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Bridging Mass Customization and Sustainability: Key Enablers for Sustainable Mass Customized Products

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1. INTRODUCTION

Mass customization (MC) strategy allows the integration of customers into configuring products whilst keeping prices similar to those of mass production (MP) [3]. MC enables lower production volumes, producing only what is needed and ordered by the customer, reducing waste and unnecessary use of resources. Furthermore, customized products, fitting customers' exact needs, will be used longer, reducing the need for new products [6][15]. Even though at first sight MC and sustainability might seem incompatible, MC is believed to be a key strategy for developing sustainability. Yet, this depends on the type of MC and its implementation.

According to the Doughnut model, sustainability is defined as maintaining a "Safe and Just Operating Space" (SJOS) that respects the nine planetary boundaries while ensuring the 12 social foundations are met for all individuals. Balancing these conditions would pave the way towards a long-term economy prosper [4]. Even though MC seems to be a promising strategy for sustainable development, this is yet to be proven and further analysis is needed. The first step is to analyze whether MC enablers can also enable sustainability.

According to the Oxford Dictionary, an enabler is "a person or thing that makes something possible". In other words, it is the possible best practices or activities that facilitates the realization of the intended term.

Several enablers of MC are found in literature. These can be categorized based on different product life phases. According to Fogliatto et al., mass customized product lifecycle could be divided into order elicitation, design, manufacture, and supply chain [5]. From a broader design-oriented perspective, product lifecycle consists of five distinct phases. First is the ideation phase representing the conceptual phase where the product is solely an idea. This is followed by the definition phase where the product is fully specified in details. The third phase is realization in which the product is converted to

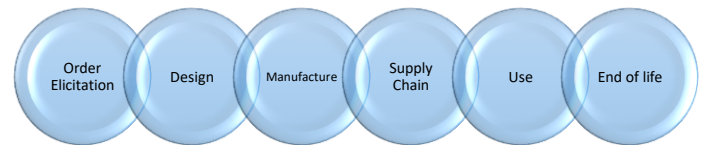


Figure 1 Customized Product Life Cycle Stages

physical form through manufacturing after which it is distributed for customers by means of supply chain. The fourth stage is use or service stage representing the customers' utilization of product. Finally, end of life phase including processes such as disposal, retirement or recycling [1]. Therefore, a merge of the two mentioned perspectives is proposed (Figure 1). The proposed categorization is based on design-oriented perspective while taking in consideration the MC strategy. By aligning MC enablers and sustainability enablers with this categorization, it becomes possible to start analyzing the extent to which MC practices could contribute to sustainability across different product life phases.

This research is the first step of many in analyzing the link between the enablers of MC and sustainability. First, a review of MC and sustainability enablers is presented in sections 2 and 3, respectively. Section 4 explores the intersection between MC and sustainability, either positively or negatively. It also identifies how MC enablers can promote sustainability, emphasizing on enablers with negative or positive relationships. Finally, Section 5 summarizes the findings of this research and presents potential future research questions for sustainable MC. Keywords like "Sustainability enabler" OR "Sustainability" AND "Mass customization enabler" were used in the search across databases like Scopus and ScienceDirect.

2. MASS CUSTOMIZATION (MC) ENABLERS

An exhaustive literature review identified around 30 MC enablers. These are categorized based on the proposed lifecycle stages and presented in Table 1. MC

Table 1 Mass Customization (MC) Enablers from product life point of view

MC enablers					
Common enablers in all life stages of the product					
Integrated information technology systems (IT) (Da Silveira et al., 2001 [7]; Selladurai, 2004 [23]; Moser, 2004 [32]; Fogliatto et al., 2012 [5])					
Enablers for each stage in product life cycle					
Order elicitation enablers	Design enablers	Manufacturing enablers	Supply Chain enablers	Use	End of Life
Customer Integration in Design and Manufacture (Moser, 2004 [32]; Pollard et al., 2008 [33])	Solution Space Development (Salvador et al., 2009 [41])	Flexible manufacturing systems (FMS) (Pine, 1993 [2]; Duray et al., 2000 [42]; Da Silveira et al., 2001 [7]; Moser, 2004 [32])	Postponement (Fogliatto et al., 2012 [5])		
Good customer relationship (Kotha, 1996 [34]; Selladurai, 2004 [23])	Modularity and Standardization (Selladurai, 2004 [23]; Pollard et al., 2008 [33])	Reconfigurable manufacturing systems (RMS) (Tseng Mitchell M. et al. 2017 [3])	Flexible and Robust Processes. (Da Silveira et al., 2001 [7]; Frutos & Borenstein, 2004 [44]; Selladurai, 2004 [23]; Moser, 2004 [32]; Helms et al., 2008 [36]; Wang, 2008 [45]; Salvador et al., 2009 [41]; Pillier et al., 2004 [46])		
Web based customer decision support system (Grenci and Watts, 2007 [35]; Helms et al., 2008 [36])	Postponement (Fogliatto, et al., 2012 [5])	Process Automation (Selladurai, 2004 [23])	Organizational culture modification (Selladurai, 2004 [23])		
E-Commerce and social media (Grenci and Watts, 2007 [35]; Helms et al., 2008 [36]; Jain et al., 2021 [37])	Vendor co-integration in design (Jain et al., 2021 [37])	Postponement (Fogliatto et al., 2012 [5])	Change management and Supply chain change adaption. (Pine, 1993 [2]; Partanen & Haapasalo, 2004 [47]; Pollard et al., 2008 [33]; Jain et al., 2021 [37])		
Customer Knowledge Management (Piller, 2004 [38]; Cross et al., 2009 [39])	Customer Integration in Design and Manufacture (Moser, 2004 [32]; Pollard et al., 2008 [33])	Agile manufacture (Barutcu, 2007 [8]; Fogliatto et al., 2012 [5])	Complexity Control caused by variability. (Blecker et al., 2006 [48])		
Quick Response to Customer (Jain et al., 2021 [37])		Lean manufacture (Barutcu, 2007 [8]; Fogliatto et al., 2012 [5])	Supply Chain coordination Piller, 2004 [38]; Dietrich et al., 2006 [49]; Pollard et al., 2008 [33]; Medini et al., 2019 [9])		
Product Configuration (Kotha, 1996 [34]; Piller, 2004 [38]; Moser, 2004 [32]; Fogliatto et al., 2012 [5])		Advanced manufacturing technologies (AMT) Fogliatto et al., 2012 [5]; Kotha, 1996 [34]; Duray, 2006 [43])	Competitive Price Offering (Jain et al., 2021 [37]) Customer Knowledge Management (Piller, 2004 [38]; Cross et al., 2009 [39])		
Choice Menu creation and Choice navigation (Fogliatto & Da Silveira, 2008 [40]; Salvador et al., 2009 [41])		Workforce Flexibility (Pine, 1993 [2]; Duray, 2006 [43])	Customer and supplier integration (Jain et al., 2021 [37])		
		Lead time and changeover time reduction (Jain et al., 2021 [37])	Inventory Management (Jain et al., 2021 [37])		

enablers are primarily absent during use and end-of-life phases. This is expected as research and industrial implementations have focused mainly on customization and on-time delivery. Various enablers are shared across different product life cycle phases, as these activities can facilitate mass customization at different stages of the product lifecycle. For example, customer knowledge management would allow for precise recommendations of products based on customers' records during order elicitation phase. The importance of knowledge management extends to supply chain phase allowing for better integration of suppliers and customers during this phase.

MC enablers can have both positive or negative impacts on sustainability depending on how MC is implemented throughout the product lifecycle. This potential is further explained in sections 4.5 and 4.6.

3. SUSTAINABILITY ENABLERS

Although sustainability enablers are not a common term in literature, some authors have used this term to indicate sustainability best practices outlining their potential in achieving sustainability. Twenty enablers have been identified in literature and they are listed in Table 2. Agile manufacture, lean manufacture, and high coordination of supply chain are common enablers between MC and sustainability as found in literature. Likewise, various enablers are shared across different product life cycle phases, as these activities can facilitate sustainable practices at different stages of the product lifecycle. For instance, energy and material efficiency can be considered during manufacturing processes, transportation, use and during end-of-life phases as well. Particularly, because certain products exhibit high energy

consumption primarily during the use phase. While it is not yet certain whether all identified enablers are inherently sustainable, this research seeks to investigate their interactions with MC enablers (practices) to anticipate their possible overall impact.

4. THE INTERSECTION BETWEEN MC AND SUSTAINABILITY ENABLERS

4.1. Order Elicitation Phase

In order elicitation phase, customers make all the decisions related to product configuration. This impacts the entire lifecycle of a product on MC enablers can promote sustainability at this stage by guiding customers towards taking more concise decisions. For example, social media and e-commerce platforms may be used to raise customers awareness of social and environmentally sustainable decisions during the selection process [50][51]. To further foster socially responsible purchasing, product configurators, web-based decision systems and choice menus can provide environmental and social sustainability performance data [15]. Moreover, researchers have agreed that customer knowledge management helps in identifying strategies needed to promote customer awareness which in turns increases the likelihood of taking sustainable choices [50]. While customers are responsible for taking configuration decisions during this phase, user is the person that will end up using this product. For example, a company could be customizing computers for their employees. Thus, these two terms are not always interchangeable. This distinction could affect the final sustainability outcomes and decisions taken. Thus, further studies have to be carried out considering this aspect to estimate its influence on sustainability.

Table 2 Sustainability Enablers from Product Life Point of View

Sustainability enablers					
Order elicitation	Design	Manufacturing	Supply Chain	Use	End of life
Awareness (Robert-Bosch-et al. 2016 [10])	Awareness (Robert-Bosch-et al. 2016 [10])	Energy and Material Efficiency (Robert-Bosch-et al. 2016 [10])	Awareness (Robert-Bosch-et al. 2016 [10])	Longevity (Robert-Bosch-et al. 2016 [10])	Awareness (Robert-Bosch-et al. 2016 [10])
Green Purchase (Grzybowska, Katarzyna, 2012 [11]; Chacón Vargas et al., 2018 [12])	Eco Design (Robert-Bosch-et al. 2016; Chacón Vargas et al., 2018 [12]; Medini et al. 2019 [9])	Awareness (Robert-Bosch-et al. 2016 [10]) Circular Economy (Robert-Bosch-et al. 2016 [10]) Green Manufacture, (Grzybowska, Katarzyna, 2012 [11]; Chacón Vargas et al., 2018 [12]; Medini et al. 2019 [9]) Green Technologies, (Grzybowska, Katarzyna, 2012 [11]; Chacón Vargas et al., 2018 [12]; Medini et al. 2019 [9])	Reverse Logistics (Grzybowska, Katarzyna, 2012 [11]; Chacón Vargas et al., 2019 [9]) Green Logistics (Grzybowska, Katarzyna, 2012 [11]; Chacón Vargas et al., 2018 [12])	Energy and Material Efficiency (Robert-Bosch-et al. 2016 [10]) Awareness (Robert-Bosch-et al. 2016 [10])	Circular Economy (Robert-Bosch-et al. 2016 [10]) Environmental cooperation with customers, (Grzybowska, Katarzyna, 2012 [11]; Chacón Vargas et al., 2018 [12]) Reverse Logistics (Grzybowska, Katarzyna, 2012 [11]; Chacón Vargas et al., 2018, Medini et al. 2019 [12])
Environmental cooperation with customers, (Grzybowska, Katarzyna, 2012 [11]; Chacón Vargas et al., 2018 [12])	Circular Economy (Robert-Bosch-et al. 2016 [10]) Environmental cooperation with customers, (Grzybowska, Katarzyna, 2012 [11]; Chacón Vargas et al., 2018 [12])	Health and Safety at Work (Chacón Vargas et al., 2018 [12])	Green Purchase (Grzybowska, Katarzyna, 2012 [11]; Chacón Vargas et al., 2018 [12])		
Competitive advantage (Chacón Vargas et al., 2018 [12])	Competitive advantage (Chacón Vargas et al., 2018 [12])	Waste management (Grzybowska, Katarzyna, 2012 [11])	Socially Responsible purchasing (Chacón Vargas et al., 2018 [12])		
Firm committed to the local community (Grzybowska, Katarzyna, 2012 [11]; Chacón Vargas et al., 2018 [12])	Firm committed to the local community (Grzybowska, Katarzyna, 2012 [11]; Chacón Vargas et al., 2018 [12])	Continuous improvement (Grzybowska, Katarzyna, 2012 [11]) Agile Manufacture (Medini et al. 2012 [13]; Medini et al. 2019 [9]) Lean Manufacture (Medini et al. 2012 [13]; Medini et al. 2019 [9]) Labour Management (Medini et al. 2012 [13]; Medini et al. 2019 [9])	High level of supply chain Coordination (Grzybowska, Katarzyna, 2012 [11]; Medini et al. 2019 [9]) Energy and Material Efficiency (Robert-Bosch-et al. 2016 [10])		

4.2. Design Phase

The majority of economic costs or environmental emissions are generated during the design phase [2]. Therefore, it is important to design the product with the aim of reuse, repair, and recycling [15]. Modularity can be one way to do that. It can be incorporated in design, production or use phases enabling eco design and circular economy [52]. The flexibility offered by modular design encourages customer collaboration during the design phase promoting the environmental cooperation. Negative impacts associated with this enabler are anticipated during the production phase, where it is expected that modular products would be more complex to optimize in terms of material and energy as it requires more complicated processes. This complexity extends to the ‘reuse phase’ as one customer requirement cannot necessarily fit another’s [6]. However, at the end-of-life phase, modular products can be energy and material efficient as they can be easily repaired and recycled [6]. Exploring the optimum proportion between modularization and standardization in the design stage can address these challenges.

Furthermore, Nepal et al. argue that modular design would lower supply chain costs [16]. To further integrate customers into the design phase, space solution can be developed encompassing all possible configurations. Another strategy facilitating sustainability inclusion during design phase is the postponement strategy. In which, design is delayed until customer requirements are received. This directly affects sustainability by ensuring the utilization of the created product. Design phase is an important stage which could affect the sustainability of all subsequent phases.

4.3. Manufacture Phase

During manufacture phase, sustainability is mainly impacted by production processes. Reconfigurable manufacturing systems (RMS) are another promising strategy linking MC and sustainability. Mohagheh, Ahlström and Blasi argue that RMS allows for quick adaptation to market changes. Empirical research revealed positive impacts of reconfigurability on economic and environmental sustainability measured in terms of energy consumption, and waste management [17]. Moreover, Ostovari states that RMS could decrease generated waste and improve agility. However, RMS is likely to have a higher possibility of work accidents and negatively affecting health and safety at work [18].

To address this issue, process automation can be used to eliminate risk and provide a safer workplace. It can also enhance process efficiency and reduce lead time. On the other hand, more e-waste would be generated. Additionally, low-skilled jobs may be eliminated [14]. Furthermore, a degree of flexibility could be lost due to excessive automation [28]. Thus, the balance between human intervention and automation must be considered.

While RMS mainly focuses on modularity, it also incorporates advanced manufacturing technologies (AMTs). AMTs could be either energy efficient or intensive. For example, additive manufacturing could result in material efficiency, waste reduction, and logistics processes reduction. However, it is energy consuming and requires significant capital cost [24].

Since additive manufacturing is a key component of industry 4.0. It is interesting to mention the impact of industry 4.0 utilization. Industry 4.0 is an evolution for AMTs relying on the internet of things (IOT). The influence of Industry 4.0 has been studied by Beltrami, Mirjam et al. [14]. Industry 4.0 has both negative and

positive impacts. It can lead to better process flexibility, process optimization, waste reduction, energy and material efficiency, cost reduction, revenue increase, and time efficiency. However, electronic waste and excessive energy could be generated. While it can result in jobs displacement, new job opportunities for skilled workers would be generated. Some industry 4.0 technologies were proven to enhance working conditions while others led to poor mental health affecting health and safety at workplace negatively [14].

Whilst AMTs leverage the manufacturing phase, IT systems enhance flow of information. Gunasekaran et al. states that technology utilization enables the successful implementation of agile manufacturing [29]. Gunasekaran et al. highlight how IT systems could be effective in sharing knowledge and increasing awareness within the enterprise [30]. Furthermore, IT systems would support the enhancement of the supply chain integration [31]. However, energy optimization has to be evaluated and considered. Moreover, postponement strategy could be applied by delaying manufacture or assembly processes until customers' requirements are received to minimize overproduction. MC enablers aligned with green manufacturing and green technologies present a possible opportunity for transitioning towards circular economy.

4.4. Supply Chain Phase

E-commerce has transformed customers' ordering process, bringing both environmental challenges and opportunities. Challenges exist in the need for more packaging materials and the number of transportation trips, which release more emissions to the environment. Opportunities exist in the absence of a physical store, reducing energy consumption by decreasing customers' visits and energy used in-store [15]. Likewise, Conventional commerce poses possible benefits and harms to sustainable development.

To address these challenges, flexible processes may be considered. Govindan et al. state that flexible processes have mixed impacts in terms of energy and material usage. For instance, urgent deliveries may increase CO₂ emissions to cope with the changing demand in logistics. In the absence of urgency, there is an ability to choose a more sustainable option [19]. Ferasso et al. indicate that flexible processes are essential to quickly adapt to emerging changes [20]. One practice of flexible processes is delaying specific processes until a customer order is received, known as the postponement strategy. This strategy can be applied at various stages of the product life cycle. Van Hoek states that the postponement strategy leads to the efficient and successful application of both agile and lean manufacturing [21]. Meanwhile, Pagh & Cooper identify a drawback of postponement, which is the need for high and more complex supply chain coordination [22].

Another aspect supporting flexible processes is the local sourcing of material. This can further decrease the transportation and its associated emissions. Additionally, socially responsible purchasing further impacts

sustainability through taking concise decisions of raw material to be used.

Close relationships with customers and suppliers further strengthen these sustainable decisions. It enables green manufacturing improvement, continuous improvement [25], and raising awareness within the enterprise [26]. Gunasekharan et al. stress that supplier integration is a great technique to achieve waste reduction as well as energy and material efficiency [27]. Integration of customers, manufacturers, and suppliers in MC framework could positively impact sustainable development.

4.5. Use Phase

Some products consume more energy during the production phase, while others, such as refrigerators or vehicles, consume more energy during the use phase. Therefore, as discussed in section 4.1, products need to be designed considering energy efficiency in the use phase. One important aspect during the use phase is longevity, in which products should be designed for a longer lifetime.

Additionally, customer integration into design reduces the possibility of product disposal before its actual end of life, thus having a better impact in terms of energy and material during the use phase. Furthermore, the easily repaired design of modular architecture allows customers to keep the product for the longest time possible, promoting product longevity [6]. It is expected that customers' decisions would extend to post-purchase phases [15].

4.6. End of Life Phase

End of life strategies include reuse, repair and service, remanufacture, recycle with disassembly, recycling without disassembly, and final disposal (Figure 2) [6].

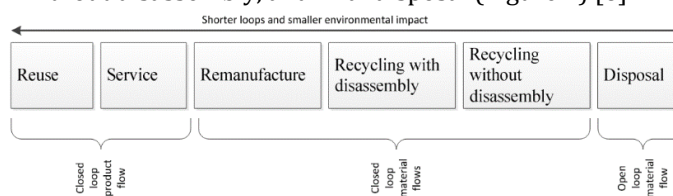


Figure 2 End of Life Strategies [6]

Having highly customized products can increase the difficulty of reusing them. Thus, a degree of standardization has to be offered. The reuse phase can also be prolonged through special repair programs offered by the manufacturer. While service, remanufacture, and recycling stages can be supported using a modular architecture. Additionally, having a product configurator system would allow for easily identifying and tracking the end customers for reverse logistics. This could be aided by proper customers knowledge management. A great potential is present in building product configurators and integrating customers. This potential is evident in the entire lifecycle, from order elicitation and design to end-of-life phase [6]. However, applying these strategies would be affected by the type of customized product.

5. CONCLUSION

With the global focus on sustainable development and the potential seen in MC. A link must be explored in a way that promotes both without compromising the success of either. To investigate this better, and as a first step, enablers of MC and sustainability were explored and areas of overlap were identified. Enablers could have positive, negative, or mixed impacts. It is expected that these impacts would vary depending on the type of product, MC strategy and the type of user. This conclusion is influenced by the qualitative analysis performed by Thomas Ditlev et.al stating that MC is not necessarily sustainable or non-sustainable strategy in its core. But it could contribute to sustainability [6]. Likewise, Pourabdollahi et.al analyzed MC practices influence on sustainability and concluded that it can be either beneficial or harmful to the environment. A tradeoff has to be considered to get the full potential of MC strategy in a sustainable framework[15]. Thus, further research is needed through empirical case studies to get a more precise understanding. Especially during use and end-of-life phases, as they remain unexplored for MC. A next step of this research is to investigate in which context and type of use, the MC enablers are in benefit of sustainability.

Future research should focus on enabling MC to achieve sustainable development. Some key areas of investigation include,

- What type of MC strategy is best fitting for sustainability?
- How to jointly promote and offer customization and sustainability to all types of customers?
- How to integrate sustainable data into a product configurator?
- How can AMTs and Industry 4.0 contribute to sustainable development while avoiding the environmental and social challenges associated with it?
- How can IT systems be designed with a sustainable focus while aligning with MC strategy?
- How can modular architecture be developed using eco-design?
- How can standardization and modularization be optimized to reuse and recycle while adhering to the MC strategy?
- What is the optimal level of process flexibility that can be achieved without affecting sustainable choices?
- How can reverse logistics be achieved through having a web interface associated with a product configurator system?
- What is the optimal level of process automation needed to overcome sustainable challenges associated with it?
- How can reconfigurable manufacturing systems be modified to obtain a safer workspace?
- What strategies can be applied to encourage environmental cooperation with customers, and how willing are they to engage?

The integration with MC has great potential to leverage all three pillars of sustainability while offering customized products at the efficiency of MP products. This offers a competitive advantage to both enterprises and customers.

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