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Mass customization in practice: Strategic implementation and insights from Polish small and medium sized enterprises

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A B S T R A C T

Implementing a mass customization (MC) strategy in manufacturing enterprises presents an ongoing challenge for both managers and researchers. To remain competitive, managers must consider adopting advanced technologies associated with Industry 4.0 and 5.0 (I4.0/5.0). This study seeks to identify solutions that support strategic decision-making aimed at enhancing the level of MC implementation. The paper begins with a literature review focused on the adoption of MC strategies within European manufacturing enterprises. It then presents findings from a questionnaire-based survey conducted among more than 100 small and medium-sized enterprises (SMEs) in Poland's automotive sector. Statistical analysis, including correlation coefficients, was used to evaluate the data. The results indicate that consumer participation in the product design process is the key driver of successful MC strategy implementation in the surveyed SMEs. Furthermore, managers recognized strong correlations between the adoption of I4.0/5.0 technologies—such as automated machinery and real-time data usage—and higher levels of MC capability. The benefits of implementing MC strategies, including increased production flexibility and waste reduction, were also highlighted. The findings offer general insights applicable to SMEs in the automotive industry.

A R T I C L E I N F O

Keywords:
Mass castomisation strategy;
Small and medium sized manufacturing enterprises;
Consumer participation;
Production flexibility;
Industry 4.0/5.0 technologies;
Automotive industry

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1. Introduction

Designing and implementing an appropriate production strategy requires managers to have adequate knowledge about the potential effects and possible scenarios of enterprise development. Mass customization (MC) involves the production of various product variants while reducing the costs of tools and equipment, minimizing changes in production processes, machinery, the number of employees, and improving production flexibility and quality [1]. Currently, the strategy of MC and personalization is one of the challenges related to the need to implement the Industry 4.0/Industry 5.0 (I4.0/5.0) concept in enterprises. MC can be treated as a production strategy that combines push and pull production paradigms to achieve a core competence [2]. Customization can be treated as the process of adapting a product or service to the customer's own needs, most often with support from information systems such as product configurators. Customized products currently respond to customer expectations and enable companies to gain a competitive advantage. An open research question remains: How can the level of MC be defined and measured, and what indicators signal the success of implementing this production strategy? According to [2], MC research has been unexplored, and therefore manufacturing companies have low competence in implementing MC. Customers increasingly demand personalized, high-quality products at competitive prices [3-4]. To identify the research gap, a preliminary literature review (Table 1) was conducted with the aim of defining key factors influencing the degree of mass customization (MC) strategy implementation, based on empirical evidence from European manufacturing enterprises.

Table 1 A literature review of current factors determining a level of MC strategy implementation in European Enterprises

MC realizing in the manufacturing enterprises	European country	Factors	Source
Small and medium enterprises, Mechanical products	Italy	Product platform development, IT-based product configuration, Group technology	[5]
Clothing (Burberry), Furniture (IKEA) and toy (LEGO) industries	UK, Denmark, Sweden	Appropriate business and marketing strategy, Operational management in accordance with sustainable production and technological development	[6]
Machine building industry (FENDT)	Germany	Highly flexible assembly line	[7]
Automotive and agricultural industries (Fiat powertrain technologies)	Italy	Use real-time data	[8]
Automotive industry (assembly a diesel particulate filter (DPF))	-	Use augmented reality technology, Dynamic production rescheduling	[9]
Semiconductor industry	-	Robot utilization, Simulation and statistical analyses	[10]
Electronic industry (laptops/PCs)	-	Product configuration mechanism	[11]
Assembly industry	-	Modeling and simulation techniques of production processes	[12]
Industrial enterprises	Czech Republic	Industry 4.0 (Flexible processes, Artificial intelligence-based solutions, Automation, Robotics, e-commerce, 3D printing, Flexible manufacturing)	[13]
Manufacturing sector	-	Collaboration networks, Business agility, Digital supply chain, Use of I4.0 technologies	[14]
Electronic industry, Automotive industry	EU	High level of modular design, Remanufacturing of modular products	[15]
Automotive industry	-	Clear description of configuration options provided to customers, Flexible manufacturing system and processes	[16]

Table 1 summarizes the findings of the literature review concerning the implementation of mass customization (MC) strategies in European manufacturing enterprises. Specifically, it presents (1) the types of European industries analyzed, (2) the countries in which these industries are located, and (3) the key factors identified as influencing the level of MC strategy implementation. To the best of our knowledge, and based on the current state of the literature (as presented in Table 1), no previous studies have explicitly investigated how these factors contribute to increasing the level of MC implementation within European manufacturing enterprises in the automotive sector. Furthermore, there is a lack of research addressing the impact of emerging technologies—specifically those associated with the Industry 4.0/5.0 paradigm—on the degree of MC implementation. While prior studies (e.g., [2]) suggest that MC is inherently linked to technological advancement, the reviewed literature (Table 1) does not provide empirical evidence on the relationship between the adoption of Industry 4.0/5.0 technologies and the enhancement of MC capabilities in manufacturing firms.

Therefore, in this paper we examine the following research questions: (1) What key factors influence increasing the level of MC in European Manufacturing Enterprises? (2) What kind of

I4.0/5.0 technologies impact the MC level, and (3) How can these relationships influence future research trends in MC research?

The I4.0/5.0 technologies in the context of MC strategy realization can be distinguished as robotics, simulation and integration, cyber-physical systems (CPSs), Internet of things (IoT), cloud computing, automated machines, AI, augmented reality (AR) and virtual reality (VR), cybersecurity, human-machine interaction (HMI), and finally human-robot collaboration (HRC). The usage of robots generally enables flexible and efficient production. But in the case of MC, it requires operators to perform responsible tasks to adapt production to individual customer requirements. Simulation of production processes allows presenting different scenarios to improve decision-making in an MC strategy [17]. CPSs integrate technologies with physical systems in order to increase the automation of MC production [18]. IoT-based solutions facilitate maintaining the operating state of the system within MC production [19]. Cloud computing allows manufacturers to respond to the fact that more and more customers are willing to participate in the design process, and it enables MC production to be flexible and scalable [20]. Automated machines enable production tailored to the customer's needs. AI-based tools provide visualization of processes, their monitoring and control, configuration of products, quality assurance, and real-time data classification to maximize process efficiency [21]. AR and VR for MC production enable product visualization for customers [9]. Cybersecurity is a set of necessary technologies in MC production for the secure collection of customer data [22]. HMI in MC enables more effective delivery of products to market [23].

This paper analyses and models the implementation of the mass customization (MC) strategy in European manufacturing, using Polish small and medium-sized manufacturing enterprises (SMEs) as a representative case study. Furthermore, it aims to identify and define the relationships between the adoption of Industry 4.0/5.0 technologies and the achieved level of MC implementation. The originality of this study is as follows:

- This study establishes the relationships between the I4.0/5.0 technologies implementation and the increased level of MC strategy for European SMEs in the automotive industry.
- It provides practical insights into MC through empirical research in over 100 European manufacturing SMEs from Poland.
- This study determines the benefits of implementing the MC strategy in the automotive industry.
- Recommendations for managers in the automotive manufacturing industry were formulated regarding necessary actions to increase the level of MC strategy.

2. Materials and methods

2.1 Questionnaire surveys on MC

The usage of a tool such as a questionnaire enables the collection of research data among many manufacturing companies in a short time, as the respondents provide answers to specific questions in writing, either traditionally or electronically. The questionnaire used in this study concerned the implementation of the MC strategy in manufacturing enterprises, factors determining the level of MC strategy realization, and the influence of the implementation of I4.0 technologies on the level of the MC strategy.

Firstly, the level of the MC strategy was defined. In our research, the MC strategy implementation level is classified according to the Technology Readiness Levels (TRL) classification. TRL is a classification that allows the determination of the technological maturity of a product, process, or service—from the creation of an idea and basic research, through conceptual and laboratory work corresponding to industrial research, to creating a prototype as part of development work, and finally, to a ready-made solution applicable in practice. TRL determines what validation activities have already been performed and what still need to be done [24]. According to TRL, five levels of implementation of the MC strategy were defined, depending on the answers given in the conducted surveys. Level I (TRL levels 1-2) is achieved if the respondent declares knowledge of the MC definition.

Level II (TRL levels 3 and 4) is achieved if, in a company, customized orders are tailored to the individual needs of customers. Level III (TRL level 5) concerns analytical and experimental confirmation of critical functions or conscepts of the technology. Level IV (TRL levels 6 and 7) refers to the stage when the technology components or its basic subsystems have been integrated, and the company plans to implement the MC strategy. Level V (TRL levels 8 and 9) is achieved when the company defines the methods for realizing the MC strategy.

Next, based on the literature research results (Table 1), it was possible to define the factors for European Manufacturing Enterprises that influence the level of the MC strategy (Table 2) in our questionnaire.

Table 2 Factors describing MC strategy

Factors describing MC strategy	Abbreviations
Consumer participation in the design process	C1
Customer participation in the product design	C2
Integration of customer preferences	C3
Product configuration mechanisms	C4
The ability to handle multiple process variations at different stages of production	C5
Highly flexible assembly line	C6
Using modeling and simulation techniques of production processes	C7
The ability to use real-time data to make efficient, quick decisions to assembly line	C8

Table 3 Industry 4.0/5.0 Technologies – Factors of implementation

Industry 4.0 technology	Abbreviations
Robotics	I1
Product simulations	I2
Material simulations	I3
Production processes simulations	I4
Cyber-physical systems (CPSs)	I5
Systems integration	I6
Industrial Internet of Things (IIoT)	I7
Cloud computing	I8
Automated machines	I9
Artificial Intelligence tools	I10
AR and VR	I11
HMI and HRC	I12
Cybersecurity	I13

Subsequently, to address the second research question, the survey incorporates items related to the implementation of selected I4.0/5.0 technologies, as outlined in Table 3.

To investigate how the identified relationships may shape future research directions in the field of mass customization (MC), empirical research was conducted among the surveyed enterprises to evaluate the benefits associated with the implementation of the MC strategy within the automotive industry (Table 4).

The questionnaire is structured to include an introductory section outlining the objectives and scope of the survey, followed by four distinct modules.

Table 4 Benefits of MC strategy implementation

Factors	Abbreviations
Annual sales increase up to 10 %	E1
Annual sales increase from 11 to 25 %	E2
Annual sales increase above 25 %	E3
Increasing the flexibility of the work surface	E4
Increasing production flexibility	E5
Reducing the amount of waste	E6
Reducing electricity consumption	E7
More effective analysis of large data sets	E8
Decentralization of decision-making	E9

The first module comprises a set of open- and closed-ended questions designed to collect essential company-related information from the respondent. This includes the company's registered office and operational location, the number of employees (enabling enterprise size classification), the primary product portfolio, and the respondent's position within the organization. These elements allow for an assessment of the respondent's familiarity with the company's management strategy and development policy.

The second module is completed by respondents whose companies have implemented a mass customization (MC) strategy. It covers questions related to expenditures incurred during implementation, methods of gathering customer preferences and requirements, approaches and outcomes of MC implementation, the level of satisfaction associated with MC deployment, the I4.0/5.0 technologies utilized to support MC, and future plans concerning the extension of MC applications within the enterprise.

The third module targets respondents from companies that have not adopted the MC strategy. It includes a multiple-choice question addressing the reasons for non-implementation, alongside the possibility to provide an open-ended explanation and indicate whether implementation is planned for the future.

The fourth module explores the perceived significance of I4.0/5.0 technologies in achieving the intended outcomes of MC strategy implementation.

2.2 Research group and data collection

The empirical study was conducted using a structured questionnaire composed of closed, multiple-choice questions. Data collection took place between January 10 and August 31, 2023, through both face-to-face interviews (29 %) and telephone surveys (71 %).

The survey followed a sample-based research design and gathered responses from 153 European manufacturing enterprises operating in Poland within the automotive sector. The sample consisted of 117 small and medium-sized enterprises (SMEs; defined as employing up to 249 individuals) and 36 large enterprises. The selection of the automotive industry as the focus of analysis is justified by its strategic importance to the European economy, accounting for nearly 7 % of the region's gross domestic product (GDP). Furthermore, the automotive sector employs approximately 13.8 million individuals in the European Union, which represents 6.1 % of the total workforce.

Notably, collaboration among partners within the automotive industry remains an open research question [25], further validating the relevance of this sector for investigation.

This study places particular emphasis on SMEs, as they constituted over 76 % of the total research sample.

The research sample may be considered representative. According to data from the Polish Central Statistical Office, 3,954 enterprises were registered in 2022 as operating in the automotive industry. The obtained sample size of 153 exceeds the minimum required number of 145 enterprises, calculated at a 95 % confidence level, with a proportion (p) of 0.5 and a maximum margin of error of 8 %. The required minimum sample size was determined using the standard formula (Eq. 1):

$$N_{min} = \frac{N_p(\alpha^2 \cdot f(1-f))}{N_p \cdot e^2 + \alpha^2 \cdot f(1-f)} \tag{1}$$

where N_{min} – minimum sample size, N_p – population size, α – confidence interval, f – fraction size, e – assumed maximum error.

Moreover, the research was conducted across the entire territory of Poland, ensuring representation proportional to the number of companies registered in each voivodeship.

2.3 Research model

Based on the results of in-depth interviews with 117 SMEs from the automotive industry, a research model (Fig. 1) was developed and analysed using the correlation and regression method to estimate the level of Mass Customization (MC) strategy implementation in manufacturing enterprises. The survey instrument used for testing the model was constructed by defining appropriate measurement scales to assess both the impact of MC strategy implementation and the influence of Industry 4.0/5.0 technologies on its realization.

The factors describing the level of MC strategy realization in Polish automotive SMEs were derived from structured feedback and are listed in Table 2. Respondents assessed the importance of each factor (c1-c8) using a binary scale: factor0 – *not very important*, factor1 – *very important* for increasing the level of MC implementation.

Similarly, the perceived benefits of MC strategy implementation (Table 4) were evaluated based on company experiences in 2022, with respondents indicating whether each benefit (E1-E9) was considered *not very important* (factor0) or *very important* (factor1).

The overall level of MC strategy implementation in the surveyed companies was classified into five levels according to the Technology Readiness Level (TRL) framework.

Subsequently, our research also examined the implementation of Industry 4.0/5.0 technologies (Table 3). The assessment of these technologies was based on structured survey responses. Respondents were asked to indicate whether their company applies specific I4.0/5.0 technologies (I1-I12), and to evaluate the perceived significance of each technology in the context of MC strategy implementation. The following binary scale was applied: factor0 – *not very important*, factor1 – *very important*.

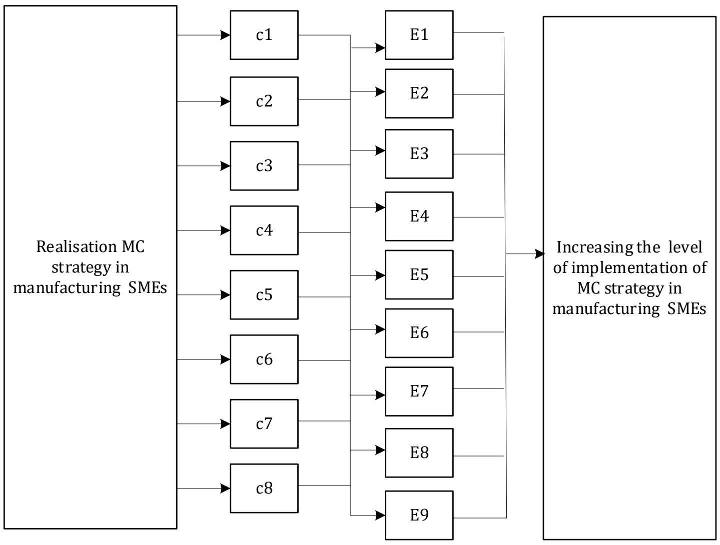

Fig. 1 Research model

3. Results

3.1 Results from the surveyed enterprises

When addressing the first research question, it can be confirmed that the factors identified in the relevant literature (Table 1) were also recognized by the surveyed enterprises. Among Polish manufacturing SMEs, 55.56 % of companies enable customer participation in the product design process, while 52.99 % of enterprises report both customer participation and integration of customer preferences. Product configuration mechanisms and the ability to utilize real-time data for efficient and rapid decision-making on the assembly line are implemented by 44.44 % of surveyed companies. A highly flexible assembly line is employed by 41.88 % of enterprises, simulation techniques for production processes are utilized by 30.77 %, and the ability to manage multiple process variations across different production stages is reported by 18.80 % of SMEs.

Furthermore, the empirical research confirms that I4.0/5.0 technologies (as listed in Table 3) are actively implemented among the surveyed manufacturing SMEs. Automated machines are utilized by 41.88 % of the surveyed enterprises, while systems integration is present in 35.04 % of enterprises. Product simulations, production process simulations, and cybersecurity solutions are adopted by 29.06 % of respondents. Material simulations are implemented by 23.93 % of enterprises. HMI and HRC are utilized by 22.22 % of SMEs, robotics by 21.37 %, and CPSs by 17.09 %, respectively. However, cloud computing is employed by only 7.69 % of SMEs, IIoT by 5.98 %, artificial intelligence tools by 3.42 %, and AR and VR technologies by 1.71 %, respectively.

These findings indicate that the most commonly adopted I4.0/5.0 technologies among European SMEs in Poland include automated machines, systems integration, simulations of products and production processes, as well as cybersecurity. Therefore, to address the first and second research questions, statistical analysis was conducted using correlation coefficients to identify the strength of relationships between the identified factors and the level of MC strategy implementation.

3.2 Analysis MC strategy realizing in Polish manufacturing SMEs

The correlation analysis is a statistical method used to examine the strength and direction of a linear relationship between two variables, quantified by the correlation coefficient r, which takes values in the interval $\langle -1, 1\rangle$. A value of −1 indicates a perfectly negative linear relationship, while +1 denotes a perfectly positive linear relationship. A value of 0 signifies the absence of a linear correlation (Bobko, 2001). The Pearson correlation coefficient is calculated according to the formula Eq. 2:

$$r = \frac{\Sigma(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\Sigma(x_i - \bar{x})^2 \Sigma(y_i - \bar{y})^2}} \quad (2)$$

where x_i and y_i are the values of the variables x and y, respectively, and $\bar{x}$, $\bar{y}$ are the mean values of these variables.

During the statistical analysis, the correlation between the factors related to the realization of the MC strategy and the increase in the level of MC strategy implementation was examined. The analysis was conducted using Statistica version 13.3 (StatSoft Polska Sp. z o.o., Kraków, Poland).

The results of the correlation analysis are presented in Table 6. The table includes the following indicators: r^2 – coefficient of determination, t – value of the t-statistic testing the significance of the correlation coefficient, and p – probability value (significance level).

A very strong positive correlation was observed between the increase in the level of MC strategy and consumer participation in the design process (r = 0.8278). Additionally, significant correlations were identified between the increase in MC strategy and both customer involvement in product design (r = 0.7861) and the integration of customer preferences (r = 0.7861). In contrast, a weak correlation was found between the increase in MC strategy and the automation of production process planning as well as the use of simulation techniques.

These findings clearly indicate that the key factors influencing the enhancement of MC strategy in Polish manufacturing SMEs include consumer participation in the design process and product design, the ability to understand customer preferences, the utilization of product configuration mechanisms, production process control, and the application of real-time data.

In response to the second research question concerning the impact of advanced technologies on the advancement of MC strategy implementation, the relationships between Industry 4.0 technologies adopted and the increase in MC strategy level were analyzed and are presented in Table 6.

A strong correlation was observed between the increase in the level of MC strategy and the use of automated machines, such as 3D printers or autonomous processing stations (r = 0.6285), as well as with systems integration (r = 0.5438). Consequently, one of the key challenges in advancing the MC strategy is undoubtedly the automation of unique and customized processes.

Table 5 Correlations between the factors describing the realization of the MC strategy and the increase in the level of MC strategy in the automotive industry

Relations	Correlation	r^2	t	p
c1/MC	0.8278	0.6853	15.8271	0.0000
c2/MC	0.7861	0.6180	13.6419	0.0000
c3/MC	0.7861	0.6180	13.6419	0.0000
c4/MC	0.6622	0.4386	9.4792	0.0000
c5/MC	0.3563	0.1269	4.0896	0.0000
c6/MC	0.6285	0.3950	8.6666	0.0000
c7/MC	0.4936	0.2436	6.0871	0.0000
c8/MC	0.6622	0.4386	9.4792	0.0000

Table 6 Correlations between Industry 4.0/5.0 technologies implemented and the increase in the level of MC strategy in the automotive industry

Relations	Correlation	r^2	t	p
I1/MC	0.3859	0.1489	4.4870	0.0000
I2/MC	0.4739	0.2246	5.7715	0.0000
I3/MC	0.4153	0.1724	4.8961	0.0000
I4/MC	0.4739	0.2246	5.7715	0.0000
I5/MC	0.3362	0.1130	3.8285	0.0002
I6/MC	0.5438	0.2957	6.9500	0.0000
I7/MC	0.1867	0.0348	2.0390	0.0437
I8/MC	0.2137	0.0456	2.3464	0.0206
I9/MC	0.6285	0.3950	8.6666	0.0000
I10/MC	0.1393	0.0194	1.5086	0.1341
I11/MC	0.0976	0.0095	1.0522	0.2949
I12/MC	0.3957	0.1566	4.6218	0.0000
I13/MC	0.4739	0.2246	5.7715	0.0000

In addressing the third research question, the survey also investigated the benefits of implementing the MC strategy within the automotive industry. Among Polish SMEs, 36.75 % reported an increase in production flexibility, 33.33 % noted a reduction in waste, and 28.21 % observed an annual sales increase of up to 10 %. Additionally, 26.50 % of SMEs declared improvements in workforce flexibility and decentralization of decision-making. A reduction in electricity consumption was reported by 24.79 % of enterprises, while 20.51 % highlighted more effective analysis of large data sets. Subsequently, the relationship between these outcomes of MC strategy implementation and the increase in the level of MC strategy was analyzed (see Table 7).

The primary relationships identified in Polish SMEs between the implementation of the MC strategy and increased production flexibility (0.5644), as well as waste reduction (0.5235), were found to be significant.

Table 7 Correlations between the outcomes of MC strategy implementation and the increase in the level of MC strategy in the automotive industry

Relations	Correlation	r^2	t	p
E1/MC	0.4641	0.2153	5.6188	0.0000
E2/MC	0.2729	0.0745	3.0431	0.0029
E3/MC	0.1564	0.0244	1.6986	0.0920
E4/MC	0.4445	0.1976	5.3223	0.0000
E5/MC	0.5644	0.3186	7.3328	0.0000
E6/MC	0.5235	0.2741	6.5904	0.0000
E7/MC	0.4250	0.1806	5.0360	0.0000
E8/MC	0.3761	0.1414	4.3535	0.0000
E9/MC	0.4445	0.1976	5.3223	0.0000

4. Discussion

The research findings provide comprehensive answers to the three posed research questions. The primary factors driving the enhancement of the Mass Customization (MC) strategy implementation level in Polish manufacturing SMEs within the automotive sector include active customer involvement in both the MC product design process and the utilization of real-time configuration tools tailored to meet customer requirements. A notable example of such an approach is the Customer-Product Interaction Life Cycle (CILC) model [26], which facilitates cost reduction and enhances customer satisfaction. Furthermore, the results demonstrate that the adoption of Industry 4.0/5.0 (I4.0/5.0) technologies, particularly automated machinery, contributes significantly to the advancement of MC strategy implementation.

The study also delineates future research directions in MC, emphasizing: (1) the development of enterprise strategies that integrate customer participation in new product and process design; (2) the incorporation of automation and robotics in alignment with MC objectives; and (3) the transformative impact of I4.0/5.0 technology adoption on MC practices.

Nevertheless, certain limitations warrant attention and suggest avenues for further investigation. First, the current study is confined to the automotive industry, focusing on customized orders. Extending this research to other industrial sectors, such as metal manufacturing, could reveal whether observed patterns are generalizable or industry-specific. Second, the study does not address manufacturer performance metrics. Financial constraints typical of SMEs restrict the deployment of I4.0/5.0 technologies, thereby limiting MC strategy realization in production processes. The substantial investment required for implementing I4.0/5.0 solutions represents a significant barrier to enhancing MC production capabilities [27]. Future research should, therefore, integrate analyses of investment expenditures with assessments of both tangible and intangible benefits derived from these technologies, as such transformations are imperative for sustaining competitive advantage.

Third, the present investigation centers on SMEs, which constitute the majority (over 90 %) of enterprises in Poland. Subsequent research should explore the interplay between Industry 4.0/5.0 adoption (i.e., acquisition and utilization of advanced technologies) and the simultaneous increase in customer satisfaction and profit margins across small, medium-sized, and large enterprises. It is crucial to recognize that these categories possess distinct financial strategies and capital limitations.

This article represents the initial phase of a broader research initiative on MC strategy implementation in manufacturing enterprises. Building on the collected data, an AI-based predictive model will be developed to validate the empirical findings and uncover potential additional or non-linear relationships undetectable through traditional correlation analyses [28]. The model will employ artificial neural networks trained and tested on survey data filtered by significance analysis. The subsequent research stage will leverage this model to simulate and identify strategies that optimize the desired level of product customization.

5. Conclusion

This paper presents a diagnostic analysis of the situation regarding Mass Customization (MC) realization on the example of Poland in the European market. In enterprises across European Union countries, notable similarities can be observed in the functioning of the market, partly due to the regulations of the European Commission. Therefore, our research results in MC can be treated as a reference framework for activities aimed at enhancing the MC level in European manufacturing enterprises. We hope that the results of our research will inspire further studies to explore these areas within other countries with varying geopolitical and economic conditions. Recommendations for managers in the automotive manufacturing sector were formulated regarding necessary actions to increase the level of MC strategy. Firstly, it is advised to implement tools that will enable customers to participate in the design of the product and process, and secondly, to develop mechanisms that will enable the analysis of real-time data and the implementation of automatic solutions, even when dealing with individual projects. This is undoubtedly a challenge and a promising avenue for further research in the field of improving MC strategy implementation.

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Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Fathi, M., Ghobakhloo, A. (2020). Enabling mass customization and manufacturing sustainability in Industry 4.0 context: A novel heuristic algorithm for in-plant material supply optimization, *Sustainability,* Vol. 12, No. 16, Article No. 6669, doi: 10.3390/su12166669.

[2] Kim, S., Lee, K. (2023). The paradigm shift of mass customisation research, *International Journal of Production Research,* Vol. 61, No. 10, 3350-3376, doi: 10.1080/00207543.2022.2081629.

[3] Patalas-Maliszewska, J., Kowalczewska, K., Rehm, M. (2023). The role of additive manufacturing in supply chain management, *Management and Production Engineering Review,* Vol. 14, No. 1, 25-33, doi: 10.24425/mper.2023.145363.

[4] Bojic, S., Maslaric, M., Mircetic, D., Nikolicic, S., Todorovic, V. (2023). Simulation and Genetic Algorithm-based approach for multi-objective optimization of production planning: A case study in industry*, Advances in Production Engineering & Management,* Vol. 18, No. 2, 250-262, doi: 10.14743/apem2023.2.471.

[5] Suzic, N., Forza, C. (2023). Development of mass customization implementation guidelines for small and medium enterprises (SMEs), *Production Planning & Control*, Vol. 34, No. 6, 543-571, doi: 10.1080/09537287.2021.1940345.

[6] Song, O., Ni, Y., Ralescu, D.A. (2021). Product configuration using redundancy and standardisation in an uncertain environment, *International Journal of Production Research,* Vol. 59, No. 21, 6451-6470, doi: 10.1080/00207543.2020.1815888.

[7] Mönch, T., Huchzermeier, A., Bebersdorf, P. (2021). Variable takt times in mixed-model asmbly line balancing with random customization, *International Journal of Production Research,* Vol. 59, No. 15, 4670-4689, doi: 10.1080/00207543.2020.1769874.

[8] Ebrahimi, M., Mahmoodjanloo, M., Einabadi, B., Baboli, A., Rother, E. (2023). A mixed-model assembly line sequencing problem with parallel stations and walking workers: A case study in the automotive industry, *International Journal of Production Research*, Vol. 61, No. 3, 993-1012, doi: 10.1080/00207543.2021.2022801.

[9] Mourtzis, D., Angelopoulos, J., Panopoulos, N. (2022). Personalized PSS design optimization based on digital twin and extended reality, *Procedia CIRP*, Vol. 109, 389-394, doi: 10.1016/j.procir.2022.05.267.

[10] He, Y., Stecke, K.E. (2022). Simultaneous part input sequencing and robot scheduling for mass customization, *International Journal of Production Research*, Vol. 60, No. 8, 2481-2496, doi: 10.1080/00207543.2021.1894369.

[11] Wang, Y., Zhao, W., Wan, W.X. (2021). Needs-based product configurator design for mass customization using hierarchical attention network, *IEEE Transactions on Automation Science and Engineering,* Vol. 18, No. 1, 195-204, doi: 10.1109/TASE.2019.2957136.

[12] Vještica, M., Dimitrieski, V., Pisarić, M.M., Kordić, S., Ristić, S., Luković, I. (2023). Production processes modelling within digital product manufacturing in the context of Industry 4.0, *International Journal of Production Research*, Vol. 61, No. 19, 6271-6290, doi: 10.1080/00207543.2022.2125593.

[13] Pech, M., Vrchota, J. (2022). The product customization process in relation to Industry 4.0 and digitalization*, Processes*, Vol. 10, No. 3, Article No. 539, doi: 10.3390/pr10030539.

[14] Bouchard, S., Gamache, S., Abdulnour, G. (2023). Operationalizing mass customization in manufacturing SMEs – A systematic literature review, *Sustainability*, Vol. 15, No. 4, Article No. 3028, doi: 10.3390/su15043028.

[15] Yang, H., Jiang, L. (2024). Modular design of new products and remanufacturing of used products under mass customization, *RAIRO-Operations Research*, Vol. 58, No. 1, 103-128, doi: 10.1051/ro/2023151.

[16] Zeng, F. (2024). Research on key technology of mass customization based on flexible manufacturing in the context of deep learning, *Applied Mathematics and Nonlinear Sciences*, Vol. 9, No. 1, 1-21, doi: 10.2478/amns-2024-0115.

[17] Nair, V.V., Kuhn, D., Hummel, V. (2019). Development of an easy teaching and simulation solution for an autonomous mobile robot system, *Procedia Manufacturing,* Vol. 31, 270-276, doi: 10.1016/j.promfg.2019.03.043.

[18] Tilbury, D.M. (2019). Cyber-physical manufacturing systems, *Annual Review of Control, Robotics, and Autonomous Systems,* Vol. 2, 427-443, doi: 10.1146/annurev-control-053018-023652.

[19] Dou, Z., Sun, Y., Wu, Z., Wang, T., Fan, S., Zhang, Y. (2021). The architecture of mass customization-social Internet of Things system: Current research profile, *ISPRS International Journal of Geo-Information,* Vol. 10, No. 10, Article No. 653, doi: 10.3390/ijgi10100653.

[20] Zhang, Z., Wang, X., Zhu, X., Cao, Q., Tao, F. (2019). Cloud manufacturing paradigm with ubiquitous robotic system for product customization, *Robotics and Computer-Integrated Manufacturing*, Vol 60, 12-22, doi: 10.1016/j.rcim.2019.05.015.

[21] Burge, T.A., Jeffers, J.R.T., Myant, C.W. (2022). Development of an automated mass-customization pipeline for knee replacement surgery using biplanar X-rays, *Journal of Mechanical Design*, Vol. 144, No. 2, Article No. 021702, doi: 10.1115/1.4052192.

[22] Sarker, I.H., Kayes, A.S.M., Badsha, S., Alqahtani, H., Watters, P., Ng, A. (2020). Cybersecurity data science: An overview from machine learning perspective, *Journal of Big Data*, Vol. 7, Article No. 41, doi: 10.1186/s40537-020-00318-5.

[23] Wang, Y., Ma, H.-S., Yang, J.-H., Wang, K.-S. (2017). Industry 4.0: A way from mass customization to mass personalization production, *Advances in Manufacturing*, Vol. 5, 311-320, doi: 10.1007/s40436-017-0204-7.

[24] Mankins, J.C. (2009). Technology readiness assessments: A retrospective, *Acta Astronautica,* Vol. 65, No. 9-10, 1216-1223, doi: 10.1016/j.actaastro.2009.03.058.

[25] Koppenhagen, F., Held, T. (2021). The implications of product modularisation on the development process, supplier integration and supply chain design in collaborative product development, *Advances in Production Engineering & Management*, Vol. 16, No. 1, 82-98, doi: 10.14743/apem2021.1.386.
[26] Zhang, X., Ming, X. (2024). A smart system of customer- product interaction life cycle (CILC) in industrial internet era for mass personalization from industrial practice survey: Identification, definition, acquisition and parsing, *Journal of Intelligent Manufacturing,* Vol. 35, 727-756, doi: 10.1007/s10845-022-02070-4.
[27] Alqoud, A., Schaefer, D., Milisavljevic-Syed, J. (2022). Industry 4.0: challenges and opportunities of digitalisation manufacturing systems, In: *Proceedings of the 19th International Conference on Manufacturing Research, Incorporating the 36th National Conference on Manufacturing Research*, Derby, UK, 25-30, doi: 10.3233/ATDE220560.
[28] Patalas-Maliszewska, J., Pająk, I., Skrzeszewska, M. (2020). AI-based decision-making model for the development of a manufacturing company in the context of Industry 4.0, In: *Proceedings of the 2020 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE*), Glasgow, United Kingdom, 1-7, doi: 10.1109/FUZZ48607.2020.9177749.