life cycles and product, materials, and components re-circulation

Closed-loop supply chains are essential for facilitating the reuse, recycling, and remanufacturing of products, materials, and components. This system minimizes waste and resource extraction by keeping materials in circulation for as long as possible. Mass customization can be integrated into this system to ensure products are designed from the outset to fit into these loops, enhancing material recoverability. Fundamental for reducing waste and crucial for achieving sustainability in manufacturing and production. Supports systemic change towards a circular economy. Also in this case, design approaches that could support the disassembly, modularity, inspectability and testability, could foster the closing of resource loops in the (re-)manufacturing of a system to be delivered in multiple cycles. In addition, the Digital Product Passport (DPP) can support the traceability of the components and materials that are included in a given system, fostering them to be introduced in a multiple lifecycle loop.

O#5: Implementation of Product-As-A-Service Strategies

This model shifts the traditional focus from product ownership to service provision, where durability, reparability, and upgradability are prioritized. It aligns incentives for companies to create better, longer-lasting products, reducing environmental impacts over time.

Transforms consumption patterns and promotes longer product lifespans, which is critical for sustainability. Shifts the business model towards sustainability and encourages long-term relationships with products.

Services support the provision of customizable features (in particular if supported by digital technologies). The provision of services not only can prolong the durability of systems but can also drive the customization of solutions that could be updated throughout their entire lifecycle being retrofitted, disassembled and/or maintained.

O#6: Innovation Capacity and Flexible Operations

Embracing MC and CE requires innovative approaches to product design, manufacturing, and logistics. Mass customization inherently requires a flexible manufacturing system that can quickly adapt to changing customer needs and technological advancements. This flexibility can drive innovation in product design and production processes, supporting the principles of CE by facilitating the rapid integration of new and sustainable practices. It also supports continuous improvement and adaptation in a rapidly changing market but is more an enabler than a direct outcome.

On the other side, production systems need to be characterized by higher levels of complexity to be able to guarantee MC and therefore a higher variation in the output produced. More advanced technologies, coming from the I4.0 paradigm, would be needed not only to be deployed, employed, and integrated in current production systems and processes (e.g., Additive Manufacturing, autonomous robots, simulation, horizontal and vertical system integration, Machine Learning) to support the creation of customized products, but also to be embedded on them (e.g., Augmented Reality, Artificial Intelligence, Internet of Things, Cyber-Physical Systems, the Cloud) to support the delivery of their functions during their entire lifecycle. Data and information management would play a pivotal role in this digital transition for enabling customization and circular flows, fostering the optimal management of material and energy flows and the minimization of waste generation and depletion during the entire lifecycle of the products (from conception up to disposal).

In addition, from a production perspective, high volumes production systems and related processes are usually considered less resource-demanding, due to a higher OEE (so better quality, availability of the equipment and performances). However, producing high volumes of a standard product, even with a very high OEE and the inclusion of circular flows of materials and/or energy, could result in a rebound effect of CE. Indeed, companies could produce more because they are more efficient and employ circular strategies in their production processes. Instead, pursuing and implementing in a combined way the CE and MC paradigms would allow organizations not only to reduce wastes during the production (reaching higher efficiency in the use of their equipment and resources) but also to limit the generation of products that could be not necessary on the market.

Innovation should be introduced both at the industrial processes and the delivered products levels. Therefore, innovation sessions dedicated to the involvement of customers (i.e., design for, with, or by customers) in the development of the products to be delivered on the market could be fruitful and pivotal in strongly enhancing the innovation capacity of the company in delivering customized and circular solutions.

O#7: Sustainable Value Co-Creation

This involves collaborative efforts among customers, producers, and other stakeholders to create products and services that offer mutual benefits and reduce ecological footprints. Engaging multiple stakeholders in the design process helps in identifying and implementing more sustainable practices.

Sustainable value co-creation encourages broader stakeholder involvement in sustainable practices essential for widespread adoption of CE principles.

Involving multiple stakeholders of a system in its development can support to address both their needs but also to better understand the way a system could be used by those different users, giving the possibility not only to avoid wastes (functions not needed) in the design but also to detect possible rebound effects of a circular system due to its nominal major efficiency.

4.2 Challenges (C)

Addressing these challenges is crucial for successfully implementing CE principles through MC. Let's explore each challenge in more detail and then rank them according to their impact on the viability and effectiveness of CE strategies.

C#1: Reuse Strategy for Customized Products

MC tailors products to individual customer specifications, which can make the reuse of such products more challenging. Since each product is designed for specific needs and preferences, it may not appeal to a second user as readily as a standard product might, potentially limiting the product's lifecycle.

In addition, modules should be realized to make the product more flexible and customizable depending on the different customers. Indeed, to make a customized product more suitable for a CE-driven lifecycle, modules should support the slowing/extension of the lifespan and the narrowing and closing of resource loops. This means that modules could bridge the prolonging of the systems lifecycle, simply making it preferable for the customers to substitute only a component against of the entire system at a certain point of the lifecycle. In addition, customized parts should be simply disassembled and substituted with new ones in case of a new owner and these modules should be made with the less possible quantity of material, that should be preferably green and bio-based.

All these decisions are taken during the beginning of life of products, impacting up to the 80% of their total environmental footprint. Therefore, timely solutions in this phase are strategic to support the alignment of MC and CE in the entire lifecycle in a sustainable stream.

C#2: Suitability for Remanufacturing

The extent to which a mass-customized product can be remanufactured depends heavily on its initial design. If the product architecture isn't designed with remanufacturing in mind, disassembly and reuse of components can become prohibitively complex and costly. In addition, MC-related features should not impact on remanufacturing costs and easiness. The sustainability of the product should indeed not be impacted by customized components that should be easy to be disassembled and substituted. As well, the entire product should be redesigned to address remanufacturing and allow the narrowing and closing of resource loops and the extension of the product lifecycle also through this phase.

C#3: Variety of Parts and Spare Parts Management

MC often involves the use of a wide variety of parts to cater to personalized customer demands. This variability can complicate the logistics of managing spare parts inventories, potentially increasing costs and inefficiencies in maintaining product support over time.

A further point contributing to higher complexity is the development of sustainable customizable spare parts compliant to the CE paradigm.

C#4: Product Parts Reusability and Integrated Lifecycle Management

Achieving efficient reuse of product parts and integrating product lifecycle management in mass customization involves complex balancing of cost, material, and energy efficiency. It requires innovative design that considers not just the initial manufacture but also the end-of-life stage of the product, which can be challenging to optimize.

Companies should opt to close the loop of resources especially for customized components. So, not only these parts are characterized by a high variety but should also be compliant to requirements (e.g., in terms of materials, shape, characteristics) that should enable them to be retrieved at the end of their life and remanufactured to give life to new customized components in an easy way. For example, automated disassembly and additive manufacturing technologies could support this kind of dynamics.

C#5: System Innovation and Organizational Change

Implementing MC requires significant changes across the entire value chain, from design and production to sales and customer service. This entails not only technological innovations but also substantial organizational changes to develop new capabilities and adapt to the flexible, customer-focused approach needed.

Also CE requires adjustments in the organization, complemented by adequate skills across it (Laurieri et al., 2020; Straub et al., 2023). Servitized business models should be implemented to deliver product-service systems capable to involve more customers in CE-related dynamics and practices. All the divisions of the organization should be involved in measuring and controlling circular performances with the aim of a continuous improvement and innovate not only the product delivered but also the related processes in its lifecycle (development, production, use, or also disposal).

4.3 Analysis of opportunities and challenges of joint adoption of CE and MC paradigms

Based on the categorization reported in Section 3, the opportunities and challenges deriving from the joint adoption of CE and MC has been discussed by the two experts (respectively in Table 2 and 3).

Table 2 refers to the recorded opportunities that MC generates with a positive impact on the implementation of CE. Concerning CE, the type of companies that could benefit more of the joint adoption of CE and MC have been detected. In addition, it has also been indicated which phase these companies could be more likely to pursue to scale-up their CE-driven business model. Instead, in the column related to MC, experts have indicated which type of MC depth has a more significant impact on the given opportunity. For example, for Opportunity#1, the design and development aligned with customer needs to reduce resource waste, could be addressed more likely by design-, service-, and waste-based companies (respectively innovating in product design/source material areas and deriving value from under-utilised external sources) instead of platform- and nature-based ones (more inclined at leveraging on technologies to exploit platforms or at revitalising the socio-economic system). In addition, the phased and synced phases of scale-up (aiming at scaling their circular effect through tactics centred on product development, re-allocation of resources and expansion of sales channels up to the definition of unconventional business plans) have been selected against the commercial one (more service- or platform-based). Concerning MC, the design and development of customized products lead to better alignment with consumer needs. Given that soft MC involves a final set of solutions from which the consumer chooses according to their needs, and hard MC allows for the production of non-standard components and even designing according to specific requirements, it follows that hard MC has a more pronounced impact on the given Opportunity#1. Following this logic, conclusions have been drawn also for the remaining opportunities.

The challenges listed in Table 3 indicate potential counter-effects of the MC strategy on the implementation of CE. Concerning CE, the CE type of companies that could be more impacted by challenges deriving by the joint adoption of CE and MC have been detected. In addition, it has also been indicated which type of phase these companies could be more likely to pursue to scale-up their CE-driven business model.

Table 1. Opportunities of joint adoption of CE and MC

	CE type of company and related scale-up phase: commercial (C); Phased (P); Synced (S)					*MC*	
	design-based	waste-based	platform-based	service-based	nature-based	*Hard*	*Soft*
Opportunity #1: Design and development aligned with customer needs – Reduces resource waste and enhances customer satisfaction.	P/S	P/S		P/S		X	
Opportunity #2: Increasing awareness of impacts – Empowers consumers to make informed decisions that support sustainability			C	C	P/S		X
Opportunity #3: Introducing multiple-life cycles, eco-design, and extended product lifetime – Pivotal for reducing waste and maximizing resource use.	P/S	P/S				X	
Opportunity #4: Introduction of closed-loop supply chains – Crucial for making the CE viable and sustainable long-term.		P/S	C	C	P/S		X
Opportunity #5: Implementation of product-as-a-service strategies – Transforms consumption patterns and supports long-lasting products.	P/S		C	C	P/S		X
Opportunity #6: Innovation capacity and flexible operations – Supports continuous improvement and adaptation in a rapidly changing market.	P/S	P/S				X	
Opportunity #7: Sustainable value co-creation – Encourages broader stakeholder involvement in sustainable practices.	P/S	P/S				X	

Table 2. Challenges of joint adoption of CE and MC

	CE type of company and related scale-up phase: commercial (C); Phased (P); Synced (S)					*MC*	
	design-based	waste-based	platform-based	service-based	nature-based	*Hard*	*Soft*
Challenge #1: Reuse Strategy for Customized Products – Important for extending product life cycles beyond the original user, this challenge is key to avoiding waste and maximizing resource utilization.		S			S		X
Challenge #2: Suitability for Remanufacturing – Central to the concept of CE, the ability to remanufacture products directly influences the sustainability and economic viability of MC.	P/S						X
Challenge #3: Variety of Parts and Spare Parts Management – While operationally significant, this challenge ranks slightly lower as it is more of a logistical issue than a strategic one.			C	C			X
Challenge #4: Product Parts Reusability and Integrated Lifecycle Management – This is critical for reducing environmental impact and ensuring that products can live multiple life cycles.	P/S	P/S			P/S		X
Challenge #5: System Innovation and Organizational Change – This is the foundational challenge that affects all aspects of implementing MC in a CE context. Without addressing this, other challenges cannot be effectively tackled.	P/S	P/S	C	C	P/S	X	

As in Table 2, also in Table 3 the last column is related to MC, indicating this time the type of customization depth more favourable for the given challenge. Taking as an example Challenge#1, the companies more suitable and willing to cope with reuse strategy of customized products are the waste- and nature-based ones (more inclined in deriving value from under-utilised external sources or pushed by the willingness of revitalising the socio-ecological system by providing goods or services). In addition, these kinds of companies can succeed in addressing this challenge more likely in the synced phase, through the adoption of unconventional business plans. Instead, related to MC, according to Challenge#1, it is considered that soft MC is more suitable for implementing a product reuse strategy by the next owner, compared to products specially designed and made for a specific customer through hard MC. Following this logic, conclusions have been drawn for the remaining opportunities.

5. DISCUSSION

Results highlight that the role of digital technologies in the common adoption and alignment of CE and MC is pivotal. It was already proved that I4.0 is beneficial for the single adoption of either MC (Franco et al., 2020; Gandhi et al., 2014; Genest and Gamache, 2020) or CE (Chiappetta Jabbour et al., 2020; Rosa et al., 2020; Taddei et al., 2024).

In conclusion, while MC offers several exciting opportunities for advancing the principles of the CE, it also presents unique challenges that need to be addressed through innovative design, supply chain management, and technology use. Collaboration between designers, manufacturers, consumers, and recyclers will be key to overcoming these challenges and fully realizing the benefits of integrating MC with CE principles. A point that so far has not been discussed in literature is which type of MC (i.e., adaptive, transparent, cosmetic, or collaborative, depending on the change in the product itself or only in its appearance) (Gilmore and Pine II, 1997) could better support the implementation of CE.

The same relation can be studied in the opposite direction. Indeed, CE, if widely applied in manufacturing (and then able to replace linear products with circular ones and to trigger the creation of circular supply chains and ecosystems capable to involve the different stakeholders in an industrial symbiosis mechanism), can reduce the environmental impact of MC (requiring by definition for major investments in technologies, higher complexity in warehousing, logistics, etc) and can trigger virtuous loops in the exploitation of resource loops used for customize products.

6. CONCLUSIONS

This paper deepened the analysis of the contact points provided a prioritization of the common opportunities and challenges. Results highlighted the need to align MC with CE to minimize negative effects. In addition, the role of digital technologies in their common adoption and alignment is pivotal.

Limitations of this study are for sure given to the research method adopted. So far, only two experts have been invovled in this analysis and, therefore, a wider number of experts contributing to enrich the link between MC and CE could improve the results obtained at this stage. In addition, a third dimension, the digital transformation, could be considered in bonding these domains.

This open rooms for further researches. First, a systematic literature review investigating the role of these technologies in enhancing the alignment of these domains and supporting their joint adoption would better support to unveil the opportunities and challenges companies and organizations to provide suitable and tailored solutions to their customers addressing also sustainable development. Second, researchers could analyse how so far companies actually applied MC to adopt CE practices in their organizations, also with the support of digital technologies. Third, the role of CE ecosystems and circular supply chains should be analysed in the joint adoption of MC and CE. Forth, how customers and users could be involved along the entire lifecycle of customized and circular solutionshas to be defined. Lastly, the role of design should be better analysed, and related suitable approaches and methods should be proposed to support the development of products to be better exploited along their life span (according to circularity principles), but mantaining at the same time their uniqueness as customized products.

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