Embracing the Digital Intelligence: A Strategic Approach to Optimizing Mass Customization

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Abstract. This paper provides an insightful exploration of Mass Customization (MC), a rising trend in the modern manufacturing landscape that couples the efficiency of large-scale production with the allure of personalized products. It elucidates MC's operational, market-related, and customer engagement challenges, offering optimization strategies grounded in digital intelligence technology and Supply Chain Agility (SCA). The paper delves into the role of 3D printing, Flexible Manufacturing Systems, data-driven designs, and Digital Twin Technology, illustrating how these technologies can enhance MC processes. It also underscores the importance of SCA in mediating the complex relationship between these technologies and MC capabilities, thus offering a nuanced understanding of its implementation. The study concludes that the integration of digital intelligence technology, paired with the enhancement of SCA, can effectively navigate the complexities of MC, providing a competitive edge in today's volatile market landscape. This research is a significant theoretical and practical guide for organizations aspiring to transition toward MC amidst the digital revolution.

1 Introduction

Enterprises operate in an environment characterized by intensified global competition and increasing heterogeneity in consumer demands. The development of e-commerce platforms has contributed to the erosion of market boundaries, enabling consumers to purchase goods or services from any location globally. The advancement of the internet has led to consumers placing greater emphasis on personalization and differentiation, seeking enhanced satisfaction in their social interactions. In this context, the goal of enterprise development has become rapidly responding to the diverse demands of consumers without sacrificing cost, time, or quality [1]. Mass production aims to manufacture goods on a large scale efficiently and economically. This is a fundamental prerequisite for competitiveness among enterprises, particularly for small and medium-sized businesses requiring swift market entry. Personalized services, incorporating a mix of production systems to produce goods in alignment with customer preferences [2], can facilitate businesses in expanding their clientele and exploring potential markets. The objectives of mass production and customization are contradictory. Hence their integration demands considerable supply chain capabilities from enterprises.

Mass customization (MC) is progressively emerging as a pivotal trend in the multifaceted landscape of contemporary manufacturing. This distinctive strategy marries the efficiency benefits of large-scale production - including cost-effectiveness, economies of scale, and streamlined operational processes - with the compelling allure of individualized products. The primary aim here is to cater to diverse consumer preferences and needs effectively. The advent of this innovative paradigm can largely be attributed to the convergence of advancements in two key technological domains: manufacturing and information technology [2]. On the one hand, innovations in manufacturing technologies - such as 3D printing, automated assembly lines, and robotics - have dramatically increased the flexibility of production processes.

On the other hand, advancements in information technologies - including data analytics, machine learning, and artificial intelligence - have enabled companies to efficiently capture, analyze, and respond to individual consumer preferences [3]. These technological strides have rendered MC plausible and systematically enhanced various aspects of its implementation. Operational efficiency has been optimized due to streamlined, automated processes; precision has been improved through a more accurate, data-driven understanding of consumer preferences; scalability has been achieved by simultaneously catering to numerous individual demands without sacrificing speed or quality.

The incorporation of MC within the manufacturing industry has grown increasingly prominent, leading to several notable examples of mature implementations. A case in point is Haier Group, a globally recognized home appliance leader. Haier has introduced a paradigm-shifting "user-single" business model, which leverages big data technology to comprehend and anticipate unique

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user requirements tied to specific scenarios [4]. The result is a precise alignment between user requirements and tailored system service solutions. This approach represents a departure from traditional linear value-chain processes, shifting towards a platform-oriented, user-centric value-creation mechanism [4]. Haier has enhanced operational flexibility and reduced costs by adopting a modular approach to delivery targeted at specific user segments. Another notable instance is the apparel sector, where the Nike Group has successfully embraced MC. The unique "Nike by You" customization service empowers consumers to design and create personalized products within predefined parameters. This innovative service, which has been fully integrated into Nike's primary sales and marketing channels - including its official website and selected physical retail outlets - allows consumers to create their products truly. The strategic importance of this service is evident from its integration into Nike's overall business strategy, with significant resource allocation underscoring its pivotal role in enhancing customer satisfaction and driving business growth.

The present study aims to provide a comprehensive analysis of MC, elucidating its challenges and proposing optimization strategies primarily anchored in digital intelligence technology and the leverage of SCA. The significance of this research lies in its potential to offer theoretical insight and practical guidance to organizations aspiring to transition toward MC amidst the digital revolution. By examining the role of 3D printing, Flexible Manufacturing Systems, data-driven designs, and Digital Twin Technology, the study aims to unfold how these cutting-edge technologies could streamline MC processes. Furthermore, through the lens of SCA, we aspire to decode the complex relationship between these technologies and MC capabilities, thus providing a nuanced understanding of how SCA can mediate to optimize the execution of MC strategies. Ultimately, this research hopes to inspire novel strategies and models to navigate MC's challenging yet promising landscape.

2. Mass Customization

2.1 The Concept of Mass Customization

MC serves as a paradigm-shifting production model that integrates the benefits of large-scale manufacturing with the appeal of personalized customization. This hybrid approach equips businesses with a unique advantage - the ability to cater to various customer needs while preserving cost efficiency. MC resolves the dichotomy between cost management and customization, equipping businesses with dual competitive capabilities. This concept, originally coined by Toffler, discusses the strategic importance of addressing consumer demands for individualization through a lens of standardized production [5].

Viewed from the perspective of industrial chains, MC reconfigures the supply and demand chains, both intra-industry and inter-industry, aiming to cater to the diversity of demand in downstream industries while requiring upstream and midstream industries to maintain the advantages of mass production. Concurrently, the organic interconnections between various economic sectors need to become more flexible to accommodate the requirements of MC. Industrial chains facilitate the flow of resources and information, realizing the efficient transfer and utilization of materials, energy, and value [6]. This is likewise reflected in mass customization production and supply systems, where these interconnected flows contribute to successfully implementing tailored solutions that address diverse customer needs. In implementing MC, upstream and midstream industries may need to adopt modular production strategies. These product modules can be combined into a myriad of different products to meet the personalized needs of consumers. The successful implementation of such modular strategies necessitates close coordination and cooperation between upstream, midstream, and downstream industries. Meanwhile, the networks between enterprises across different industries must also become more flexible. This network should be customer-centric and efficiently transform resources to enhance overall value.

From the supply chain management standpoint, MC is incorporated into each critical juncture. Firms must intertwine consumer designs with products and, during the production stage, automate the generation of various products. Ultimately, the products are packaged and dispatched per the consumer's requirements during distribution. Studies have demonstrated that when the lead time for customization is within an acceptable limit, and the likelihood of customer satisfaction with the product quality is high, an integration between the manufacturer and the customizer can lead to a mutually beneficial situation for all supply chain members [7]. Additionally, by integrating a push-pull supply chain management strategy that amalgamates standardized production with personalized design, the realization of MC is further facilitated.

Examining from the viewpoint of the value chain, an enterprise's entire production process is segmented into distinct stages, with the value contributed by each stage being calculated to pinpoint the origins of profits and their proportional distribution during the manufacturing phase [8]. MC straddles two activities - production and research & design, that fall at the lower and higher value-added portions of the “smile curve” respectively (Figure 1). The potency of MC lies in its capability to amplify the value derived from the design stage by delivering supplementary services to customers, all the while maintaining or even reducing costs associated with production, thereby diminishing the proportion occupied by low value-added sections. By escalating towards the high value-added extremities of the value chain, MC paves the way for businesses to tap into broader profit margins. This shift allows enterprises to augment their earnings and optimize their resource allocation, increase customer satisfaction, and, ultimately, drive long-term business growth.

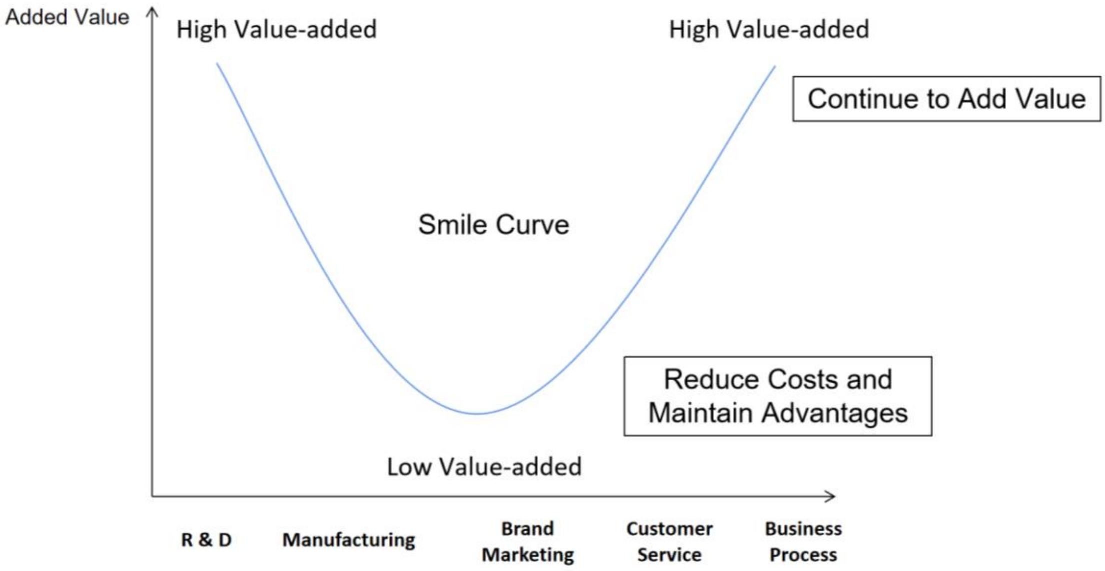

Figure 1. The Smile Curve Under the Influence of MC. (Photo/Picture credit : Original)

2.2 The Current Challenges of Mass Customization

2.2.1 Operational and Production Challenges

Implementing MC significantly alters the dynamics of production processes, fundamentally reshaping the role of quality control and cost management. This shift from conventional mass production imposes new demands on the manufacturing ecosystem, requiring a delicate balance between efficiency and diversity. Internal factors, such as production processes, quality control, and cost control, become more complex and multidimensional [5], necessitating a fundamental rethink of existing operational models and strategies. Moreover, the flow of information also escalates due to the demand for customized products, increasing the complexity and challenges in managing, interpreting, and acting upon such vast amounts of data.

2.2.2 Market and Competitive Challenges

The market competition landscape and customer demand diversification present a challenging environment for MC. It compels businesses to grapple with market uncertainties that arise from the individualized nature of customer demands and intensified competition. In particular, Small and Medium Enterprises (SMEs) are pressured to maintain their competitive advantage in the face of mounting challenges, including rising production costs, the need for quicker delivery times, and heightened expectations for product quality [1].

2.2.3 Customer Engagement and Service Challenges

MC significantly intensifies the need for deep customer engagement and superior service provision. Delivering customized products and services requires businesses to delve deeper into the customer psyche to understand their unique needs and desires [9]. The transition towards a more customer-centric operational model can pose significant challenges, as it often necessitates considerable changes to the existing management structure, operational procedures, and corporate culture. The rising product variety and increased system complexity inherent in MC further exacerbate these challenges, necessitating a strategic balance between efficiency and individualization.

3. Optimization Strategies for Mass Customization

3.1 Digital Intelligence Technology

Advancements in digital and manufacturing technologies offer unprecedented potential to revolutionize traditional production and service delivery methods. These technologies, collectively termed “digital intelligent technologies” encapsulate two significant facets - manufacturing technology and information technology. Leveraging these, businesses can significantly enhance their adaptive capacity to pivot towards MC, swiftly respond to market flux, and meet unique customer demands with alacrity. Moreover, they hold the potential to optimize overall organizational structures to manage complexity better, thus augmenting operational efficiency.

3.1.1 Manufacturing Technology

Strategically, 3D printing technology, fundamentally operating by additive manufacturing wherein successive layers of materials are methodically applied under computer control to create an object, hold substantive significance in the realm of MC. Regarded as a transformative manufacturing technique, it facilitates the production of customized commodities on a certain scale while maintaining cost-effectiveness [5]. This technology allows manufacturers to enhance the efficiency of their design and personalization processes, resulting in a reduced production cycle [5]. By encoding product specifications in a digital model, 3D printing allows precise control over the manufacturing process, making intricate and complex designs unachievable by traditional methods. The strategic incorporation of 3D printing in factory planning and design provides the means to select manufacturing equipment judiciously, strategize the factory layout, and formulate optimal logistic strategies for suppliers [10]. Additionally, 3D printing is perceived as a key factor influencing material flow in the manufacturing process [10]. Thus, 3D printing technology significantly bolsters a factory's adaptability and flexibility, which is indispensable for modern manufacturing requirements.

In practical applications, 3D printing technology elucidates its profound impact on MC. An exemplification of this is present within the clothing industry, where manufacturers amalgamate traditional production modalities with modern information technology to facilitate the creation of customized manufacturing platforms. Such platforms combine technologies encompassing 3D scanning systems, CAD tools, big data, RFID, and intelligent production systems to cater to unique customer requirements [5]. Furthermore, 3D printing technology enhances consumer engagement within the design process. For instance, Loewe's deployment of 3D printing in their leather manufacturing process, allowing customization based on distinct foot shapes, exhibits the capacity of this technology to incorporate direct customer input within the production process [7]. These instances underscore the capacity of 3D printing technology to foster the MC trend.

A Flexible Manufacturing System (FMS) can be described as an adaptive production machine designed to address variegated and evolving consumer demands efficiently. A flexible manufacturing system encompasses multiple unit resources, including robots, machines, fixtures, and buffer zones [11]. It can process various part types through the shared resources following a predefined sequence of operations [11]. This characteristic enhances the system's versatility, making it integral for manufacturing domains with diverse product line-ups and variable demand scenarios. The control system at the helm synchronizes all operations. It directs the routing and scheduling of parts, thereby instilling the FMS with the agility to adapt to product design and volume modifications expeditiously and efficiently.

Incorporating FMS into MC involves a comprehensive design process consisting mainly of standardized and generic product design and process specifications, modular production, and information-driven dynamic process control [12].

Standardization and Generic Product Design & Process Specifications: An integral part of FMS, this concept aims at creating a set of uniform guidelines for product design, thereby simplifying the manufacturing process. The standardized design and process specifications allow various products to be produced using the same set of machines and operations. This inherent flexibility of FMS to swiftly adjust and reprogram operations as per product specifications results in an efficient, streamlined production system.

Modular Production: Modular production systems are a key component of FMS that allow for a diverse range of products to be created simultaneously. By breaking down the production process into distinct, independent modules, manufacturers can produce various customized products without significantly increasing production time or costs. Each module can perform different operations and be reprogrammed according to the product requirements [12]. This enables FMS to handle a diverse range of products, thus effectively addressing the dynamic demands and requirements of MC.

Information-driven Dynamic Process Control: FMS relies heavily on advanced automation and control technologies to coordinate operations, oversee routing, and schedule parts [13]. This information-driven dynamic process control system allows the FMS to adjust to product design and volume changes promptly. This central control system, aided by robust data analytics, fosters a manufacturing environment that supports MC, aiding companies in delivering a high degree of product customization swiftly and effectively.

An FMS's key tenets and attributes become particularly salient in the context of MC. MC necessitates fulfilling distinct customer specifications while preserving efficiency levels that closely mirror mass production—an endeavor aptly facilitated by an FMS's inherent versatility and adaptability. By integrating avant-garde automation and control technologies, an FMS can respond promptly to the dynamic demands intrinsic to MC. It can manage smaller batch sizes and variable designs without a corresponding increase in production time or costs, rendering it an optimal solution for manufacturers striving to deliver a high degree of product customization. An FMS's nimble and efficacious reaction to rapidly shifting and diverse customer requirements fosters a manufacturing environment conducive to the objectives of MC, thereby equipping companies with the capacity to deliver enhanced value to their clientele.

3.1.2 Information Technology

Data-driven strategies, characterized by the strategic utilization of vast amounts of information to gain insights and inform decision-making processes, have emerged as a significant force in the contemporary manufacturing industry. Data-driven methodologies leverage extensive data types, such as customer preferences, operational statistics, and product usage specifics [14]. This contributes to a diversified data set capable of forming a generative design framework that promptly caters to a substantial volume of unique customer requirements [14]. A data-driven environment transforms raw data into a valuable commodity, enabling strategic decisions formulated by hard evidence rather than intuition or conjecture.

In the realm of MC, the applicability and importance of data-driven strategies have become particularly evident. Given the inherently customer-centric nature of MC, the capacity to gather, process, and analyze consumer data is indispensable. By computing and analyzing vast amounts of data, enterprises can unveil insights concealed within the data, thereby exposing potential opportunities and threats [15]. This process imparts a competitive advantage to businesses by enabling them to make more informed decisions and align their strategic initiatives with tangible evidence derived from their operational environment. Using such diverse data sets, including user-product interaction data, allows for an improved level of personalization and automation in design processes, thus enhancing the overall quality of customization [14]. Data-driven strategies also allow for the optimization of internal processes, such as supply chain management and production scheduling, thus supporting the efficient execution of MC strategies. In essence, by harnessing the power of data, businesses can elevate their MC capabilities to new heights, ultimately leading to superior competitive positioning and improved business performance.

Digital twin technology is predicated on creating data models to achieve real-time synchronization between physical manufacturing systems and digital spaces [16]. With digital twin technology, information in various product design, manufacturing, and maintenance stages can be shared without hindrance. It allows businesses to perform simulations and tests without actual costs, making rapid iteration and upgrade of products possible. Digital twin technology can monitor manufacturing processes in real-time, transforming the product from a physical state to a digital one and providing a more transparent production perspective. Through online model training, real-time monitoring, simulation, and model validation, it can continuously predict the production status of the physical workshop [17].

Digital twin technology serves a crucial role in achieving MC. Providing a mirrored digital representation of physical systems enables businesses to analyze and improve the production process without incurring the costs and risks of physical testing. Digital twin technology assists companies in exploring a variety of design alternatives, testing them under simulated conditions, and determining the best approach for customization. The real-time data provided by digital twin technology allows companies to respond promptly to customer needs and design products accordingly, enhancing customer satisfaction and operational efficiency. Digital twin technology offers an innovative approach for companies to scale their customization efforts without sacrificing efficiency. It enables real-time production process monitoring, allowing businesses to identify and address issues or inefficiencies instantly [18]. This increased visibility allows for better quality control, resulting in products accurately reflecting each customer's unique demands. In addition, by integrating emerging Industrial 4.0 technologies, including the Internet of Things, Big Data, and Cyber-Physical Systems, digital twin technology aids in the real-time exchange of vital information between human operators and machines, fostering cooperation and flexibility in human-machine interactions [19]. This advanced amalgamation of technologies substantially enhances the cohesiveness of industrial value chains, leading to elevated productivity and overall efficiency in the manufacturing process [16].

3.2 The Mediating Role of Supply Chain Agility

Supply Chain Agility (SCA) can act as a regulatory mechanism that mediates the intricate relationship between various digital technologies and MC abilities [20]. SCA, comprising five key elements - speed, visibility, flexibility, innovation, and leadership – can be tactically employed to augment MC [21].

From a multi-dimensional standpoint, several avenues can be explored to leverage SCA. Firstly, increasing supply chain speed can lead to quicker responses to customer requirements, thus aiding the process of MC. Secondly, enhancing supply chain visibility allows for better coordination between different stages of the manufacturing process, resulting in optimized customization operations. Thirdly, the flexibility of the supply chain, in terms of swiftly switching from one manufacturing process to another, can assist in better serving unique customer demands. The fourth aspect, innovation, can drive the creation of unique, customized products. Lastly, effective leadership is crucial in ensuring the smooth functioning of the entire supply chain for MC.

Implementation methods for SCA involve using advanced analytics tools for better decision-making, automation technologies for improving speed and flexibility, and cross-functional teams to drive innovation and leadership. The positive impact of SCA on MC is substantial. Through SCA, businesses can swiftly adjust production plans and process orders, leading to the effective allocation of resources, reduction in inventory, acceleration in delivery speed, and diminishment of waste within the supply chain [22]. SCA facilitates quicker responses to changing customer demands, fosters better coordination between the various entities in the supply chain, enhances the ability to meet unique customer requirements, and ultimately leads to more diverse and innovative products. By employing effective leadership and modern technologies, SCA can significantly increase the feasibility of MC implementations.

4. Conclusion

This research has explored the concept of MC, its inherent challenges, and the potential optimization strategies leveraging digital intelligence technology. MC, characterized by the simultaneous realization of economies of scale and consumer personalization, faces operational & production, market & competitive, and customer engagement challenges that impede its broad implementation.

To overcome these, the paper discussed the application of smart manufacturing technologies. Manufacturing technology strategies, such as 3D printing and flexible manufacturing systems, offer cost-effective custom production and adaptability opportunities. Meanwhile, information technology strategies, like data-driven design and digital twin technology, enhance the capacity for customer engagement, rapid iteration, real-time monitoring, and transparent manufacturing. Significantly, the mediating role of SCA, encapsulating speed, visibility, flexibility, innovation, and leadership, was underscored. SCA can amplify the beneficial impact of digital intelligence technology on MC by ensuring a swift response to market changes, transparent operations, flexible production systems, continuous innovation, and efficient leadership.

Looking toward the future, two salient avenues of research are recommended to optimize MC strategies further. First, investigating ways to integrate the discussed technologies into a comprehensive ecosystem based on the supply chain offers a promising opportunity. This ecosystem would be an intuitive and effective reference for businesses seeking to enhance their MC capabilities. One potential area of exploration is integrating this ecosystem with existing enterprise resource planning (ERP) systems, embedding MC modules directly within the established operational framework. Further research should explore how these modules could leverage digital intelligence technology across different supply chain stages, ultimately fostering a more coherent and efficient MC process. Second, research focusing on reverse logistics solutions for customized products would benefit the field. While the forward logistics of MC have received considerable attention, the reverse logistics-especially concerning the return and reuse of customized products-remain underexplored. Future research could investigate how these processes could be managed on a large scale while maintaining environmental sustainability. This exploration could lead to the development of strategies that not only improve operational efficiency but also contribute to the global sustainability agenda.

Authors Contribution

All the authors contributed equally,
and their names were listed alphabetically.

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