Smart manufacturing paradigms in the context of industry 4.0 : bibliometric analysis

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Abstract. Following each industrial revolution, spanning from Industry 1.0 to Industry 4.0, a distinct manufacturing paradigm has consistently emerged. In the current manufacturing environment and consumer-driven markets, Mass Customization and Mass Personalization are the newer smart manufacturing paradigms. Those novel approaches are designed to offer customers personalized products and services, all while preserving the efficiency of Mass Production. Within this framework, a bibliometric analysis was conducted in order to review and analyse the existing literature. The main findings reveal numerous parallels and differences between Mass Customization and Mass Personalization, especially in aspects such as scope, customer involvement, product variety and flexibility. Simultaneously, there are various limitations revolving around data availability and product uncertainty. Those smart manufacturing paradigms are studied within the context of Industry 4.0, and thus our study also focus on the impact and challenges of this fourth industrial revolution on Mass Customization and Mass Personalization.
Keywords – Smart Manufacturing, Industry 4.0, Mass Customization, Mass Personalization, Bibliometric Analysis

1 Nomenclature

AI	Artificial Intelligence
CPPR 4.0	Cyber-Physical Production Resource 4.0
CPS	Cyber Physical System
CPSS	Cyber-Physical Social System
ERP	Entreprise Resource Planning
I4.0	Industry 4.0
IIOT	Industrial Internet of Things
MES	Manufacturing Execution System
SME	Small and Medium-sized Entreprise

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2 Introduction

The term industrial revolution applies to technological advancements that introduce new ways of life, leading to profound societal transformations [1].

From Industry 1.0 characterized by steam engines to the age of digital transformations, the manufacturing industry has undergone a profound evolution [2]. The figure 1 presents the four different industrial revolutions.

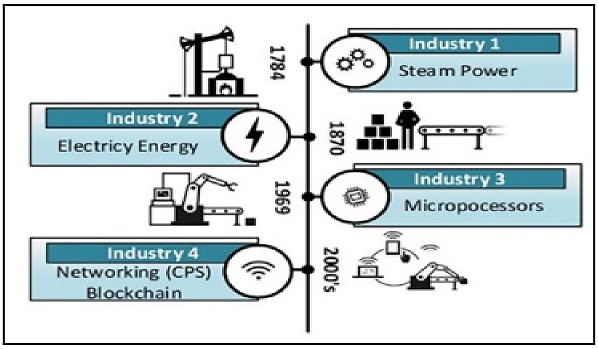

Fig. 1. The four different industrial revolutions [2]

Each revolution in industry marked significant changes in production methods and market dynamics, driven by technology and evolving customer expectations. [3][4]

The manufacturing sector shifted from craft production, where products were created based on customer's requests at a high cost, in Industry 1.0, with manual and later machine production. To mass production in Industry 2.0, characterized by assembly line and low-cost, uniform products. Industry 3.0 introduced mass customization, enabling flexible production systems using technologies driven by automation, information and computers. Finally, Industry 4.0 brought mass personalization, focusing on meeting specific customer demands through advanced information and communication technologies. [5][6][7]
The evolution of production modes is described in Fig. 2 [5].

This shift driven by changes in consumer behaviour, where there is a greater emphasis

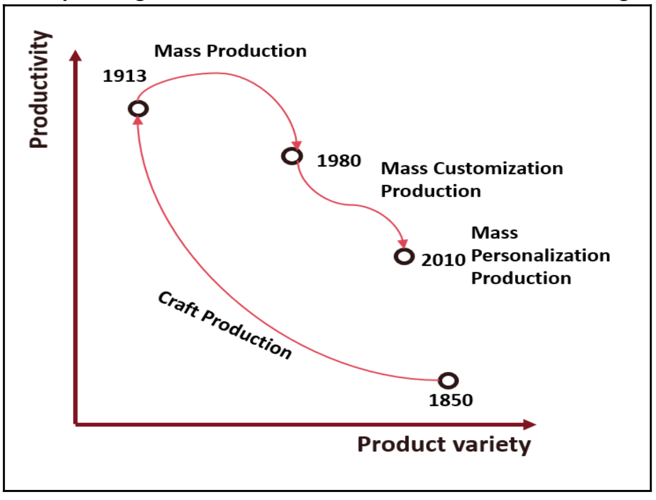

Fig. 2. The evolution of production modes
on individuality and uniqueness in product choices, show the importance and relevance of our study in the current industrial landscape.

This paper aims to present a bibliometric analysis and a summary of previous research and studies work related to Industry 4.0 and its two smart manufacturing paradigms : Mass Customization and Mass Personalization.

We address the following research inquiries in order to provide a comprehensive perspective on the intersection of these concepts :

- Q1 : What are the key concepts, the main themes and emerging trends in this research area, how has the volume of research publications evolved ?
- Q2 : What are the impacts and challenges of Industry 4.0 on Mass Customization and Mass Personalization strategies ?

This paper will be structured into six primary sections. The first section serves as the introduction, providing the context of our keywords and outlining the paper's objectives. Afterwards, on the second section, we will provide a theorical background on our main concepts. Section 3 is about the methodology used for the search of our three areas of study, the selection criteria and the process of extracting and synthesizing data from the selected studies. On the fourth section we present the bibliometric analysis findings for several performance factors. Then, on the section 5 we will cover key findings of the intersection of our keywords and engage in discussion regarding limits and potential avenues for future research. Lastly, the conclusion will summarize the overall significance of the study and reiterate its main contributions.

3 Main Concepts

3.1 Industry 4.0

Industry 4.0, the fourth industrial revolution, integrates connectivity and intelligence into production systems, creating smart factories through key technologies. [2][8]

This paradigm shift enhances manufacturing by enabling intelligent, personalized, high-quality production and blurring the lines between physical and digital realms. Smart factories adapt to shorter product life cycles, increased competition, and individual customer preferences, thriving in a highly integrated ecosystem. [9]

3.2 Mass Customization

In the late 1980s, Mass Customization emerged as a strategy to balance product variety and cost in response to customer demand, enabling global competition in cost quality and flexibility. [6], [7] This production paradigm delivers personalized products with efficiencies close to mass production by modularizing products, employing flexible processes and integrating supply chain partners, including customers. The fundamental idea involves producing divers, customized products alongside standardized ones. [10]–[13]

3.3 Mass Personalization

The transition to Mass Personalization in the economy is rooted in Industry 4.0 [7], [14], it gained recognition at the 24th CIRP Product Design International Conference in April 2014 [5].

This shift from mass personalization and mass customization to mass personalization is driven by the demand for complex, individualized products, short product life cycles and buyer's market [15]. Consumers actively shape product design, emphasizing their role in creation and innovation [6], [16]. Also, amid the COVID-19 pandemic, businesses had to adapt to meet specific consumer requirements, making personalization a necessity [14].

4 Research Methodology

In our study we employed a bibliometric analysis methodology. This methodology encapsulates the application of quantitative techniques on bibliometric data. [17]

The bibliometric methodology has the potential to introduce a systematic, transparent, and reproducible review process based on the statistical measurement of science, scientists, or scientific activity. [18]

The choice of this methodology is explained by the fact that unlike other the bibliometric analysis provides more objective and reliable analysis. [18]

In order to conduct a coherent review, we select the following steps. The Figure 3 illustrates the process review followed in this study. [8], [19]

- Selection of the Keywords
- Data Collection
- Data Selection
- Data Descriptive Analysis
- Data evaluation and Interpretation

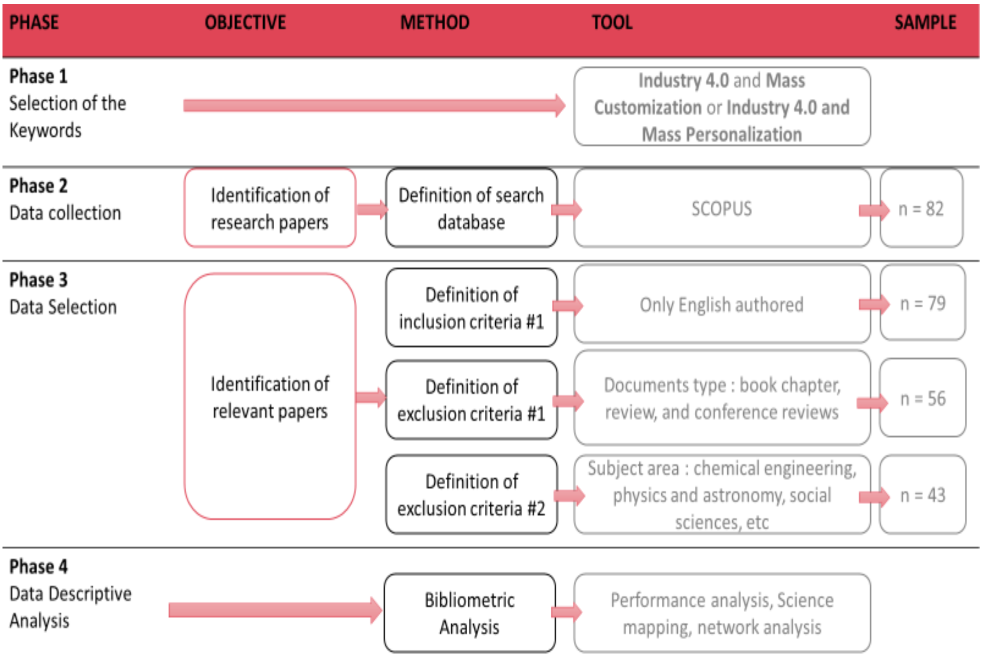

Fig. 3. The 4 phases of our research methodology

4.1 Selection of the Keywords

The selected keywords for our research, which consists the first phase of our methodology, aims to examine papers that address the crossing of three areas : 'Industry 4.0', 'Mass Customization' and 'Mass Personalization'.

4.2 Data Collection

The second phase of our methodology, involves identifying research papers. It was conducted on Scopus Database. While Scopus and Web of Science are the most commonly utilized databases, Scopus database contains 60% additional content than the Web of Science database [19].

The search query was arranged using Boolean operators (AND OR), and to include the paper's title, keywords and abstract, as : TITLE-ABS-KEY (("Industry 4.0" OR "Smart factory" OR "smart technology" OR "digital transformation" OR " Smart manufacturing" OR "digital factory") AND ("Mass Customization" OR "Mass Customisation") OR ("Industry 4.0" OR "Smart factory" OR "smart technology" OR "digital transformation" OR " Smart manufacturing" OR "digital factory") AND ("Mass Personalization" OR "mass personalization")).

We were not required to use any temporal restrictions in our study. Results of the research inquiry already presents documents published in the period between 2016 to 2024. This time frame also aligns with the emergence of Industry 4.0.

Consequently, 82 articles in all were chosen from this first search.

4.3 Data Selection

In order to focus the research and maintain relevance, we applied inclusion and exclusion criteria. We restricted documents to those authored in English, narrowing the results to 79 documents. We then excluded documents type such as : book chapters, reviews and conference reviews, reducing the count to 56 papers. Afterwards, we eliminated documents that were not pertinent to the subject area, like chemical engineering, astronomy etc, resulting in 43 publications. Finally, we excluded articles lacking in-depth examination of the specific keywords or unavailable in full text, confirming 43 documents for analysis and reporting of findings.

5 Descriptive Analysis

The techniques for bibliometric analysis can be classified into two primary categories 'Performance Analysis' and 'Science Mapping'. Additionally, there is a third category 'Network analysis'. [17]

The performance analysis mainly considers the contributions made by research constituents, while science mapping mostly examines the relationships between these elements. The network analysis serves as a bibliometric analysis enrichment toolbox. [17] This section presents the bibliometric analysis findings for several performance factors.

5.1 Research growth

Figure 4 illustrates the annual publication of documents from 2016 to May 2024. Early interest in Industry 4.0 began in 2016, with a slight decrease in 2017. Then, research volume rose from 2018 to 2019, reflecting growing awareness. The dip in 2020 was due to Covid-19 disruptions and a temporary shift in research focus. Significant increases from 2021 to 2023 were driven by advancements in Industry 4.0 technologies. Finally, the drop in 2024 is because the data extends only to May 2024.

Overall, the curve displays an increasing trend, indicating a recent surge in interest in this research area.

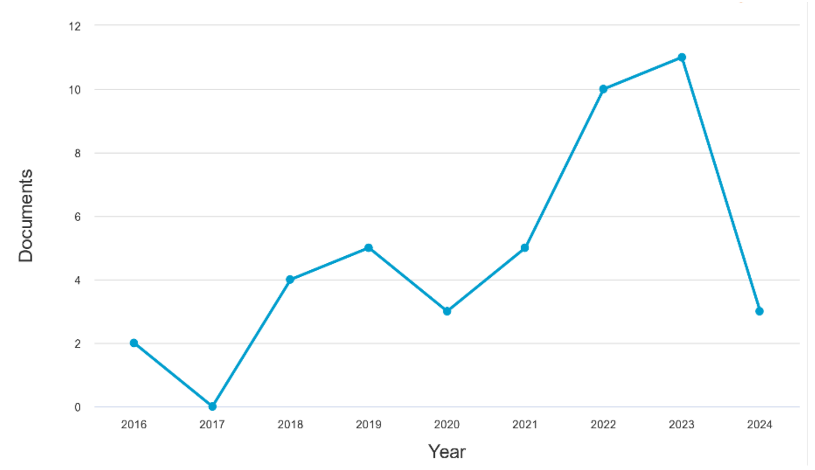

Fig. 4. Distribution of research documents publications over 2016 - 2024

5.2 Distribution by source

Table 1 highlights the distribution of publications across the journals and sources. Proocedia CIRP leads with five publications, followed by the Journal of Manufacturing systems with three. Computers and Industrial Engineering, Machines, and Manufacturing Letters each have two publications. Eighteen publication are spread across various other journals, reflecting diverse interest and interdisciplinary contributions in Industry 4.0, Mass Customization and Mass Personalization. This underscores the need to monitor a variety of sources to capture the full scope of research advancements.

Table 1. Distribution of research documents by source

Source	Number of publications
Procedia CIRP	5
Journal Of Manufacturing Systems	3
Computers And Industrial Engineering	2
Machines	2
Manufacturing Letters	2
Other jounals (1 publi.)	18

5.3 Distribution by subject area

The pie chart, presented in figure 5, displays the distribution of paper publications by subject area. Engineering represents the largest share at 48%, followed by Computer Science at 32%. The field Business and Management comprises 9.3% of published works, underscoring the significance of research in organizational and economic studies.

Mathematics plays a fundamental role in supporting engineering and computer science, contributing by 5.3%. Both Decision Science and Economics each make 2.7% of the total.

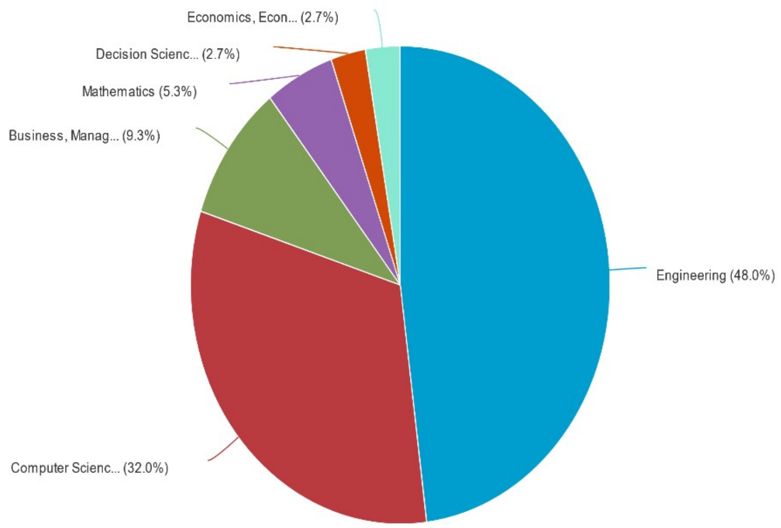

Fig. 5. Distribution of research documents by subject area

5.4 Keywords co-occurrence

In this section, we employed the VOS viewer, a high popular information visualization software, to identify the most frequently used keywords by the authors in their papers. The VOS viewer graph visualizes the co-occurrence of keywords in research publications, indicating clusters of related terms.

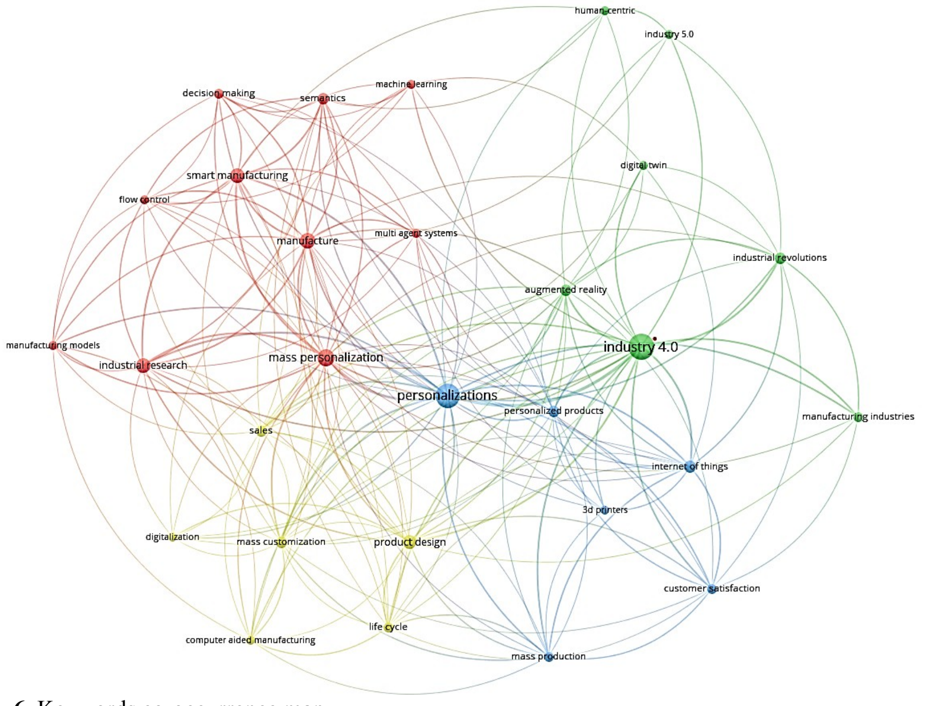

Fig. 6. Keywords co-occurrence map

The graph presented in the figure 6, shows mainly 3 different cluster colors :

• Green Cluster (Industry 4.0 and related concepts): The central node 'industry 4.0' connects strongly with terms like industrial revolutions, digital twin, augmented reality and industry 5.0. This cluster focuses on the advancements and technologies driving the fourth industrial revolution and the transition toward the next one.

• Blue Cluster : The node 'personalizations' is linked to the keywords constituting the other clusters. It emphasizes the role of personalization in manufacturing in the context of industry 4.0, and the link between Mass Customization and Mass Personalization.

• Red Cluster : key terms such as 'mass personalization', 'smart manufacturing', and 'machine learning'. It highlights the integration of advanced technologies like machine learning to achieve mass personalization and smart manufacturing.

• Yellow Cluster : Its main node 'mass customization' is linked to 'digitalization', 'life cycle' and other key words, emphasizing the links of mass customization.

The VOS viewer graph reveals that Industry 4.0, provides the technological backbone for personalizations. The represented clusters, all together, depict a comprehensive, interconnected landscape where Industry 4.0 technologies drive the evolution towards mass customization and mass personalization.

6 Discussion

Mass customization and mass personalization represent smart manufacturing paradigms aimed to deliver individualized products with mass production efficiency, using technology for large-scale customization. Personalization technologies analyse customer data to create tailored features. [10]

These successive industrial revolutions have reshaped manufacturing and company-customer dynamics [20]. Mass personalization surpasses mass customization by allowing customers to co-design products, making every product potentially unique [10], [21]. Thus, the consumer's role has evolved from 'buying' in mass production, to 'choosing' with mass customization, and ultimately 'designing' with mass personalization, hence demanding more responsive manufacturing systems, as shown in Fig. 7 [22].

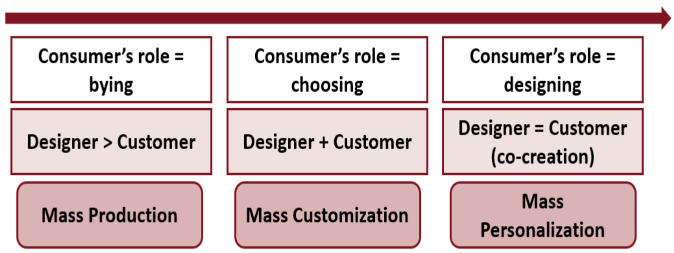

Fig. 7. The evolution of the consumer's role throughout Mass Production, Mass Customization and Mass Personalization

Therefore, the evolving consumer demand for a more diversified and customized choices of products has significant implications for both the economy and society [5].
On the contrary, mass personalization highlights a more personalized and interactive customer experience. This could entail direct communication and collaboration between customers and suppliers to address individual preferences [23]. Regarding the production process, Mass customization commonly utilizes a flexible and agile production process, facilitating the efficient customization of products or services [24].

In contrast, mass personalization demands a more sophisticated production process, often harnessing technologies like Industry 4.0, to enable the efficient manufacturing of highly individualized products [21].

The following Table 2 outlines the core similarities and distinctions between mass customization and mass personalization.

Table 2. Similarities and distinctions between Mass Customization and Mass Personalization

Aspect	Mass Customization	Mass Personalization	References
Time Market environment	Since 1990s	Since the 21st Century	[25]
Scope	Tailors products to customer segment.	Tailors product to individual customers	[13], [26] [27]–[30]
Customer Role	Choose Buy	Design Choose Buy	[6], [15][29]
Customer Involvement / Engagement	Customers configure from predefined options Limited customer involvement in design and selection of predefined customization options	Customer actively participate in design and creation Active and direct customer involvement in the design stage, allowing for personalized product variations	[31]–[36]

Product Variations	Offers predefined products and limited number of design options within a product catalog;	Provides unique, one-of-a-kind products	[6], [8], [13], [21],[27]
Flexibility	Combines variety with mass production efficiency. It clusters common functions, materials, and appearances, offering a balance between customization and efficiency.	Focus on agility; responsiveness, real-time adjustments and changeability.	[7], [15],[35], [37]–[40]
Support systems	ERP, MES, Supply chain platforms	Information platform based on AI, Big Data, Cloud Computing	[14], [15],[25]

Both mass customization and mass personalization have their limitations. While mass customization may not engage customers as intimately as mass personalization, the latter requires deeper customer involvement in the design process, which might not be suitable for all customers. The table 3 below outlines those limitations.

Table 3. Limitations of Mass Customization and Mass Personalization

Aspect	Mass Customization	Mass Personalization	References
Cost and Complexity	Can be expensive due to the need to maintain a diverse product range. It requires adaptable production processes.	Can be costlier and more complex as it involves creating entirely unique products for each customer.	[20], [21], [35], [39]
Implementation in SMEs	Implementation can be difficult for small and medium enterprises (SMEs) with limited resources and capabilities.	SMEs may face challenges in implementing mass personalization due to resource limitations, making it less accessible for some SMEs.	[20],[28],[41], [42]
Data Availability	Requires customer initiative for customization, which may not always align with company objectives	Depends on customer data, which may not be readily available or sufficient for personalization	[12], [21]
Product Uncertainty	Provides predictability with predefined options	Increases risks due to uncertainty and evaluation	[13], [20]
Supply Chain Design	Focuses on modularization and postponement strategies.	Requires more adaptable supply chain designs that account for design complexity and supplier capabilities	[43]

Mass customization is often mentioned as a key value proposition in the ongoing discussion about Industry 4.0. However, it is important to recognize that mass customization has been a strategy for meeting customer requirements dynamically and efficiently long before the emergence of I4.0 technologies [44].

Industry 4.0 is profoundly transformative, with primary goals focused on driving organizations to achieve key success metrics. It aims to seamlessly integrate the physical environment with the digital world [45]. The most common strategic objectives for adopting Industry 4.0 technologies include enhancing efficiency, improving customer service, automating development, and integrating manufacturing and supply chains. [9]

Integrating mass customization with Industry 4.0 technologies can significantly enhance product completion rate, customer satisfaction rate, equipment utilization, and waiting in time in queues [46]. Moreover, Industry 4.0 technologies provide excellent support for the management and workflow in enterprises that adopt a mass customization strategy, resulting in increased production efficiency [44].

Also, Industry 4.0 provides powerful tools to enhance productivity and flexibility in assembly for mass customization, effectively managing the complexities of production systems [7], [42], [47]. This concept enables innovative forms of personalization, allowing direct customer input in the design and production of customized products, resulting in shorter cycle times and lower costs [7].

Industry 4.0 facilitates the production of highly customized products with shorter cycle times and lower costs, effectively meeting the growing demand for personalization [7]. By integrating personalized products alongside core offerings, small- and medium-sized enterprises (SMEs) can respond to this demand, adding value through individualization [11]. The primary objective of Industry 4.0 is to achieve sustainable success in a market driven by consumers who seek personalized products and services. This era is marked by a transition from mass production to high personalization of mass products, with affordable personalization as a key focus.[48]

Moreover, with the capabilities of those technologies facilitate the scalable and cost-efficient production of personalized products with the Mass Personalization. [49]

CPSS (Cyber-Physical-Social Systems) allows manufacturing facilities to use physical sensors, known as the Industrial Internet of Things (IIoT), to continuously collect data on human-machine and machine-to-machine interactions. This Big Data is transmitted to cyberspace for filtering, analysis, and real-time feedback. These systems enhance connectivity and efficiency, enabling the development of new manufacturing capabilities like flexible modular factories, cobotic systems, digital twins, and advanced techniques such as additive manufacturing. [7][35]

Simultaneously, with the Industry 4.0's new technologies and innovative ideas that are emerging and being widely adopted to meet the growing consumption demand, the manufacturing companies and organizations face unprecedented competition and challenges. [7]

Industry 4.0 strives to secure the future competitiveness of the manufacturing sector by empowering companies to swiftly and reliably adapt to rapid product changes and disruptions through reconfigurability. The CPPR 4.0 framework illustrates this approach by incorporating the value proposition-creation-capture cycle within the context of a manufacturing organization's customer, product, process, and resource perspectives, showcasing its practical application [50].

7 Conclusion

In conclusion, Mass Customization and Mass Personalization are emerging as prominent smart manufacturing paradigms, aiming to deliver individualized products and services while retaining mass production efficiency.

In order to get a successful implementation of Mass Customization and Mass Personalization, and enhance their capabilities, companies need to undergo organizational changes in areas such as products, technology and supply chain management [42]. Both strategies heavily rely on flexible and responsive supply chain management. A dynamic supply chain is crucial for efficiently handling diverse product configurations and personalized demands [51]. The supply chain in mass customization and personalization is complex, combining unpredictable customer orders with extended lead times for the delivery of raw material, making production planning challenging [52]. In the field of Supply Chain Management, where Demand Forecasting holds a critical role, helps in estimating future demand for products, enabling better inventory management. Accurate forecasts assist in maintaining optimal inventory levels, preventing overstocking and stockouts [51], demand forecasting for mass customization and personalization is highly volatile due to short product life cycles, long lead times for raw material purchases and the complexity of product structure graphs [52].

Future research should focus on adapting existing forecasting methods and developing new approaches based on Artificial Intelligence and Machine Learning to meet the specific needs of these dynamic industries. As this research advances, it is expected that enhanced forecasting practices will play a crucial role in the further evolution of Mass Customization and Mass Personalization.

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