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Mass customization: Literature review and research directions

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Abstract

Mass customization relates to the ability to provide individually designed products and services to every customer through high process flexibility and integration. Mass customization has been identified as a competitive strategy by an increasing number of companies. This paper surveys the literature on mass customization. Enablers to mass customization and their impact on the development of production systems are discussed in length. Approaches to implementing mass customization are compiled and classified. Future research directions are outlined.

Keywords: Mass customization; Customer-driven manufacturing; User involvement; Agile manufacturing

1. Introduction

Mass customization relates to the ability to provide customized products or services through flexible processes in high volumes and at reasonably low costs. The concept has emerged in the late 1980s and may be viewed as a natural follow up to processes that have become increasingly flexible and optimized regarding quality and costs. In addition, mass customization appears as an alternative to differentiate companies in a highly competitive and segmented market.

In this paper, we present a literature review on mass customization (MC). Our main objective is to provide a framework to understand the several developments that emerged in the literature in the past 10 years. We also point to future research directions, based on the current state-of-the-art of the subject. In view of the expanding number of articles and books dealing with MC, there is clear need for a research agenda developed based on existing gaps in the study of MC.

We developed a framework for presenting a survey where MC is deployed from concept to practice in four sections. We start by conceptualizing MC. We want to explore the extent at which theoretical MC concepts describe a production strategy that may be indeed pursued in practice. We then look at the different levels at which MC may be implemented. In other words, we classify levels of individualization that may be provided to customers. After, we move to more applied matters, listing a number of factors that, according to several authors, may lead to a successful implementation of MC. Finally, we discuss in length the enabling

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processes and methodologies to MC implementation.

There are two main contributions here. First, this article presents a comprehensive guide that should help researchers to screen the vast MC literature in search of references on specific topics. Through a structured framework, seemingly unconnected aspects of MC are brought together and explored in enough detail to provide a useful introduction to the subject. Second, we set a research agenda covering a variety of important and unexplored facets of MC that should motivate both academics and practitioners to further explore the subject. Despite the increasing attention it has been receiving in the literature, MC is still a novel concept lacking more extensive development. While there is little contention on theoretical aspects such as the MC concept, objectives and justification, the debate over more specific and often practical questions remain somewhat inconclusive.

2. Mass customization concept

Mass customization (MC) can be defined either broadly or narrowly. The broad, visionary concept was first coined by Davis [1] and promotes MC as the ability to provide individually designed products and services to every customer through high process agility, flexibility and integration [2–4]. MC systems may thus reach customers as in the mass market economy but treat them individually as in the pre-industrial economies [1]. MC systems are positioned below the main diagonal of Hayes and Wheelwright's [5] product–process matrix, i.e. having medium to high-volume process types such as manufacturing cells or assembly lines that are able to deliver the high product varieties usually associated to functional or fixed-type operations.

Many authors propose similar but narrower, more practical concepts. They define MC as a system that uses information technology, flexible processes, and organizational structures to deliver a wide range of products and services that meet specific needs of individual customers (often defined by a series of options), at a cost near that of mass-produced items [4,6–9]. In any case, MC is seen as a systemic idea involving all aspects of product sale, development, production, and delivery, full-circle from the customer option up to receiving the finished product [6,10].

The justification for the development of MC systems is based on three main ideas [4,7,11,12]. First, new flexible manufacturing and information technologies enable production systems to deliver higher variety at lower cost. Second, there is an increasing demand for product variety and customization (according to Kotler [13], even segmented markets are now too broad as they no longer permit developing niche strategies). Finally, the shortening of product life cycles and expanding industrial competition has led to the breakdown of many mass industries, increasing the need for production strategies focused on individual customers.

3. Levels of mass customization

Determining the level of individualization characterizing truly mass-customized products seems to be a major point of contention in the MC debate. Purists may attribute the MC concept only to products that contemplate all requirements made by individual customers. Pragmatists suggest MC to be simply about delivering products following customer options, independent of the number of options actually offered. According to Hart [4] the solution for this contention lies in careful determination of the range in which a product or service can be meaningfully customized, and how individuals make options upon this range. To Westbrook and Williamson [14] successful MC systems should be able to mix true individualization with high part variety and standardized processes.

Several authors [15,16] propose a continuous framework upon which MC may be developed; namely, MC can occur at various points along the value chain, ranging from the simple "adaptation" of delivered products by customers themselves, up to the total customization of product sale, design, fabrication, assembly, and delivery. Gilmore and Pine [16] identify four customization levels based mostly on empirical observation: collaborative (designers dialogue with customers), adaptive (standard products can be altered by customers during use), cosmetic (standard products are packaged specially for each customer), and transparent (products are adapted to individual needs). Lampel and Mintzberg [15] define a continuum of five MC strategies (and therefore levels) involving different configurations of process (from standard to customized), product (from commodities to unique) and customer transaction (from generic to personalized). A recent study provided empirical evidence of these levels [17]. Pine [12] suggests five stages of modular production: customized services (standard products are tailored by people in marketing and delivery before they reach customers), embedded customization (standard products can be altered by customers during use), point-of-delivery customization (additional custom work can be done at the point of sale), providing quick response (short time delivery of products), and modular production (standard components can be configured in a wide variety of products and services). Spira [18] develops a similar framework with four types of customization: customized packaging, customized services, additional custom work, and modular assembly. The combination of these frameworks leads to eight generic levels of MC, ranging from pure customization (individually designed products) to pure standardization; these levels are presented in Table 1.

Design is the top level in Table 1 and refers to collaborative project, manufacturing and delivery of products according to individual customer preferences (e.g. residential architecture [15]). Level 7 (fabrication) refers to manufacturing of customer-tailored products following basic, predefined designs (e.g. Motorola's Bandit pager [3]). Level 6 (assembly) deals with the arranging of modular components into different configurations according to customer orders (e.g. Hewlett-Packard products [19]). In levels 5 and 4, MC is achieved by simply adding custom work (e.g. Ikea's furniture [1]) or services (e.g. Burger King's hamburgers [1]) to standard products, often at the point of delivery. In level 3, MC is provided by distributing or packaging similar products in different ways using, for example, different box sizes according to specific market segments (e.g. Wal-Mart's peanuts [16]). In level 2, MC occurs only after delivery, through products that can be

Table 1
Generic levels of mass customization

MC generic levels	MC approaches [16]	MC strategies [15]	Stages of MC [12]	Types of customization [18]
8. Design	Collaborative; transparent	Pure customization		
7. Fabrication		Tailored customization		
6. Assembly		Customized standardization	Modular production	Assembling standard components into unique configurations
5. Additional custom work			Point of delivery customization	Performing additional custom work
4. Additional services			Customized services; providing quick response	Providing additional services
3. Package and distribution	Cosmetic	Segmented standardization		Customizing packaging
2. Usage	Adaptive		Embedded customization	
1. Standardization		Pure standardization		

adapted to different functions or situations (e.g. Lutron's lighting systems [16]). Finally, level 1 refers to Lampel and Mintzberg's [15] pure standardization, a strategy that can still be useful in many industrial segments.

4. Success factors of mass customization systems

The success of MC systems depends on a series of external and internal factors. The existence of these factors justifies the use of MC as a competitive strategy and supports the development of MC systems. The six factors most commonly emphasized in the literature are presented next. Factors 1 and 2 are primarily market-related factors. Factors 3–6 are primarily organization-based factors.

1. *Customer demand for variety and customization must exist*. The need to deal with increasing customer demand for innovative and customized products is the fundamental justification for MC [2,20,21]. The success of MC depends on the balance between, on the one hand, the potential sacrifice that customers make for MC products (i.e. how much they will pay and wait for the delivery of mass-customized products [21,22]) and, on the other hand, the company's ability to produce and deliver individualized products within an acceptable time and cost frame.
2. *Market conditions must be appropriate*. According to Kotha [7], a company's ability to transform MC potential into actual competitive advantage greatly depends on the timing of this development. In other words, being the first to develop an MC system can provide substantial advantage over competitors, since the company may get well entrenched in this position, and start being seen by people as innovative and customer-driven.
3. *Value chain should be ready*. MC is a value chain-based concept. Its success depends on the willingness and readiness of suppliers, distributors, and retailers to attend to the system's demands. The supply network must be at close proximity to the company to deliver raw materials efficiently [19,21]. Most important, manufacturers, retailers, and other value chain entities must be part of an efficiently linked information network [21,23–25].
4. *Technology must be available*. The implementation of advanced manufacturing technologies (AMTs) is fundamental to enable the development of MC systems [2,20,21,26,27]. One could argue that the very concept of MC appeared only after some companies were able to successfully integrate a series of information and process flexibility technologies. MC is one of the best opportunities offered by coordinated implementation of AMTs and information technology (IT) across the value chain.
5. *Products should be customizable*. Independent units that can be assembled into different forms compose a modular product [19]. Successful MC products must be modularized, versatile, and constantly renewed. Although modularity is not the fundamental characteristic of MC (true MC products are individually made), it enables simpler and lower-cost manufacturing of products with similar effectiveness if compared to true customization. Also, MC processes need rapid product development and innovation capabilities due to typical short life cycles presented by MC products [2,20].
6. *Knowledge must be shared*. MC is a dynamic strategy and depends on the ability to translate new customer demands into new products and services. To achieve that, companies must pursue a culture that emphasizes knowledge creation and distribution across the value chain. That requires the development of dynamic networks [2] along with manufacturing and engineering expertise [28], and in-house development of new product and process technologies [7].

These factors have direct practical implications. First, they corroborate the idea that MC is not every company's best strategy, for it must conform to specific market and customer types. Second, they assert the complexity involved in MC implementation. In other words, MC implementation involves major aspects of operations including product configuration, value chain network, process and information technology, and the development of a knowledge-based organizational structure.

Table 2
MC enablers and related success factors

Enablers	Related success factors (organization-based)
Processes and methodologies	
Agile manufacturing	Knowledge
Supply chain management	Value chain
Customer-driven design and manufacturing	Customizable products
Lean manufacturing	Value chain
Enabling technologies	
Advanced manufacturing technologies	Technology, customizable products
Communication and networks	Technology, knowledge

5. Enablers of mass customization implementation

MC enablers are the methodologies and technologies that support the development of the organization-based factors (i.e. factors from 3 to 6) described above (Table 2). This section is divided in three subsections discussing (i) processes and methodologies enabling MC, (ii) technologies enabling MC and (iii) how technologies support information transfer, that is perhaps the major implementation problem with MC.

5.1. MC processes and methodologies

MC processes and methodologies address the organizational and cultural aspects of implementing an MC system. They concern the main elements of a manufacturing strategy supporting the development of successful MC systems, capable of providing the elements cited in the previous section. Analysis of the literature points to the existence of at least four main business practices relating to the MC concept: agile manufacturing [29,30], supply chain management [3,31], customer-driven design and manufacture [1,7,18], and lean manufacturing [32,33].

Agile manufacturing has been defined as the ability to thrive and prosper in a competitive environment of continuous and unanticipated change to respond quickly to rapidly changing markets driven by customer-based valuing of products [34]. Agile manufacturing is characterized by the conscious usage of a changing environment as a means to be profitable. While a flexible manufacturer is characterized by a reactive adaptation behavior (waiting for a change to occur to act), an agile manufacturer has a proactive behavior [35]. DeVor et al. [36] identify the main strategic dimensions of agile manufacturing as (i) value-based strategies that enrich customers, focusing on delivering value; (ii) cooperating to enhance competitiveness; (iii) organizing to master change and uncertainty; (iv) leveraging the impact of people and information.

These dimensions lead to the concept of internal and external agility [30]. Internal agility may be viewed as the ability to quickly respond to market and customer demands for new products and product features. That requires re-programmable, re-configurable and continuously changeable production systems able to operate economically with very small lot sizes [37]. Researchers have also discussed the cultural aspects associated with agility. Owen and Kruse [30], for example, point out that a true learning organization is necessary for agility to succeed.

External agility is associated with the idea of virtual enterprises [38–40]. A virtual enterprise consists of several individual companies linked in a collaborative effort to design high-quality and customized products [41]. Virtual organizations have the following main characteristics [40]: product orientation, team-collaboration style, short-term relationships between individuals, speed, and flexibility. This organizational model is enabled by the availability of sophisticated information technologies and telecommunication systems [42].

Supply chain management concerns the co-ordination of resources and the optimization of activities across the value chain to obtain competitive advantages [43]. As previously discussed, efficient supply chain management is one of the key success factors in systems. Eastwood [3], Feitzinger and Lee [19], Lau [20], Kotha [7], and Moad [44] describe how improving supply management provides organizational coordination required in MC systems. Such conditions include: (i) development of an interconnected information network involving a selected group of trained suppliers; (ii) successful balance of low stocks with high delivery service; (iii) design of innovative products with active collaboration of suppliers; and (iv) cost-effective delivery of the right product to the right customer at the right time.

Customer-driven design and manufacture is in the core of MC systems. Jagdev and Browne [37] define this business practice as "to actively consider the market trends in general and individual customer requirements in particular during the design, manufacturing and delivery of the products". Some authors call this practice "One-of-a-Kind Production" (OKP [45]). The application of customer-driven practices in MC systems aims fundamentally at (i) providing conditions for the customer to initiate the design process of a product, and (ii) building an infrastructure to develop new products driven by the market. The number of different product variants (Bally Engineered Structures, Inc., for example, have about 100,000 items in catalogue [46]) is a consequence of implementing customer-driven ideas. Section 6.2 describes a sequence of steps to establish a consumer–manufacturer communication link within the consumer-driven design and manufacture principles.

Lean manufacturing is an efficient way to satisfy customer needs while giving producers a competitive edge [47]. The MC production addresses four elements of lean production: product development, the chain of supply, shop floor management, and after-sales services [48]. For a successful implementation of an MC production system, it is essential (i) to define value based on the customer, (ii) to concentrate in the activities that create value and to eliminate all wastes, in all production steps, and, finally, (iii) to reorganize the value-creating activities into efficient processes, without interruptions and incorporating production variant at high levels.

5.2. MC enabling technologies

Main enabling technologies supporting MC are AMTs, such as computer numeric control (CNC) and flexible manufacturing systems (FMS), and communication and network technologies such as computer-aided design (CAD), computer-aided manufacturing (CAM), computer integrated manufacturing (CIM), and electronic data interchange (EDI) [26,27,49]. As previously mentioned, many researchers [2,7] consider such technologies fundamental to MC implementation.

The use of AMTs is justified by their inherent capability to alter the economies of manufacturing and remove barriers to product variety and flexibility [50]. These technologies enable the development of factories that can exploit the benefits of such fundamental MC attributes as agility and flexibility.

Case examples such as the NBIC [7], Motorola [3], and Perkins [51] stress the important role of AMT in MC system development. NBIC employed CAD/CAM, advanced computer-controlled machines, and robots in implementing their MC manufacturing system. Motorola used CIM-related technologies (such as Cartesian and gantry robots) to implement two MC factories. Perkins based their MC system on a hybrid CAD/CAE (computer-aided engineering) system with flexible manufacturing assembly lines.

The main motivation behind the extensive use of communications and networks based on information technology is to provide direct links between work-groups (e.g. design, analysis, manufacturing, and testing), and to improve the response time to customer requirements. The communication and network technologies are tools to integrate previously isolated components of a productive chain into coherent and coordinated competitive weapons.

Bally [46] and Betchel [50] are examples of the use of intensive information technology to implement MC concepts. Bally employed advanced information technology, based on artificial intelligence methods, to move from CIM to CDIN, a computer-driven intelligence network; this system links their sales representatives and suppliers in one single information network. Betchel developed an advanced information system consisting of an integrated collection of engineering, procurement, construction, and project management software modules.

5.3. *Enabling technologies at work: Information transfer*

The efficiency in information transfer from customers to manufacturers determines largely the success of an MC program [42]. In MC programs, customer demands regarding a product are captured and transmitted to a production unit, where a product tailored to meet those demands is manufactured. Agents of information transfer are the manufacturer and its customers. The manufacturer defines to what extent customers may customize their order; customers feed back the information on their choice of design elements. The customer–manufacturer interface is uniquely defined according to the company developing and implementing an MC program. The following sequence of steps attempts at describing activities involved in establishing a customer–manufacturer communication link: (i) defining a catalogue of options to be offered to customers; (ii) collecting and storing information on customer choices; (iii) transferring data from retail to manufacturer; and (iv) translating customer choices into product design features and manufacturing instructions.

The degree at which products are customized (see the discussion on MC levels above) is unlikely to exclude any of the steps above; it defines, however, the volume of information transferred in each step. In the following paragraphs, a literature survey on customer involvement in MC is presented using the four steps above as guidelines.

Step 1 – Defining a catalogue of options to be offered to customers. The catalogue of options offered to customers defines the degree of customization of a product. Highly customized products present extensive catalogue of options, covering most of their relevant features. Medium- and low-customized products offer choices that are more restricted to customers. Some products are offered in models developed based on the analysis of customer's past demands. In other words, customer may choose from several pre-determined models with design features likely to match their needs. This corresponds to a very low degree of customization, in which customer interaction in the product design is indirect. Table 3 lists examples for these customization options. It is important to note that the offer of choices, although essentially customer driven, must be coherent with the manufacturer's technological development [52].

Step 2 – Collecting and storing information on customer choices. There is no prolific literature on the collection and storage of information from customers. As expected, approaches for data collection are developed to attend specific MC situations. Data on customer choices may be gathered by a store employee or sales representative trained to guide him or her through the decision process [1,18,21,46,53,54], or may be collected using a computer interface with minimum human interference [16]. In other situations, customer and designer jointly develop a project from scratch [1,55]. In any case, it is implicit that customers must be offered an easy-to-handle set of options to select. Information is commonly stored on order sheets [21] or electronically, using a computer system [1,16,18,46,53]. Genetic algorithms and autonomous agents are also presented as facilitators in the data acquisition process [56].

Step 3 – Transferring data from store to manufacturer. In all reported cases, orders are sent from store to manufacturer by FAX [21,46] or computer link [1,16,18,53]. More recent cases present the Internet as a means to link store to manufacturing, e.g. automobile (Fiat, Pontiac), and textile industries (Levi's). Information on customer preferences are then entered in a computer system that generates a product ID, such as a bar code, used to track the product throughout the manufacturing stages.

Step 4 – Translating customer choices into product design features and manufacturing instructions. In most reported cases, specifications on design elements are fed into CAD and CAM systems and then converted into production instructions [7,18,57]. It is evident that the success of MC implementations is heavily dependent on the existence

Table 3
MC examples and their main information-handling characteristics

Product	Translating customer choice	Data transfer	Data storing	Data gathering	Catalogue of options
Cable control system	—	—	—	—	High
Diesel engines	—	—	—	—	High
Printers	Forecasting	—	—	—	Low
Bicycles	CAD/CAM	FAX	Order sheet	Store employee	High
Refrigeration system	CAD	FAX	Comp. interface	Sales rep.	Low
Computers	Forecasting	Computer	Comp. interface	Sales rep.	Low
Lighting controls	CAD/CAM	Computer	Comp. interface	Sales rep.	High
Insurance	—	—	—	Sales rep.	Low
Power generator	CAD/CAM	—	—	—	Low
Houses	CAD/CAM	Computer	Comp. interface	Sales rep.	Low
Eyeglasses	—	—	Comp. interface	Store employee/ computer	High
Shoes	CAD/CAM	Computer	Comp. interface	Store employee/ computer	Medium
Pagers	CAD/CAM	—	—	—	High

of a computerized manufacturing environment. Therefore, CAD and CAM systems are key when attempting any MC strategy. This is expected since, in essence, MC relies on flexibility and quick responsiveness. CAD systems allow customer-driven design changes to be implemented and deployed into production instructions in due time; CAM systems handle the diversity of parts ordering while maximizing machine use.

Table 3 lists examples of mass-customized product along with their main information-handling characteristics.

6. Research agenda

Future research on MC should focus on the formulation of methodologies that enable rapid reconfiguration of existing organizational structures and processes into a mass-customized production system. In this sense, further developments in MC research tend to point towards more applied issues.

6.1. Customization level assessment

As seen earlier, the literature provides a series of frameworks describing different levels of customization that may be adopted in practice [12,15,18]. However, these studies do not provide enough knowledge on how to determine the appropriate level of customization for a specific product or service. High-level customization involves significant competitive benefits but also operational costs. Determining the right level of customization depends on appropriate analysis of customer requirements and existing operational capabilities.

An important contribution to the MC literature could come in the form of a methodology for determining the appropriate level of MC for a product or service, e.g. customized design, fabrication, or assembly. Such methodology would most likely address three important problems: (a) measuring the value customers provide to a level of customization, (b) measuring the system's ability to deliver a level of customization, and (c) comparing and combining these seemingly conflicting measures.

One idea is to forge that methodology from earlier methods such as quality function deployment (QFD [58]) and the importance–performance matrix (IPM [59]). QFD in conjunction with suitable sample survey techniques could be used to identify and rank customizable features in products and services that could potentially meet customers' demand. IPM in conjunction with selected flexibility indices [60] may be used in measuring the ability to deliver the required level of customization.

Development of such methodology requires (i) exploratory, case-based research to identify the main issues involved with assessing customer requirements and process capabilities relating to customization and (ii) theoretical or action research to propose and validate such a methodology

6.2. Mass customization in services

The lack of studies dealing with MC in service operations is perhaps one of the main gaps in the current MC literature. The existing research is still largely focused on manufacturing operations, specially batch industries. Table 3 provided a summary of examples of mass-customized products in the literature; in 13 examples, only one came from the service industry (insurance). In addition, all examples in the discussion on MC levels referred to manufacturing goods, with the possible exception of Burger King.

The need to develop research on mass-customized services becomes even greater if we consider the many differences between manufacturing and services operations, and the implications these differences may have in the design of MC systems. In comparison to manufacturing, service operations are (i) more labor-intensive, (ii) have greater customer involvement, (iii) are more sensitive to quality errors, (iv) have tighter delivery times, (v) are unable to rely on inventories to adjust to demand fluctuations, and (vi) are more dependent on information reliability [61,62]. Besides, service products are intangible, usually transient, and have more subjective qualities than manufactured products. All these elements can pose challenges to MC implementation, e.g. how to develop a flexible and skilled workforce, how to deliver products that match closely the customer requirements, how to guarantee quality and safety despite changes in service parameters, and how to promise short delivery times for mass-customized services.

Research on MC in services could be either theoretical (e.g. matching categories of manufacturing versus service industries, and how these relate to MC elements), exploratory (e.g. survey of service industries to identity practices), or descriptive (e.g. case studies of service companies).

6.3. Information management

An MC system is highly dependent on well-designed information systems that provide direct links between internal work-groups, such as manufacturing, design, and testing, and external work-groups, represented by suppliers and customers. However, there is a void in the literature on how to implement the information management processes required in MC.

It is possible to identify the following opportunities for research topics involving this important issue:

- Design of an effectively decentralized, or multi-agents, control architecture for MC systems. This control system is composed of autonomous components. Its implementation will reduce the complexity, increase flexibility, and enhance fault tolerance needed to successfully implement a team of independent but cooperating producers.
- Application of modeling architectures in MC environment. In particular, enterprise modeling, such as open systems architectures for computer integrated manufacturing (CIMOSA) and architecture for integrated information systems (ARIS) [63]. Enterprise modeling encompasses modeling, analysis, design, and implementation of integrated information systems [64]. The construction of an enterprise model for an MC firm should embrace overall system architecture, product design, project management, software specification, and establishing the data model for data base design [65].
- Development of an information management infrastructure for MC systems based on the integration of different standards or tools: Internet, STEP, and object-oriented paradigm. This infrastructure may enable the software tools for MC systems.

6.4. Quality control and monitoring

On-line and off-line quality control practices are applied for measuring the performance of processes or products. That is usually accomplished by monitoring the behavior of selected quality characteristics (QCs) over time. For that purpose, many strategies have been presented in the literature, most notably those proposing the use of statistical control charts [66] and poka-yoke devices [67]. Two key points determine the success of most quality control schemes: (i) definition of relevant QCs to be monitored; these characteristics must be chosen to reflect customers' quality demands, and (ii) availability of data on the QCs to be monitored from which a reference behavior may be inferred.

MC systems are characterized by single product lots, which are unlikely to be repeated over time. Consequently, traditional quality control schemes such as statistical control charts, which operate based on periodical checking on selected QCs, would not be easily adapted to MC environments. The problem rises in complexity as one notes that a new set of QCs is defined whenever a product is customized. It is natural to expect most relevant QCs to remain unchanged as customization takes place, since they relate to basic operational functions of products. However, new explicit QCs are likely to arise, which implies in their identification and establishing of a monitoring scheme for them.

It seems clear from the discussion above that quality control issues should be taken into account when deciding upon product customization; they are likely to bind the level of customization admissible to products and services, if these are to comply to current quality standards. It is important to note that the current MC literature lacks any in depth study on how to assure quality in mass-customized products.

One possible approach to ease the burden of product quality monitoring, and therefore allow for customized products, is to guarantee on-target product QCs mostly through monitoring of processes. For that purpose, one shall determine the mathematical relationships between product-related QCs and those that are process-related. One idea is to ground product development on methods such as QFD and favor intensive use of statistical tools such as design of experiments [68], and robust parameter optimization [69]. QFD allows for qualitative determination of relationships between product QCs and process QCs. Such relationships could then be mathematically measured using design of experiments. Finally, the number of process QCs to be monitored could be reduced through robust parameter optimization (based on the proposition that robust processes require less intensive monitoring). Development of such methodology requires (i) theoretical research to propose methodological steps to guide MC quality optimization studies; (ii) case-based research to test and refine the steps proposed in (i).

6.5. Reliability analysis of mass-customized products

The reliability of a component or system is defined as the probability that it will adequately perform its specified purpose for a specified period of time under specified environmental conditions [70]. To assess such probability, the lifetime of components or systems must be determined from empirical data. Data may be gathered from field observation of failures or from lab tests carried under normal environmental conditions or under accelerated stress [71]. In any case, reliability studies tend to be time consuming and, in most practical situations, unavoidable if products or systems are to comply with international reliability standards.

MC products have short life cycles and ever changing characteristics. Reliability analyses of such products would imply an accelerated testing which are, in most instances, very costly. Depending on the product level of customization, reliability testing of one basic product would suffice for all variants that may arise from its customization; that would be the case when cosmetic or adaptive customization are the manufacturer's choice. However, upon practicing of collaborative or transparent customization, grounding of reliability inferences on data from basic designs, subjected to several changes after customer intervention, tends to offer undependable results.

There are many cases in the MC literature dealing with products typically subjected to reliability testing. For example, printers in Feitzinger and Lee [19], cable control systems in Owen and Kruse [30], pagers in Eastwood [3], and power generators in Choi and Jarboe [57]. These references do not provide any indication on (i) how reliability testing of products were performed, or (ii) how reliability constraints influenced the choice of customization level. Clearly, such issues are central in the design of customized products, deserving further research.

Most manufactured MC products are defined upon combining pre-determined choices from a finite set of options. In that context, a relevant contribution to the MC literature could come in the form of a method for assessing product reliability resulting from different combinations of choices. Such method would probably rely on computer simulation of product operation, since accelerated testing of all possible combinations of choices would be economically infeasible. One idea is to measure the reliability of parts or components defining the product, rather than measuring the product reliability itself. Whenever a combination of choices generated a new customized product, reliability could be assessed upon analysis of the resulting reliability block diagram [72]. Such approach would require knowledge of the dependence among parts in the product under study [72]; combining information from the reliability block design and the dependence evaluation, mathematical models on which simulations could be based would be at hand. Development of such methodology tends to be heavily based on theoretical research, in particular topics dealing with time (and failure) dependent reliability, validated by empirical testing.

7. Conclusions

MC has become an important manufacturing strategy. Agility and quick responsiveness to changes have become mandatory to most companies in view of current levels of market globalization, rapid technological innovations, and intense competition. MC broadly encompasses the ability to provide individually designed products and services to customers in the mass-market economy.

However, MC should not be viewed as a monolithic solution. Manufacturing processes are too complex and context sensitive for a single black-box idea to generate flexible, agile, and focused systems. To implement MC it is necessary to integrate different manufacturing technologies into a structured framework capable of combining human and technological factors.

This paper presents a literature review on MC. The objective is to identify required conditions and situations where MC implementation is suitable. In addition, fundamental principles and concepts in MC theory are thoroughly discussed.

The study reveals that, while there is little contention on theoretical aspects concerning MC concepts and objectives, there are several pending issues regarding its practical implementation. Literature on MC implementation is still incipient. Most claims are drawn from limited case examples or based on educated guesses from authors rather than from hard evidence obtained through exhaustive research. The paper closes presenting some directions for further research.

References

[1] S. Davis, From future perfect: Mass customizing, Planning Review 17 (2) (1989) 16–21.

[2] J. Pine, B. Victor, A. Boyton, Making mass customization work, Harvard Business Review 71 (5) (1993) 108–111.

[3] M. Eastwood, Implementing mass customization, Computers in Industry 30 (3) (1996) 171–174.

[4] C. Hart, Mass customization: Conceptual underpinnings, opportunities and limits, International Journal of Service Industry Management 6 (2) (1995) 36–45.

[5] R. Hayes, S. Wheelwright, Linking manufacturing process and product life cycle, Harvard Business Review 57 (1979) 133–140.

[6] M. Kay, Making mass customization happen: Lessons for implementation, Planning Review 21 (4) (1993) 14–18.

[7] S. Kotha, Mass customization: Implementing the emerging paradigm for competitive advantage, Strategic Management Journal 16 (1995) 21–42.

[8] A. Ross, Selling uniqueness, Manufacturing Engineer 75 (6) (1996) 260–263.

[9] A. Joneja, N.-S. Lee, Automated configuration of parametric feeding tools for mass customization, Computers and Industrial Engineering 35 (3–4) (1998) 463–469.

[10] J. Jiao, M. Tseng, V. Duffy, F. Lin, Product family modeling for mass customization, Computers and Industrial Engineering 35 (3–4) (1998) 495–498.

[11] P. Ahlstrom, R. Westbrook, Implications of mass customization for operations management: An exploratory survey, International Journal of Operations and Production Management 19 (3) (1999) 262–274.

[12] J. Pine, Mass customizing products and services, Planning Review 21 (4) (1993) 6–13.

[13] P. Kotler, From mass marketing to mass customization, Planning Review 17 (5) (1989) 10–13.
[14] R. Westbrook, P. Williamson, Mass customization: Japan's new frontier, European Management Journal 11 (1) (1993) 38–45.
[15] J. Lampel, H. Mintzberg, Customizing customization, Sloan Management Review 38 (1996) 21–30.
[16] J. Gilmore, J. Pine, The four faces of mass customization, Harvard Business Review 75 (1) (1997) 91–101.
[17] G. Amaro, L. Hendry, B. Kingsman, Competitive advantage, customization and a new taxonomy for non make-to-order companies, International Journal of Operations and Production Management 19 (4) (1999) 349–371.
[18] J. Spira, Mass customization through training at Lutron Electronics, Computers in Industry 30 (3) (1996) 171–174.
[19] E. Feitzinger, H. Lee, Mass customization at Hewlett-Packard: The power of postponement, Harvard Business Review 75 (1) (1997) 116–121.
[20] R. Lau, Mass customization: The next industrial revolution, Industrial Management 37 (5) (1995) 18–19.
[21] S. Kotha, From mass production to mass customization: The case of the National Industry Bicycle Company of Japan, European Management Journal 14 (5) (1996) 442–450.
[22] C. Hart, Made to order, Marketing Management 5 (2) (1996) 10–23.
[23] M. Haglind, J. Helander, Development of value networks – an empirical study of networking in Swedish manufacturing industries, Proceedings of the International Conference on Engineering and Technology Management, 1999, pp. 350–358.
[24] J. Kim, Hierarchical structure of intranet functions and their relative importance: using the Analytic Hierarchy Process, Decision Support Systems 23 (1) (1998) 59–74.
[25] J. Magretta, The power of virtual integration: An interview with Dell Computer's Michael Dell, Harvard Business Review 76 (2) (1998) 72–84.
[26] B. Hirsch, K.-D. Thoben, J. Hoheisel, Requirements upon human competencies in globally distributed manufacturing, Computers in Industry 36 (1–2) (1998) 49–54.
[27] P. Kanchanasevee, G. Biswas, K. Kawamura, S. Tamura, Contract-net based scheduling for holonic manufacturing systems, Proceedings of the SPIE – The International Society for Optical Engineering 3203 (1999) 108–115.
[28] S. Kotha, Mass-customization: a strategy for knowledge creation and organizational learning, International Journal of Technology Management 11 (7/8) (1996) 846–858.
[29] E. Adamides, Responsibility-based manufacturing, International Journal of Advanced Manufacturing Technology 11 (1996) 439–448.
[30] D. Owen, G. Kruse, Follow the customer, Manufacturing Engineering 118 (4) (1997) 65–68.
[31] T. Gooley, Mass customization: How logistics makes it happen, Computers and Industrial Engineering 37 (4) (1998) 49–54.
[32] J. Womack, D. Jones, D. Ross, The Machine that Changed the World, Rawson, New York, 1990.
[33] J. Womack, D. Jones, Lean Thinking, Simon & Schuster, New York, 1996.
[34] Iacocca Institute, 21st Century Enterprise Strategy, Vol. 1, Lehigh University Press, Bethlehem, PA, 1991.
[35] R. Gutman, R. Graves, The agile manufacturing enterprise – both a new paradigm and a logical extension of flexible and lean, EAMRI Report ER95-10, Rensselaer Polytechnic Institute, Troy, NY, 1995.
[36] R. DeVor, R. Graves, J. Mills, Agile manufacturing research: Accomplishments and opportunities, IIE Transactions 29 (10) (1997) 813–823.
[37] H. Jagdev, J. Browne, The extended enterprise – a context for manufacturing, Production Planning and Control 9 (3) (1998) 216–229.
[38] S. Gutman, R. Graves, K. Preiss, Agile Competitors and Virtual Organizations, Van Nostrand Reinhold, New York, 1995.
[39] I. Shekhar, R. Nagi, Automated retrieval and ranking of similar parts in agile manufacturing, IIE Transactions 29 (10) (1997) 859–876.
[40] L. Song, R. Nagi, Design and implementation of a virtual information system for agile manufacturing, IIE Transactions 29 (1) (1997) 839–857.
[41] S. Powell, F. Gallegos, Securing virtual corporations, Information Structure: The Executive's Journal 14 (4) (1998) 34–38.
[42] K. Turowski, A virtual electronic call center solution for mass customization, Proceedings of the 32nd Annual Hawaii International Conference on Systems Sciences, 1999, pp. 152–164.
[43] A. Boyton, B. Victor, J. Pine, New competitive strategies: Challenges to organizations and information technology, IBM Systems Journal 32 (1) (1993) 40–64.
[44] J. Moad, Let customers have it their way, Datamation 41 (April) (1995) 34–39.
[45] J. Wortman, Factory of the future: Towards an integrated theory of one of a kind production, in: B. Hirsch, K. Thoben (Eds.), One of a Kind Production: New Approaches, North-Holland, Amsterdam, 1992, pp. 31–74.
[46] B. Pine, T. Pietrocini, Standard modules allow mass customization at Bally Engineered Structures, Planning Review 22 (4) (1993), 20–22.
[47] R. Storch, S. Lim, Improving flow to achieve lean manufacturing in shipbuilding, Production Planning and Control 10 (2) (1999) 127–137.
[48] H. Warnecke, M. Hüser, Lean production, International Journal of Production Economics 41 (1995) 37–43.
[49] W. King, IT-enhanced productivity and profitability, Information Systems Management 15 (3) (1998) 70–72.
[50] J. Meredith, Automating the factory, International Journal of Production Research 25 (10) (1987) 1493–1510.
[51] G. Vasilash, Mass customization at Perkins: An engine with one-trillion possibilities, Automotive Manufacturing and Production 109 (2) (1997) 42–44.
[52] E. McCarthy, Mass-customizing client service through high-tech, high-touch communications, Journal of Financial Planning 10 (3) (1997) 58–63.

[53] R. Beaty, Mass customization, Manufacturing Engineering 75 (5) (1996) 217–220.
[54] H. Martin, Mass customization at personal lines insurance center, Planning Review 21 (4) (1993) 27–56.
[55] J. Kubiak, A joint venture in mass customization, Planning Review 22 (4) (1993) 19–25.
[56] B. Fulkerson, A response to dynamic change in the market place, Decision Support Systems 21 (3) (1997) 199–214.
[57] K. Choi, T. Jarboe, Mass customization in power plant design and construction, Power Engineering 100 (1) (1996) 33–36.
[58] L. Cohen, Quality Function Deployment – How to Make QFD Work for You, Addison-Wesley, Reading, MA, 1995.
[59] N. Slack, The importance-performance matrix as a determinant of improvement priority, International Journal of Operations and Production Management 14 (5) (1994) 59–75.
[60] A. Sethi, S. Sethi, Flexibility in manufacturing: A survey, International Journal of Flexible Manufacturing Systems 2 (1990) 289–328.
[61] R. Murdick, B. Render, R. Russel, Service Operations Management, Allyn and Bacon, Needham Heights, MA, 1990.
[62] C. Voss, Operations Management in Service Industries and the Public Sector: Test and Cases, Wiley, Chichester, 1985.
[63] G. Doumeingts, D. Chen, State-of-the-art on models, architectures and methods for CIM systems design, in: G. Olling, F. Kimura (Eds.), Proceedings of the IFIP TC5/WG 5.S, Eighth International PROLAMAT Conference: Human Aspects in Computer Integrated Manufacturing, Elsevier Science, Amsterdam, 1992, pp. 27–40.
[64] F. Venadat, Enterprise Modeling and Integration: Principles and Applications, Chapman & Hall, New York, 1997.
[65] M. Aguiar, R. Weston, A model driven approach to enterprise modeling, International Journal of Computer Integrated Manufacturing 8 (1995) 210–224.
[66] D.C. Montgomery, Introduction to Statistical Quality Control, 3rd Edition, Wiley, New York, 1996.
[67] S. Shingo, Zero Quality Control: Source Inspection and the Poka-Yoke System, Productivity Press, Cambridge, 1986.
[68] D.C. Montgomery, Design and Analysis of Experiments, 3rd Edition, Wiley, New York, 1991.
[69] S. Park, Robust Design and Analysis for Quality Engineering, Chapman & Hall, London, 1996.
[70] L. Leemis, Reliability: Probabilistic Models and Statistical Methods, Prentice-Hall, Englewood Cliffs, NJ, 1995.
[71] W. Nelson, Accelerated Testing: Statistical Models, Test Plans and Data Analyses, Wiley, New York, 1990.
[72] E.A. Elsayed, Reliability Engineering, Addison-Wesley, Reading, MA, 1996.