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Systematic Review

Unlocking the Potential of Mass Customization Through Industry 4.0: Mapping Research Streams and Future Directions

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Abstract

Mass customization (MC) has become a pivotal manufacturing strategy for addressing the growing demand for personalized products without compromising cost efficiency and scalability. The emergence of Industry 4.0 (I4.0) has further expanded the potential of MC by enabling intelligent, flexible, and interconnected production systems. This paper presents a systematic literature review covering the period from 2011 to 2024, aimed at examining how I4.0 technologies influenced the conceptual evolution, technological enablers, and supply chain implications of MC. A total of 3441 publications were retrieved from Scopus and analyzed using a combination of bibliometric mapping and qualitative synthesis. The review identifies three primary research streams: (1) MC conceptual frameworks and performance metrics, (2) enabling technologies and methods across the product lifecycle, and (3) supply chain strategies tailored to MC environments. Key enablers such as product modularity, customer co-design platforms, additive manufacturing, and reconfigurable production systems are discussed, along with barriers related to complexity, integration challenges, and sustainability trade-offs. The study highlights a gradual convergence toward mass personalization, supported by real-time data, artificial intelligence, and predictive analytics. The findings offer a structured understanding of MC in the I4.0 context and point toward future research opportunities involving digital twin integration, cross-disciplinary implementation models, and sustainability-driven customization frameworks.

Keywords: mass customization; Industry 4.0; literature review; product variety

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Academic Editor: Mirco Peron

Received: 20 May 2025
Revised: 16 June 2025
Accepted: 23 June 2025
Published: 25 June 2025

Citation: Naldi, L.D.; Galizia, F.G.; Bortolini, M.; Gabellini, M.; Ferrari, E. Unlocking the Potential of Mass Customization Through Industry 4.0: Mapping Research Streams and Future Directions. *Appl. Sci.* **2025**, *15*, 7160. https://doi.org/10.3390/app15137160

1. Introduction and Research Positioning

Over the past four decades, product variety has grown rapidly across nearly all categories [1,2], as companies strive to meet rising customer demand for personalized offerings [3]. In this context, the mass customization (MC) paradigm has received increasing attention from both academia and industry for its potential to combine product variety with production efficiency and flexibility [4,5].

Originally introduced by Davis [6], MC refers to the ability to serve a large customer base with individually tailored products, combining the scale of mass production with the personalization of pre-industrial craftsmanship. Pine [7] expanded this definition, emphasizing high variety and customization at prices comparable to standard goods. Thus, MC seeks to fulfill individual needs while maintaining near mass production efficiency.

Over time, MC has evolved from a niche concept to a widely adopted strategy across industries [8,9]. It has proven effective in sectors such as automotive, apparel, and electronics [10,11], with successful implementations by companies like HP, Kodak, Dell, Nike, and Volkswagen [12]. MC has also demonstrated value for small and medium enterprises (SMEs) [13].

Despite its promise, implementing MC remains complex, requiring manufacturers to adapt offerings and processes quickly and cost-effectively in response to changing customer demands [10,14]. Over the years, research has focused on enablers such as product family design, platforms, and postponement strategies [11]. Technologies like CAD [15,16] and supply chain coordination methods [17,18] also played a crucial role.

Information systems (IS), including IT, are crucial to integrating customer input into production [13] and synchronizing data across company functions and supply chains. Online configurators and e-commerce platforms further engage customers and collect preference data [19], while web technologies and real-time interconnectivity [20,21] paved the way for a new industrial paradigm.

The fourth industrial revolution—Industry 4.0 (I4.0)—emerged in 2011, marked by the integration of technologies such as cyber-physical systems (CPS), Internet of Things (IoT), artificial intelligence (AI), and cloud computing to create smart manufacturing systems [22–24]. I4.0 and MC are closely linked: growing customization demands have driven the adoption of I4.0 technologies to achieve greater flexibility, automation, and reconfigurability [21,23]. As noted by Schmidt et al. [25], MC is not only enabled by I4.0 but also acts as a driving force in its development.

Numerous literature reviews on MC exist, e.g., [11,26,27], yet most predate the rise of I4.0. The disruptive nature of I4.0 calls for updated analysis on how these technologies reshaped MC and enabled new levels of personalization. A comprehensive analysis about the current technologies and methodologies commonly adopted to reach product customization is missing. This paper addresses that gap by reviewing the evolution of MC and its technological enablers between 2011 and 2024, focusing on the influence of I4.0 technologies in managing product variety. The review begins in 2011, the year Industry 4.0 was formally introduced, to capture the academic and technological evolution of MC within this paradigm. The selected time frame thus reflects the emergence, development, and consolidation of I4.0's influence on MC over the past decade.

The remainder of this paper is organized as follows: Section 2 describes the research methodology and bibliometric analysis; Section 3 presents the classification and discussion of selected papers, while Section 4 outlines key findings. Finally, Section 5 concludes the paper with final remarks and future research opportunities.

2. Research Methodology

This study adopts a systematic review methodology to explore how MC has evolved after the advent of I4.0. The review is conducted according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses 2020 (PRISMA 2020) guidelines [28]. The protocol was defined in advance, including objectives, eligibility criteria, search strategy, data extraction, and analysis procedures.

The aim of the review is to systematically identify, analyze, and synthesize the most relevant contributions on MC within the framework of I4.0 over the period 2011–2024. The selection of documents was based on predefined inclusion and exclusion criteria to ensure the relevance and quality of the literature reviewed.

Inclusion criteria:

- Peer-reviewed journal articles, conference papers, reviews, and book chapters;
- Documents published between 2011 and 2024;
- Documents written in English language, only;
- Documents focused on MC and related enabling technologies;
- Documents indexed in the Scopus database;

- Documents belonging to the following subject areas: Engineering, computer science, business management and accounting, decision sciences, mathematics, materials science, social sciences, and economics econometrics and finance.

Exclusion criteria:

- Editorials, commentaries, letters, and non-peer-reviewed material;
- Articles unrelated to MC or Industry 4.0;
- Duplicates or retracted papers;
- Papers without accessible full text.

The literature search was conducted using the Scopus database due to its extensive coverage of scientific publications in engineering, management, and information systems in September 2024. The article selection process followed the main, if applicable, steps of the PRISMA 2020 methodology guidelines. The term "mass customization" was used as the primary keyword, searched in the title, abstract, and keywords fields. The search initially yielded 4013 records. The Scopus tools were used, applying the subject area filters and listing the publications according to the number of citations and relevance criteria, leading to a pool of 349 documents with no duplicates. These publications were checked for their availability as full text, removing 119 papers. A final selection of 229 highly relevant publications was fully read and reviewed, focusing on the technological, methodological, and managerial dimensions of MC.

The screening process was conducted independently by two authors. The initial abstract screening was performed separately by both reviewers. In case of disagreement, a discussion was held to reach consensus. Full-text screening was also performed in duplicate, and any unresolved conflicts were resolved by a third author. The inclusion/exclusion decisions were recorded in a shared spreadsheet, and screening consistency was periodically validated. The PRISMA flow diagram in Figure 1 summarizes the identification, screening, eligibility, and inclusion phases of the review process.

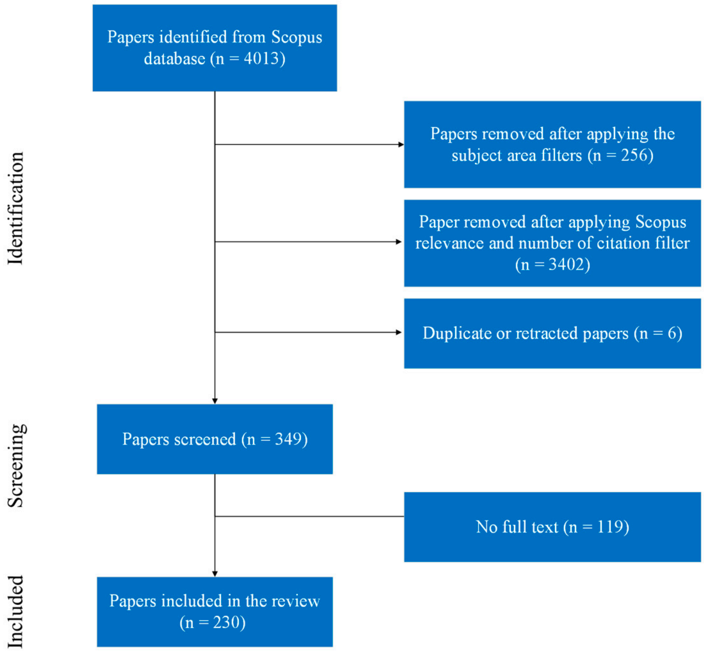

Figure 1. PRISMA 2020 flow diagram for document identification, screening, and inclusion process.

2.1. Bibliometric Mapping and Conceptual Clustering

To uncover conceptual trends and dominant research themes, a keyword co-occurrence analysis was conducted using the VOSviewer software (version 1.6.19). Only keywords occurring in at least 60 documents and co-occurring in a minimum of 10 were included in the network map. The resulting conceptual network consisted of 48 nodes, with “mass customization” as the central hub, surrounded by clusters of related concepts and technologies, as in Figure 2.

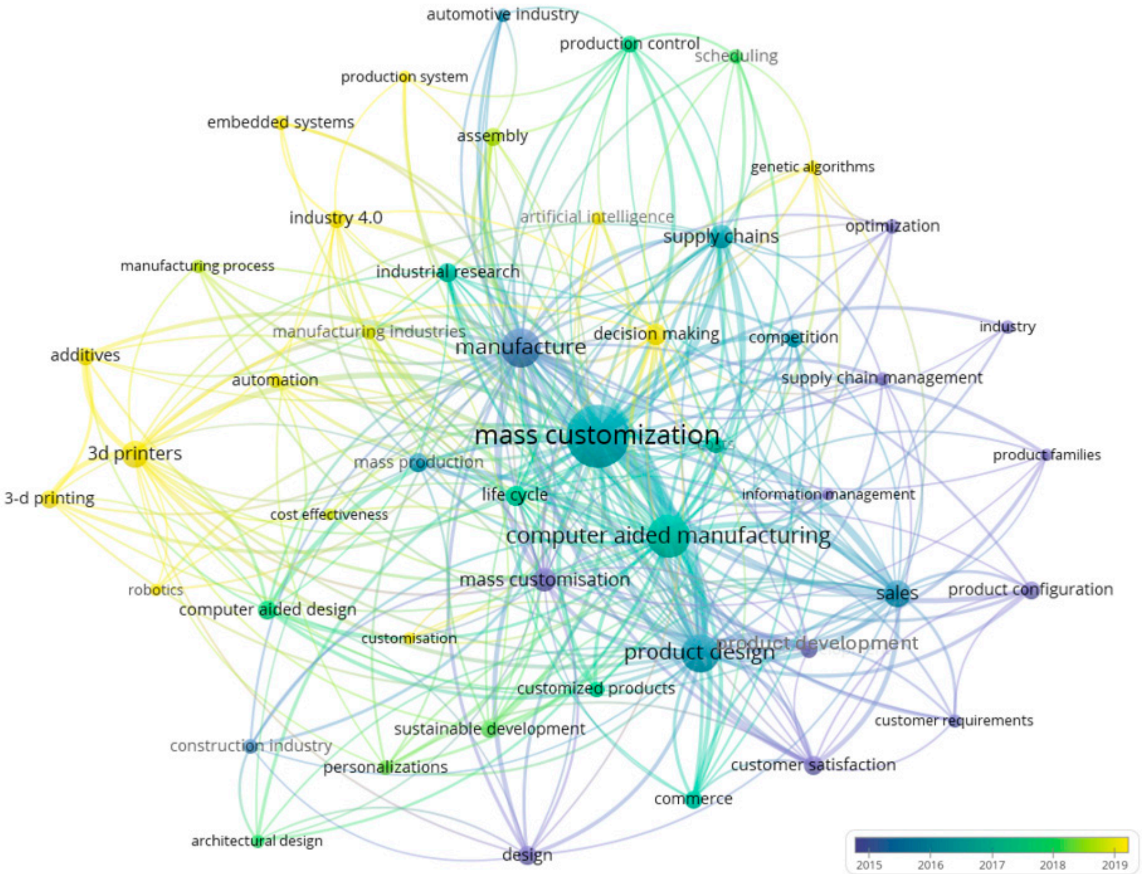

Figure 2. VOSviewer bibliometric analysis of MC related keywords—overlay visualization.

The overlay visualization provided by VOSviewer enabled a temporal analysis of the literature, showing a gradual shift from product configuration and design in the early 2010s toward advanced manufacturing technologies—such as artificial intelligence, additive manufacturing, and cyber-physical systems—in more recent years. This shift reflects the growing integration of MC with I4.0 paradigms.

Moreover, the conceptual network revealed three main research clusters: MC fundamentals and evaluation metrics—addressed by keywords like mass customization and personalizations—enabling technologies and product/process innovation—addressed by keywords like product design and production control—and supply chain strategies and integration patterns—addressed by keywords like supply chain management and production systems. This mapping provided the basis for publication classification into three main research streams (RS1-RS3), which structure the thematic core of this review.

2.2. Literature Classification and Thematic Coding

Each of the 229 selected papers was manually reviewed and assigned to one or more RS based on its primary focus:

- RS1—MC general concepts and metrics: addressing foundational definitions, conceptual distinctions (e.g., customization vs. personalization), and performance evaluation models.

- RS2—MC technologies and methods: focusing on technological and methodological enablers of customization across the product lifecycle. Due to the high number of contributions within RS2, it was further divided into three sub-streams:
  - ○ RS2.1: customer–manufacturer interaction
  - ○ RS2.2: product design methodologies
  - ○ RS2.3: production architecture and manufacturing systems
- RS3—MC and supply chain management: analyzing how MC is implemented and supported within extended and reconfigurable supply chains.

The thematic assignment of each paper was based on a combination of bibliometric clustering (see Figure 2) and qualitative content analysis. Two researchers independently coded the documents based on abstract and full-text content. Classification into research streams (RS1–RS3) was guided by a shared coding framework developed during the review. In case of disagreement, consensus was reached through discussion, with the involvement of a third author when necessary. Although no formal expert workshop was conducted, the classification is supported by both quantitative mapping and a shared interpretative protocol, which ensures conceptual coherence and replicability.

Next, Section 3 analyzes the identified RSs, discussing the main contributions for each of them.

3. Research Stream Analysis

3.1. RS1: MC General Concept and Metrics

Since its initial conceptualization by Davis [6] and Pine [7], the MC concept has evolved from a niche approach into a widely adopted manufacturing strategy [8]. It enables the creation of products, minimizing the gap between what customers ideally want and what is available, by meeting individual needs and preferences while maintaining costs comparable to those of mass-produced goods [27]. This is achieved primarily through modular product/service design, flexible processes, and integration across the supply chain [11]. The core idea of MC is to deliver meaningful customization at a mass scale [1], thus addressing the paradox of offering individualized products at low cost [29].

Salvador and Forza [30] identify three fundamental capabilities required for mass customizers to succeed:

- ✓ solution space development, which involves identifying the dimensions along which customer needs vary;
- ✓ robust process design, which focuses on reusing or recombining existing organizational and value chain resources to meet diverse customer needs efficiently;
- ✓ choice navigation, which supports customers in selecting tailored solutions while minimizing complexity and decision fatigue.

Table 1 reports the classification of literature contributions related to RS1 topics.

Table 1. Classification of the contributions related to RS1.

Author(s)	Year	Personalization Approach	Implementation Context	Performance Evaluation Metrics	Sustainability-Oriented MC
[29]	2011		✓		
[31]	2011	✓			
[32]	2011				✓
[11]	2012	✓			
[33]	2012		✓		
[34]	2012a				✓
[35]	2012b				✓

Table 1. *Cont.*

Author(s)	Year	Personalization Approach	Implementation Context	Performance Evaluation Metrics	Sustainability-Oriented MC
[36]	2012				✓
[37]	2012	✓			
[38]	2013		✓		
[39]	2013	✓			
[1]	2013	✓			
[20]	2013	✓			
[40]	2013				✓
[41]	2013		✓		
[42]	2013				✓
[43]	2013a			✓	
[44]	2013			✓	
[27]	2014	✓			
[45]	2014			✓	
[46]	2014				✓
[47]	2014				✓
[48]	2014				✓
[49]	2014	✓			
[50]	2014			✓	
[51]	2015		✓		
[52]	2015				✓
[53]	2015			✓	✓
[54]	2015				✓
[55]	2015	✓			
[56]	2015		✓		
[57]	2016				✓
[8]	2015		✓		
[58]	2016				✓
[59]	2016			✓	
[60]	2017a			✓	
[61]	2017		✓		
[62]	2017		✓		
[63]	2017	✓			
[64]	2017	✓			
[65]	2017			✓	
[66]	2017			✓	
[67]	2017			✓	
[68]	2018			✓	
[69]	2018			✓	
[70]	2018		✓		
[71]	2018			✓	
[72]	2019	✓			
[73]	2019		✓		
[74]	2019		✓		✓
[75]	2019	✓			
[76]	2019			✓	
[77]	2020				✓
[78]	2020		✓		
[79]	2020		✓		
[80]	2020				✓
[81]	2020			✓	
[82]	2021			✓	
[83]	2022				✓
[84]	2023	✓			

Table 1. *Cont.*

Author(s)	Year	Personalization Approach	Implementation Context	Performance Evaluation Metrics	Sustainability-Oriented MC
[85]	2023				✓
[86]	2023	✓			
[87]	2024			✓	✓
	63	15	14	17	20

The reviewed contributions under RS1 converge on the conceptual evolution of MC as a manufacturing and business paradigm grounded in data-driven personalization, strategic flexibility, and performance alignment. A foundational distinction is made between customization and personalization: while both aim to deliver tailored offerings at scale, they differ in scope and data dependency. Customization, deeply rooted in operations management and engineering, leverages explicit customer input through predefined configuration options [20,31]. In contrast, personalization—more prevalent in communication and health sciences—relies on implicit data, such as user behavior and preferences, to predict latent needs [49,55]. Several authors position personalization as a more advanced stage of MC, addressing the "market of one" through AI-driven systems, dynamic profiling, and feedback loops enabled by I4.0 technologies like IoT, CPS, and RFID [64,75]. This shift is not merely technological: it reflects a deeper transformation in how firms conceptualize value co-creation with customers [1,72].

At an implementation level, studies investigate MC maturity across contexts—from engineer-to-order (ETO) systems [62] to SMEs [33] and service sectors [41]. Organizational readiness, managerial capability, and integration between design and manufacturing are identified as critical enablers [51,74].

Performance measurement is another core theme. Drawing on Salvador and Forza's [30] conceptualization of MC capabilities—solution space development, robust process design, and choice navigation—various metrics have been proposed. These range from configurability indexes [43,45] to intellectual capital indicators [67] and leadership-related variables [71,76]. Complexity-related metrics focus on assessing product variety, architecture, and design constraints [59,81].

Sustainability is increasingly integrated into MC performance evaluation. Studies adopt the triple bottom line (TBL) framework to assess environmental, social, and economic dimensions [32,77]. Contributions explore how MC can reduce waste, extend product lifecycles, and enable modular reuse [52,57]. More recent works classify sustainability impacts across the product lifecycle, particularly under the influence of digital technologies [48,85]. The integration of I4.0 further enhances the synergy between customization and sustainability. By embedding real-time data, intelligent sensing, and autonomous decision making, digital MC environments can optimize resource usage while increasing customer satisfaction [81,83]. This convergence is crystallizing into a new paradigm: Sustainable Mass Customization 4.0, where personalization, efficiency, and sustainability are co-optimized within smart manufacturing ecosystems.

3.2. RS2: MC Technologies and Methods

The second research stream collects papers proposing practical technologies and methods, useful to manage variety in different phases of the product lifecycle, from the customer demand collection, through the design of product variants, to the final product manufacturing. These three main phases are used to further classify the papers belonging to RS2, constituting three sub-streams:

RS2.1: MC technologies and methods for customer–manufacturer interaction
RS2.2: MC technologies and methods for product design
RS2.3: MC technologies and methods for production architecture

3.2.1. RS2.1: MC Technologies and Methods for Customer–Manufacturer Interaction

The 26 papers falling into this sub-stream, reported in Table 2, concern the possible methodologies used by companies to predict or identify customer requirements, supporting customer integration in the product design phase.

Table 2. Classification of the contributions related to RS2.1.

Author(s)	Year	Customer Co-Design Mechanism	Decision Support Tools for Customers	I4.0 Technologies for Interaction	Customer Preference Prediction Models
[88]	2011			✓	
[89]	2012				✓
[90]	2013	✓	✓		
[91]	2013			✓	
[92]	2013				✓
[93]	2013			✓	
[94]	2013	✓		✓	
[49]	2014	✓			
[95]	2014				✓
[96]	2014		✓		
[97]	2016			✓	✓
[98]	2016			✓	
[57]	2016	✓			
[99]	2017b		✓		
[100]	2017	✓			
[101]	2017			✓	
[63]	2017		✓		
[102]	2018			✓	
[103]	2018				✓
[104]	2020	✓			
[105]	2020	✓		✓	
[106]	2020				✓
[107]	2020	✓			
[84]	2023			✓	
[108]	2024	✓		✓	
[109]	2024		✓		
	26	9	5	11	6

Customer co-design is widely recognized as a key element of MC, considered a distinctive feature [93], a core aspect [57], or even a prerequisite [90] to address individual needs. Hsiao and Chiu [49] emphasize customer involvement through a model structured in four phases: need analysis, service design and modularization, co-creation, and satisfaction evaluation. Similarly, Pallant et al. [107] identify four roles customers may assume in MC processes—co-design, co-production, co-configuration, and co-construction—depending on their level of engagement. Effective customer–manufacturer interaction helps reduce "misfit costs" [104], while co-creation fosters innovation and faster market adaptation [100].

Despite its value, acquiring customer requirements remains one of the most challenging aspects of MC [91]. The complexity of options can overwhelm customers—a problem known as "mass confusion" [63]—while some customers may struggle to articulate their needs. To support decision making and mitigate confusion, recommender systems using data mining, e.g., [90], and mobile apps incorporating AR for product visualization [96,99] have been developed.

Additional tools to capture customer preferences include 3D scanners, augmented reality (AR) viewers, interactive questionnaires, pattern analysis systems, and web configurators [92]. The increasing use of ICT and network technologies enables a shift from in-store to online "screen-to-face" interactions [101]. E-commerce platforms gather user data—such as location, preferences, and purchase behavior—to deliver tailored offerings and recommendations [88,93]. ICT advancements are integrated into knowledge management systems [93] and e-commerce design models supporting MC [101], leading to the emergence of "e-mass customization" [94,98,105].

Predicting trends and preferences through web data is another key area. Saldivar et al. [97] propose a predictive framework combining I4.0 technologies (e.g., IoT, cloud computing, CPS, big data) and digital production systems for customers' needs prediction and consequent selection of optimal product design. Similar approaches include data mining on websites [92], neural networks for behavior prediction [95], and decision support tools for product portfolio optimization [89,103,106].

3.2.2. RS2.2: MC Technologies and Methods for Product Design

As the design phase is generally considered a critical decision factor to the final product form, cost, reliability, and market acceptance, it is believed that MC can be best approached with an up-front effort in the early stages of the product development process [110]. The 45 papers falling in this sub-stream were reviewed to detect technologies and methods used for MC during the product design phase, following and applying the customer requirement data collection and analysis discussed in the previous paragraph, as evident in Yetis and Karakose [111]. The main results are collected in Table 3.

Table 3. Classification of the contributions related to RS2.2.

Author(s)	Year	Design of Product Platforms	Use of Modularity in Product Design	Product Family Architecture	Postponement Strategies in Design	Virtual Prototyping	Rapid Prototyping
[112]	2011	✓		✓			
[113]	2011	✓	✓	✓			
[114]	2011	✓	✓	✓			
[110]	2011	✓	✓	✓			
[115]	2011	✓	✓	✓			
[116]	2012	✓					
[88]	2011		✓		✓		
[117]	2013	✓	✓	✓			
[118]	2013		✓				
[119]	2013	✓	✓	✓			
[92]	2013		✓	✓			
[120]	2014	✓	✓				
[121]	2014	✓	✓	✓			
[122]	2014				✓		
[123]	2014	✓	✓	✓			
[124]	2014		✓	✓			
[125]	2015	✓	✓	✓			
[126]	2015a	✓	✓	✓			
[127]	2015b	✓	✓	✓	✓		
[128]	2015	✓				✓	
[129]	2015		✓				
[130]	2015	✓					
[131]	2016					✓	
[132]	2016		✓				

Table 3. *Cont.*

Author(s)	Year	Design of Product Platforms	Use of Modularity in Product Design	Product Family Architecture	Postponement Strategies in Design	Virtual Prototyping	Rapid Prototyping
[133]	2016	✓					
[14]	2016					✓	✓
[134]	2017	✓	✓	✓			
[135]	2017	✓	✓	✓			
[136]	2017					✓	✓
[102]	2018	✓	✓		✓		
[111]	2018		✓				
[5]	2020	✓		✓	✓		
[137]	2021	✓		✓			
[138]	2021						✓
[139]	2022						✓
[140]	2022						✓
[141]	2023a	✓		✓	✓		
[142]	2023b	✓	✓		✓		
[143]	2023	✓	✓		✓		
[144]	2024a	✓	✓	✓			
[145]	2024b	✓	✓	✓			
[108]	2024					✓	
[146]	2024	✓	✓	✓			
[147]	2024		✓		✓		
	45	28	28	22	9	5	5

The reviewed papers identify five key concepts in product design: product platform design, modular product design, product family architecture, postponement strategies, and virtual and rapid prototyping. Most studies focus on product platforms, which are seen as a central strategy for managing product variety and production efficiency. According to Meyer and Lehnerd [148], a product platform consists of subsystems and interfaces that enable efficient production of derivative products. This approach reduces costs, enhances material selection, and increases flexibility. While traditional platforms are "internal," external platforms, i.e., products, services, or technologies that provide the foundation upon which outside firms can develop their own complementary products, technologies, or services, can also be developed for innovation [123].

Modular product design, highlighted in several studies, is an important enabler of mass customization (MC), offering benefits like flexibility, lower production times, and reduced costs [129,135]. The concepts of product platforms, modularity, and product family architecture are interrelated, with companies often using modular design to maximize the benefits of platform-based strategies [129].

The concept of a product family, defined by Meyer and Lehnerd [148], involves products derived from a common platform but designed to meet specific market needs. Product families and platforms help manage increasing product variety while achieving economies of scale [114,121]. Several papers propose frameworks and methodologies to optimize product family design and platform development, using tools like Pareto optimization and fuzzy cluster analysis [92,110].

Postponement, also known as delayed product differentiation (DPD), is another key strategy for MC. It delays product customization until the latest point in the production flow to balance variety and cost-efficiency [5,122]. This approach reduces complexity and forecasting errors by deferring production decisions until after orders are received.

Some studies integrate modularity with postponement strategies to improve production efficiency [88,127].

Finally, CAD and CAE technologies are essential for virtual prototyping, allowing for design validation before physical prototypes are made. These technologies are crucial for MC and are increasingly enhanced with machine learning and computational intelligence [131]. Additionally, additive manufacturing, particularly 3D printing, is used for rapid prototyping, enabling MC but facing challenges in large-scale production. Research is exploring how to integrate I4.0 technologies to improve additive manufacturing efficiency [14,138].

3.2.3. RS2.3: MC Technologies and Methods for Production Architecture

Traditional production system design focuses on goals like improving productivity, reducing inaccuracies, and minimizing time loss during changeovers. However, in today's competitive environment, manufacturing companies must offer a wider range of personalized products. This shift requires transforming production systems into more flexible and agile setups. According to Haddou Benderbal et al. [149], production systems need to be flexible and responsive to external changes, enabling rapid product introduction without compromising quality or cost. In addition to product design, smart production control concepts are crucial for efficiently implementing MC strategies [14]. Concurrent product-process-supply chain engineering, along with process modularity and group technologies, are identified as key enablers for MC [102]. Next Table 4 proposes a classification of the contributions related to RS2.3.

Table 4. Classification of the contributions related to RS2.3.

Author(s)	Year	Process-Level Postponement Design	Manufacturing Modularity Practices	Advanced Manufacturing Technologies	Production Planning and Scheduling	Smart Technology (I4.0 Enablers)	Human-Robot Collaboration and Interface
[114]	2011	✓					
[88]	2011	✓					
[150]	2011					✓	
[151]	2011				✓		
[152]	2012			✓			
[153]	2012			✓			
[154]	2013						✓
[118]	2013	✓	✓				
[155]	2013			✓			
[92]	2013			✓			
[156]	2014			✓	✓		
[157]	2014				✓	✓	
[122]	2014	✓					
[158]	2014	✓					
[159]	2014		✓				
[160]	2014			✓			
[129]	2015		✓				
[161]	2015			✓		✓	
[162]	2015					✓	
[163]	2016						✓
[164]	2015			✓			
[165]	2015			✓			
[97]	2016					✓	
[14]	2016				✓	✓	
[166]	2016		✓	✓	✓		
[167]	2016						✓
[168]	2016			✓			

Table 4. *Cont.*

Author(s)	Year	Process-Level Postponement Design	Manufacturing Modularity Practices	Advanced Manufacturing Technologies	Production Planning and Scheduling	Smart Technology (I4.0 Enablers)	Human-Robot Collaboration and Interface
[134]	2017				✓		
[169]	2017						✓
[23]	2017					✓	✓
[149]	2018			✓			
[170]	2017			✓			
[171]	2017			✓			
[172]	2017				✓		
[173]	2017					✓	
[174]	2018				✓		
[102]	2018		✓				
[175]	2018			✓			
[176]	2018			✓	✓		✓
[177]	2018			✓			
[178]	2019				✓	✓	
[179]	2019				✓	✓	
[180]	2019			✓			
[181]	2019						✓
[182]	2019			✓	✓		
[183]	2019				✓		
[184]	2020						✓
[185]	2020				✓		
[186]	2020			✓			
[187]	2020					✓	
[188]	2020					✓	
[189]	2021a			✓			
[190]	2021						✓
[191]	2021			✓			
[192]	2021			✓		✓	✓
[193]	2021			✓			
[138]	2021					✓	
[194]	2021			✓		✓	
[195]	2022			✓			
[196]	2022b			✓			
[197]	2022				✓		
[198]	2023			✓		✓	✓
[143]	2023	✓	✓				
[199]	2023					✓	
[200]	2024			✓	✓		✓
[201]	2024			✓		✓	
	66	6	6	30	16	18	12

Product variety refers to the range of products a system offers, which can be managed through product modularity, while process variety concerns the complexity of manufacturing processes, influenced by product variety and alternative processes for each variant. Process modularity is defined as the degree to which production processes are divided into standardized, reconfigurable modules [118]. This modular approach is extended from product to process design, enhancing system flexibility [166]. Shaik et al. [129] further developed modularity principles, focusing on standardization, resequencing, and postponement to improve customization.

Process-level postponement, closely related to modularity, defers specific production steps until customer orders are received, enhancing flexibility [88,114]. Types of postponement include labeling, packaging, assembly, and manufacturing postponement [122].

Advanced manufacturing technology (AMT) refers to modern technologies, including flexible manufacturing systems (FMS), computer integrated manufacturing (CIM), and cyber-physical systems (CPS), to improve productivity, flexibility, and cost efficiency [175,202]. CIM systems evolved into CPS, integrating physical processes with software and global networks, enabling real-time communication and information exchange [150,161]. CPS technology requires multidisciplinary collaboration and is essential in various fields, including manufacturing, healthcare, and autonomous systems [23].

FMS has been critical in achieving high flexibility and low cost in MC, offering systems that can quickly adapt to customer needs [14]. FMS adoption is still prevalent in industries like automotive manufacturing due to its ability to manage high variability with cost efficiency [156]. However, its flexibility is limited by the predefined boundaries of the system [160], leading to the rise of reconfigurable manufacturing systems (RMS), which offer greater adaptability to changing market demands [170]. RMS combines flexibility, modularity, and scalability, making it suitable for high-demand, MC environments [149]. RMS and modular product design are closely linked, with approaches for optimizing product-family configurations and manufacturing systems to handle variable customer demands efficiently [195]. Technologies like IoT and cloud computing enhance the adaptability of RMS and other manufacturing systems by facilitating real-time data exchange and predictive maintenance [23,162].

The advent of I4.0 technologies is transforming manufacturing systems into “smart” factories, where the integration of IoT, CPS, and cloud computing enables dynamic production scheduling and improves system efficiency [184]. These systems also incorporate advanced robotics for flexible automation and human–robot collaboration, which is pivotal for future manufacturing flexibility and customization [167,176] towards the establishment of the Industry 5.0 paradigm [198].

Despite high automation levels in systems like RMS, human involvement remains crucial, especially in areas like material handling and tool setup. Human–robot interaction is being enhanced with intelligent systems, such as those using machine learning, computer vision, and collaborative robots, which improve both safety and flexibility [23,190].

3.3. RS3: MC and Supply Chain Management

MC can be addressed as a “chain-based concept” whose success largely depends on the readiness and willingness to cooperate among chain members [203]. In this context, companies need integrated and reconfigurable supply chains to convert materials into individually customized products [92]. Table 5 collects the classification used for the contributions related to this research stream.

Table 5. Classification of the contributions related to RS3.

Author(s)	Year	Link Between Product Architecture and Supply chain	Supply Chain Postponement Strategies	Supplier Integration and Collaboration	End-to-End Process Integration	Supply Network Structure and Reconfigurability
[88]	2011		✓			
[204]	2011			✓		
[205]	2011			✓		✓
[206]	2012			✓	✓	
[207]	2012	✓				
[208]	2012			✓	✓	
[209]	2012	✓				
[118]	2013		✓	✓		
[210]	2013					✓

Table 5. *Cont.*

Author(s)	Year	Link Between Product Architecture and Supply chain	Supply Chain Postponement Strategies	Supplier Integration and Collaboration	End-to-End Process Integration	Supply Network Structure and Reconfigurability
[211]	2013					✓
[92]	2013					✓
[212]	2013	✓		✓	✓	
[213]	2013					✓
[214]	2013					✓
[215]	2015					✓
[216]	2014					✓
[217]	2014			✓		
[122]	2014		✓			
[158]	2014		✓			
[218]	2014					✓
[219]	2014		✓	✓		
[220]	2015					✓
[221]	2014				✓	
[222]	2015	✓				
[130]	2015	✓				
[223]	2015	✓			✓	
[224]	2015			✓		
[225]	2016			✓		
[226]	2016		✓			
[227]	2017	✓			✓	
[228]	2018	✓	✓			
[229]	2018				✓	
[230]	2019					✓
[231]	2019	✓			✓	
[232]	2019		✓			
[233]	2019		✓			✓
[234]	2019				✓	
[235]	2019			✓		
[203]	2023				✓	
[143]	2023		✓	✓	✓	
[236]	2024			✓		✓
	41	9	10	13	11	13

In recent years, the relationship between product architecture design and supply chain design has gained increasing attention [130], with papers exploring the concurrent integration of product and supply chain optimization. According to Baud-Lavigne et al. [207], this integration faces two main barriers: first, while it is well established that product design significantly impacts manufacturing and logistics, there is a lack of research on the reverse relationship, i.e., the impact of supply chain modeling on the product design phase. Second, adding new decision variables related to product architecture increases the complexity of supply chain design problems. Pashaei and Olhager [222] also highlight the limited work done on decision support models for concurrent supply chain and product design, and as noted by Nepal et al. [209], the type of product architecture ultimately influences supply chain configuration. Studies by Nepal et al. [209], Shou et al. [227], and Pashaei and Olhager [222] link various aspects of product architecture to supply chain characteristics, including modularity and product platform strategy.

Xiong et al. [228] and Weskamp et al. [233] integrate decisions regarding modular product platforming (MPP) with global production and distribution planning, considering the importance of the postponement strategy in the supply chain, which helps optimize decisions related to costs and supply chain configurations. Postponement is a key strategy in supply chain management, enabling reduced inventories and improved customer satisfaction [88]. Van Hoek [237] and Li et al. [238] define postponement as the delay of certain activities in the supply chain until customer orders are received, improving overall efficiency and lowering operational costs.

Collaboration among supply chain partners is crucial for the successful implementation of a postponement strategy, and some authors emphasize the importance of strong integration between partners to effectively manage resources. Supplier integration, as highlighted by Lai et al. [208], is essential for managing intra- and inter-organizational relationships in the supply chain, while other studies explore the impact of sourcing policies and flexibility strategies on inventory management [205,217]. Quality in the supply chain is another important topic, with the concept of "supply chain quality integration" (SCQI) emphasizing collaboration to effectively manage quality-related relationships [231,234].

Efficiency in manufacturing supply chain network design and planning is addressed by several studies [205,213], while the importance of transparency in information and coordination between partners to improve MC capability is discussed by Yinan et al. [218]. Other studies, such as those by Shao [211] and Kim [122], explore the impact of centralized/decentralized supply chain configurations and channel design on business performance, as well as the importance of reverse logistics for managing residual inventories [230].

4. Key Outcomes and Discussion

The review reveals several significant findings that shape the current understanding and future development of MC:

- ✓ Evolution and maturity of MC: MC has evolved from a niche concept to a mainstream production strategy, enabled by digitalization and I4.0. The convergence of customization with technologies such as CPS, IoT, and AI marks a shift from traditional modularity-based approaches to real-time, data-driven customization paradigms.
- ✓ Three major research streams identified around three key domains:
  - ○ RS1—MC general concepts and metrics: focusing on MC definitions, strategic principles, and performance measurement, including sustainability metrics.
  - ○ RS2—MC technologies and methods: covering enablers such as product configurators, modular product design, and flexible production systems; structured into three sub-streams—customer interaction, product design, and production architecture.
  - ○ RS3—MC and supply chain management: emphasizing supply chain agility, integration, postponement strategies, and supplier collaboration as key to supporting MC systems.
- ✓ Technological enablers and integration: enabling technologies such as product configurators, recommender systems, additive manufacturing, and digital twins play a pivotal role in making MC feasible and scalable. Their integration is essential to overcoming the operational complexity introduced by high product variety and dynamic customer preferences.
- ✓ Customer involvement and co-design: a recurring theme in the literature is the centrality of customer involvement. Co-design, co-creation, and preference elicitation are key to ensuring that customized offerings deliver value. Tools such as AR, mobile interfaces, and interactive web platforms are widely used to support this involvement and reduce decision fatigue or "mass confusion".
- ✓ Barriers to adoption: despite its advantages, MC implementation is hindered by multiple challenges. These include high initial costs, lack of integration with legacy systems,

difficulties in managing real-time data, and low digital readiness—particularly in SMEs. Moreover, aligning the customization strategy across product, process, and supply chain levels remains a complex endeavor.

- ✓ Sustainability considerations: MC holds potential for environmental and economic sustainability through reduction in overproduction, minimized waste, and localized manufacturing. However, the operationalization of sustainability in MC environments is still in its infancy, with limited standardized metrics and few empirical validations.
- ✓ Shift toward personalization: A growing body of literature suggests that MC is transitioning toward "mass personalization," where AI-driven systems and real-time customer data are used to anticipate needs and deliver one-to-one tailored experiences. This paradigm shift implies a more granular, flexible, and intelligent MC framework aligned with the principles of I4.0.

4.1. Enablers and Barriers in the Implementation of Mass Customization

The effectiveness of MC strategies depends on the interaction between facilitating factors and implementation constraints. The following overview consolidates these two perspectives to provide a balanced understanding.

Enablers of MC

- ✓ Product modularity and platform strategies: modular product architectures and shared platforms support the creation of product variants without excessive complexity. These design strategies enable flexibility and scale economies.
- ✓ Advanced manufacturing technologies: technologies such as additive manufacturing, flexible manufacturing systems (FMS), reconfigurable manufacturing systems (RMS), and CPS enable agile production of customized products with minimal downtime and reconfiguration costs.
- ✓ Customer integration tools: co-design platforms, web configurators, and recommender systems facilitate active customer participation, helping translate individual preferences into feasible product configurations.
- ✓ Postponement and process modularity: delayed product differentiation (DPD) and modular production lines allow final customization to occur at later production stages, reducing inventory and operational uncertainty.
- ✓ Supply chain reconfigurability: agile supply chains enabled by real-time data exchange and collaborative planning allow rapid adaptation to customer orders and enhance service levels.
- ✓ Sustainability-oriented design: modular design and localized production reduce environmental impact. MC aligns well with circular economy principles by enabling repairability, reuse, and resource optimization.

Barriers to MC

- ✓ High initial costs and investment risks: developing modular architectures, acquiring new manufacturing technologies, and integrating ICT systems often require significant capital and organizational transformation.
- ✓ Data and IT integration challenges: many companies struggle with poor interoperability between systems, fragmented customer data, and cybersecurity concerns. These issues limit the capacity to automate and personalize effectively.
- ✓ Organizational complexity and resistance: MC demands cross-functional integration and cultural change, which may be resisted by staff and management. Legacy processes and siloed departments can obstruct implementation.
- ✓ Customer-related constraints: despite technological tools, many customers find customization processes confusing or time consuming. Poorly designed interfaces can reduce engagement and lead to suboptimal configurations.

- ✓ Rigid supply chains: traditional supply chains may not accommodate high-variety, low-volume production. Without flexibility in procurement, manufacturing, and distribution, the benefits of MC are diluted.
- ✓ Lack of standardized evaluation metrics: the absence of commonly accepted KPIs makes it difficult to assess MC success consistently across industries or compare alternative approaches.

Despite their enabling role, several I4.0 technologies face significant implementation challenges. AI-based systems require large, high-quality datasets and may raise concerns about transparency, explainability, and bias. IoT devices introduce new cybersecurity and data privacy vulnerabilities, while CPS and advanced analytics involve substantial infrastructure investment and skilled personnel. These limitations may hinder adoption, especially among SMEs or in environments with legacy systems. Moreover, the integration of these technologies often requires deep organizational change and cross-functional coordination, which can create resistance or inertia within firms.

4.2. Limitations of the Analysis

While this review follows PRISMA guidelines and uses both bibliometric and qualitative synthesis methods, some limitations must be acknowledged. First, the literature search was limited to the Scopus database and based on a single keyword (“mass customization”), which may have excluded relevant studies using alternative terminology. Second, although inclusion/exclusion criteria were systematically applied, the thematic classification relied on interpretive coding, which may introduce subjectivity despite being conducted by multiple reviewers. Third, the bibliometric clustering provided a valuable foundation but may oversimplify conceptual nuances. Finally, the rapid evolution of Industry 4.0 means that the literature is still emerging, and findings may be time sensitive or biased toward recent publications. These methodological boundaries should be considered when interpreting the scope and generalizability of the results.

5. Summary and Future Research

This review provides a comprehensive synthesis of the academic literature on mass customization (MC), mapping its conceptual foundations, technological enablers, and implementation challenges. It confirms that MC has become a central pillar of modern manufacturing strategy, increasingly supported by digital and intelligent systems.

However, several areas remain underexplored or insufficiently validated, paving the way for a future research agenda and open areas:

- ✓ Empirical testing and industrial validation: while conceptual models and frameworks are abundant, empirical studies demonstrating real-world MC implementation across diverse sectors, especially SMEs, are still limited. Future research should prioritize case-based and longitudinal studies to validate MC effectiveness.
- ✓ Integration with digital twin and predictive analytics: the application of digital twins and AI-based predictive tools in MC environments offers promising avenues for real-time customization and operational optimization. Research should explore how these technologies can close the gap between customer intent and production reality.
- ✓ Sustainability-oriented MC models: the dual pursuit of customization and sustainability calls for novel frameworks that quantify trade-offs and synergies across the product lifecycle. Metrics assessing environmental, economic, and social impacts of MC should be further developed and standardized.
- ✓ Human-centered MC: as automation increases, the human factor remains critical—particularly in co-design, configuration interface usability, and decision-making sup-

port. Interdisciplinary studies that blend design thinking, cognitive ergonomics, and MC technology are needed to enhance user experience and system adoption.

- ✓ Supply chain reconfigurability: the dynamic nature of personalized production requires agile and reconfigurable supply chains. Research should delve into decentralized and platform-based supply networks that can adapt rapidly to fluctuating demand without compromising efficiency or cost-effectiveness.

In summary, MC is at a pivotal point. To fully realize its potential, future studies must move beyond theoretical exploration to offer actionable insights and validated frameworks that align technological, organizational, and customer-centric dimensions.

Author Contributions: Conceptualization, L.D.N., F.G.G. and M.B.; methodology, L.D.N., F.G.G. and M.G.; formal analysis, L.D.N. and F.G.G.; investigation, L.D.N. and M.B.; data curation, L.D.N. and M.G.; writing—original draft preparation, L.D.N. and M.G.; writing—review and editing, F.G.G., M.B. and E.F.; supervision, F.G.G., M.B. and E.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

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