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Industry 4.0: a way from mass customization to mass personalization production

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Abstract Although mass customization, which utilizes modularization to simultaneously increase product variety and maintain mass production (MP) efficiency, has become a trend in recent times, there are some limitations to mass customization. Firstly, customers do not participate wholeheartedly in the design phase. Secondly, potential combinations are predetermined by designers. Thirdly, the concept of mass customization is not necessary to satisfy individual requirements and is not capable of providing personalized services and goods. Industry 4.0 is a collective term for technologies and concepts of value chain organization. Based on the technological concepts of radio frequency identification, cyber-physical system, the Internet of things, Internet of service, and data mining, Industry 4.0 will enable novel forms of personalization. Direct customer input to design will enable companies to increasingly produce customized products with shorter cycle-times and lower costs than those associated with standardization and MP. The producer and the customer will share in the new value created. To overcome the gaps between mass customization and mass personalization, this paper presents a framework for mass personalization production based on the concepts of Industry 4.0. Several industrial practices and a lab demonstration show how we can realize mass personalization.

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1 Introduction

Manufacturing is an essential part of today's economy. Smart manufacturing will be able to rapidly adjust physical and organizational structures and facilities to changes in technology as manufacturing becomes faster, closer, and more responsive to customer requirements and changing global markets.

Industrial production continues changing just as it has since the very beginning. The term "revolution" is leveraged to describe the powerful change. The production paradigm has changed three times, and is now experiencing the fourth change. Figure 1 illustrates the evolution of the production paradigm.

1.1 Craft (customer) production (CP)

The first industrial revolution is referred to as "Industry 1.0", or "CP", in which products were manufactured based on the requirements of users at a high cost and with a limited number of products. CP is leveraged to depict the production paradigm change from entirely manual production to machine production. The weaving and cotton-spinning mills were first influenced by CP in England in 1770. This great breakthrough took place after the invention of the steam engine by James Watt in 1782. From then on manual work was not restricted by location and it was possible to have an energy supply anywhere.

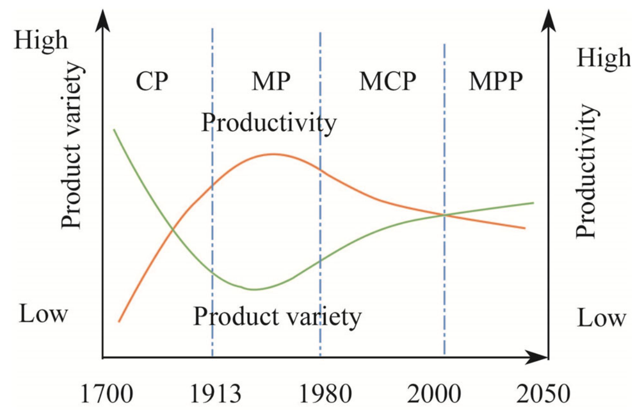

Fig. 1 Evolution of production paradigm

1.2 Mass production (MP)

In the second industrial revolution, called "Industry 2.0" or "MP", low-cost products were made using large-scale production systems. The variety offered by MP was very small and limited. In 1926, Ford pointed out that "Any customer can have a car painted any color that he wants so long as it is black" [1]. "MP" featured the principles of rationalization by Taylor. It was mainly based on precision engineering, division of labor, standardization, and assembly line work. The first conveyor belt was introduced at the beginning of the 20th century by Henry Ford to produce the T-model and acquired huge success with it in the automobile industry [2].

1.3 Mass customization production (MCP)

The third industrial revolution is referred to as "Industry 3.0" or "MCP". In the late 1980s, customer demand for a large variety of products led to the development of "Mass customization" [3]. It was based on the development of information, automation technology, and the computer. This led to numerically controlled (NC) machines, such as industrial robots, flexible manufacturing systems (FMS), and computer integrated systems (CIM), as well as manufacturing management systems, such as product life management (PLM), enterprise resource planning (ERP), and manufacturing executive system (MES), which could be modified much faster than conventional mechanically automated machines and processes. Consequently, flexible production was developed and systems featured high productivity, low cost, and large varieties.

1.4 Mass personalization production (MPP)

Most companies have focused on maximizing their value for many years. There is currently a trend of shifting focus from a company's value to customer demand [4]. Customer desire is the key driving force leading to the new industrial evolution or revolution. The fourth industrial revolution, called "Industry 4.0", is approaching. Information and communication technologies (ICTs) are increasing jointly and influencing all aspects of our life and business. Embedded software is integrated into the global communication network, connects and controls devices and systems in our environment. The boundaries between the real world and the virtual world are clearly overlapping. These new technologies will enable wholly new forms of "MCP". The historic split between cheap mass-produced products, creating value from economies of scale, and more expensive customized products, will be reduced across a wide range of product types.

With Industry 4.0, manufacturing companies and organizations are confronted with unprecedented competition and challenges. At the same time, new technologies and innovative ideas are emerging and widely used to satisfy increased consumption demand. The contradictions between customer demand for personalized product and the relative shortage of personalized production have become increasingly prominent. In order to effectively solve the conflict between demand diversification and large-scale manufacturing, MPP will provide the modern manufacturing enterprise with the advantages of cost, quality, flexibility, time, and variety. In the near future, a new wave of industrial revolution will begin to sweep the world, and manufacturing will be most impacted.

Industry 4.0 is a hot topic discussed not only among practitioners but also theorists. The concepts of Industry 4.0 will facilitate the construction of smart factories [5, 6]. It was introduced to illustrate a new trend towards the networking of traditional industries, such as manufacturing, at Hanover fair in Germany in 2011. Similarly, the smart manufacturing leadership coalition (SMLC) is also working on strategy for the future of manufacturing [7] in the United States. In addition, the UK has been working on an initiative called "bring manufacturing back to the UK" [8]. The strategy of "smart manufacturing" was adopted by China to seek innovation-driven development, and is called "China Manufacturing 2025" or "Made in China 2025" [9]. Many similar projects and programs exist in the world, such as "Intelligent manufacturing system" from the European Union, Switzerland [10],"Future of manufacturing" from Norway [11] and "Ubiquitous manufacturing" from South Korea [12].

The concept of Industry 4.0 is closely related to other technological terms, such as radio frequency identification (RFID) technology [13], cyber-physical system (CPS) [14], the Internet of things (IoT), machine-to-machine (M2M) communication [15], the Internet of service (IoS) [16], cloud computing [17], decision-making/supporting system

[14], computational intelligence (CI), and data mining (DM).

However, most research institutions and industries do not have a clear understanding of what exactly Industry 4.0 is and what it will be. Moreover, it is not very clear how Industry 4.0 supports the manufacturing strategy of MPP. This study focuses on the previously listed subjects from industries and research. The authors are trying to adopt an understandable definition of Industry 4.0 for the purpose of developing a framework of MPP. A lab case study is used to show how the framework can be implemented to realize MPP in practice.

The paper is organized as follows. Section 1 offers a comprehensive overview of the historic evolution paradigms of production from CP to MPP. The general concept of MPP is described in Sect. 2. The main components and definition of Industry 4.0 are given in Sect. 3. Section 4 presents the framework for MPP based on the concept of Industry 4.0. In Sect. 5, we list ongoing Industry 4.0 projects. A detailed lab case is presented in Sect. 6. Conclusions and future research are summarized in Sect. 7.

2 Mass personalization production

Price and customization have been two of the most important features to the consumer since the earliest craftsmen provided items for sale. This is still true today, but with a few twists. A breakthrough came when the French military used interchangeable parts for cannons and muskets at the end of the 18th century.

By the middle of the 19th century, many more products were produced with interchangeable parts. This paradigm shift resulted in the widespread buying of standard products that were cheaper and easier to repair. The underlying reason why MP became dominant was that it enabled ordinary people to afford complex products such as automobiles. The general tendency of cheap standard designs and expensive customized products persisted until about two decades ago [18].

The recent industrial production shift from MP to mass customization was forecasted in 1987. The ability to produce customized products that meet each consumer's requirements at the cost of near MP is the ultimate goal of mass customization. Giving customers the chance to have a product wherever they want it, any way they want it, and whenever they want it, resonates well with customers. The quantity of mass customized products is gradually increasing as are the customized services, and this kind of production paradigm is called mass personalization.

Retailers should be able to provide a variety of channels and orders in keeping with mass personalized products and delivery methods by 2025. Except for traditional retail outlets and kiosks, customers will want to order with their own computers and mobile phones and perhaps as-yet-unimagined channels. Delivery modes will change from long lead time delivery to next-day delivery, same-day delivery, and even same-hour delivery [18].

The pervasive existence of computing and the internet and the availability of new responsive manufacturing systems, e.g., 3D printing, signifies a great chance for a new production paradigm, namely MPP. The personalization of production is adapted to the individual customer's requirements and needs [19]. Customers produce creative products and gain value through cooperating with manufacturers. Based on different known customer needs by marketing analysis, customers are categorized into different market segments in customization. The customers will receive similar or parameter-based customized products from a predefined product family if they are categorized in the same group. The basic modules, configuration mechanism, product architectures, and critical parameters have been kept stable within the predefined realm of configuration [20]. Computer configuration is a classic example of mass customization. Computer manufacturers estimate the possible ranges of products that customers would like to buy beforehand. Then producers determine the common denominators to find the best set of building blocks for customers to mix and match to satisfy their needs [20]. As a result, the essence of mass customization is to configure various product variants through modularity with commonality embedded in the product platforms to reuse proven design among product families [21]. On the other hand, in the paradigm of mass personalization, it requires product fulfillment to be changeable, adaptable, and configurable, because not only the final product but also the basic design and product structure must be able to differentiate at the module and parameter level to meet individual's unique needs.

As shown in Fig. 2, mass personalization is different from personalization, which can be dated back to CP. In contrast to the products at that time, with an excessively high price tag, mass personalization provides personalized

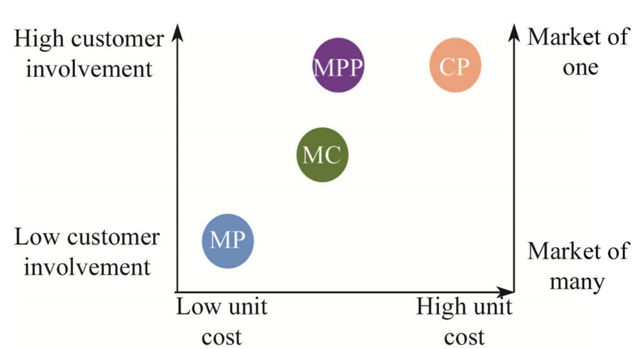

Fig. 2 Taxonomy of paradigms of production

products with affordable fulfillment cost for both customers and producers. Mass personalization brings more value to both producers and customers. By supplying customers with customized products, producers can obtain differentiation. Meanwhile, customers can be provided with products with less lead time and high quality. Additionally, customers feel they are treated distinctively by the firm. Though CP makes personalization possible to the extent of a market of one, the cost of production is relatively high. In the paradigm of MP, there is no involvement of customers because products are standardized by designers. Mass customization showcases a process of customers making choices passively from established offerings, and customers are guided by producers with restricted involvement [21]. Based on these choices, firms can then prepare supply chains to satisfy orders with little or even no customer participation. However, in the paradigm of mass personalization, customers are intensively integrated into the production process. Active customer participation is a crucial factor to satisfy user experience-related requirements, because experience is influenced by a chain of human cognitive activities. Thus, active customer participation is an important driving force for the whole production process, which affects the final product offering directly in personalization.

Based on the discussion above, it can be seen that mass personalization is the advanced stage of mass customization. Mass personalization addresses a market of one, which is the extreme case of mass customization. Compared to the limited customer involvement in mass customization, customers need to be actively involved in the product design process for mass personalization.

3 Industry 4.0

3.1 Industry 4.0 key components

Industry 4.0 allows the production of individual products at the cost of MP. This specifically means that production companies are capable of solving the principle interface issues between production, product development, and product usage, and hence drive all major value-added processes towards the requirements of customers. In addition, by leveraging IT-based communication and interaction services, tools, machines, and products, Industry 4.0 allows flexible and smart production control. The communication of M2M and networking not only boosts the company's orientation towards the customer, but also connects departments. In general, Industry 4.0 has four components: (1) CPS, (2) mobile and cloud computing and IoT, (3) big data, DM and knowledge discovery, and (4) IoS.

3.1.1 Cyber-physical system

CPS is an important component of Industry 4.0. CPS connects the virtual world with the physical world. The development of CPS has undergone three phases. The first generation of CPS includes RFID technologies, which can uniquely identify objects. The centralized service is analytics and storage. The sensors and actuators used in the second generation of CPS exhibit a narrow range of functions. The third generation of cyber physical systems, provided with various sensors and actuators, are not only network compatible but also capable of storing and analyzing data.

3.1.2 Mobile and cloud computing and Internet of things

The ability to access knowledge from stationary computing devices is magnificent progress in the information revolution. We have reached the stage in history in which it is possible to communicate with others, act on decisions, obtain knowledge, and engage in commerce anytime and anywhere. Mobile computing is changing the way we live. The IoT enables "things or objects" to exchange information with each other and collaborate with their intelligent components to reach common objectives. Based on the introduction of CPS, CPS can be defined as "things or objects". Thus, the IoT can be regarded as a network where CPS interacts with each other by unique addressing schemes. Every year, sensor technology is building smarter devices that can share information with the internet without human intervention. The growing array of functions that these sensors perform is advancing at an incredible speed as is the accuracy they can achieve. In the future, sensors that automatically communicate with the internet without human intervention could be almost pervasive. Relying on sensors communicating directly with the internet at every step of the manufacturing process, operators would be warned of problems and be told precisely what to do.

3.1.3 Big data, data mining and knowledge discovery

"Big data" refers to the huge amount of data sets that companies now collect and store about their customers, sales, operations, and almost all transactions of interest. "Real-time big data" represents the process of keeping a great deal of data in a data warehouse and discovering interesting patterns and knowledge from large amounts of data. It can be considered the result of the natural evolution of information technology and an essential process, where intelligent methods are leveraged to extract data patterns and discover knowledge from data. The data sources can include databases, data warehouses, the web, other information repositories, or data that are streamed into the system dynamically. DM is capable of discovering and analyzing rules, patterns, and excavating knowledge from big data gathered from various sources. Thus, the right decision can be made at the right time.

3.1.4 Internet of service

Service vendors are enabled by IoS to provide their services through the internet. The IoS is composed of four parts: infrastructure, participants, business models, and services. Multiple suppliers provide services and integrate them into value-added services [2]. Consumers and users are able to access the services and communicate to them via various channels.

The general and explicit definition of Industry 4.0 can be summarized according to the four key components of Industry 4.0.

3.2 Definition of Industry 4.0

Based on the literature review, the general definition of Industry 4.0 can be summarized as follows. As a collective term, Industry 4.0 involves value chain organization and technology. CPSs keep track of physical processes, connect the virtual world with the physical world, and make decentralized decisions within the smart factories of Industry 4.0. Moreover, the IoT enables real-time collaboration and communication between CPS. Decision-making processes are supported by DM, which is able to discover knowledge from various sources [2]. Participants can utilize both the cross-organizational and internal services via the IoT.

4 Framework of mass personalization production

Based on the concepts of Industry 4.0, the framework of MPP is proposed for efficiently and effectively satisfying customer requirements through providing individually distinct products with a positive user experience. The emerging technologies of IoT, CPS, IoS, and RFID are integrated into the framework to realize MPP. Figure 3 illustrates the framework of MPP. It comprises network layer, IoS, warehouse management system (WMS), CPS, MES, and enterprise information system (EIS). The details of the subsystems are elaborated on in the next few sections.

4.1 Network layer

In the network layer, customers are provided with all needed carrier networks, such as 4G, cellular networks, satellite networks, or wireless networks, for access to various resources, services, and information anytime and anywhere. This enables customers to be involved in the process of product co-creation.

4.2 Internet of service

Customers and users are integrated into the product design process through the IoS. The IoS describes an infrastructure that uses the internet as a medium for offering and selling services, which includes technologies such as web or cloud services. Unlike the mass customization strategy, which is aimed at the market segment of similar customers and focuses on satisfying the requirements of a group of similar people, the mass personalization strategy is proposed to meet the needs of an individual customer and aims to attain the market segment of one customer [22]. To achieve the mass personalization, customers need to participate in the design process actively.

4.3 Cyber-physical system

CPSs bridge the cyber world, such as information, communication, and intelligence, to the physical world through lots of sensors and actuators. CPSs are constructed by integrating networking, computation, and physical processes. Embedded networks and computers monitor and control the physical processes, with feedback loops where physical processes affect computations, and vice versa. An RFID system is a typical CPS. By deploying RFID technology to various manufacturing objects, the real-time data of manufacturing production processes can be sensed and captured. In doing this, manufacturing data such as material consumptions, workforce situations, machine statuses, and order progress are collected and managed at a level that is accurate, complete, and real-time [23]. The manufacturing data are then transferred to an MES for processing.

4.4 Manufacturing execution system

The internet of knowledge transforms the data captured by RFID technology into information and knowledge and makes manufacturing intelligent. DM, artificial intelligence, and optimization algorithms are leveraged to analyze and discover patterns, rules, and knowledge from data collected from multiple sources, so one can make the right decision at the right time and right place. Based on the information extracted from the internet of knowledge, MES can realize work in process (WIP) management, resource allocation, production planning, and production scheduling. MESs mainly concentrate on managing shop-floor operations such as timely informing shop-floor supervisors in terms of equipment status, material delivery, and

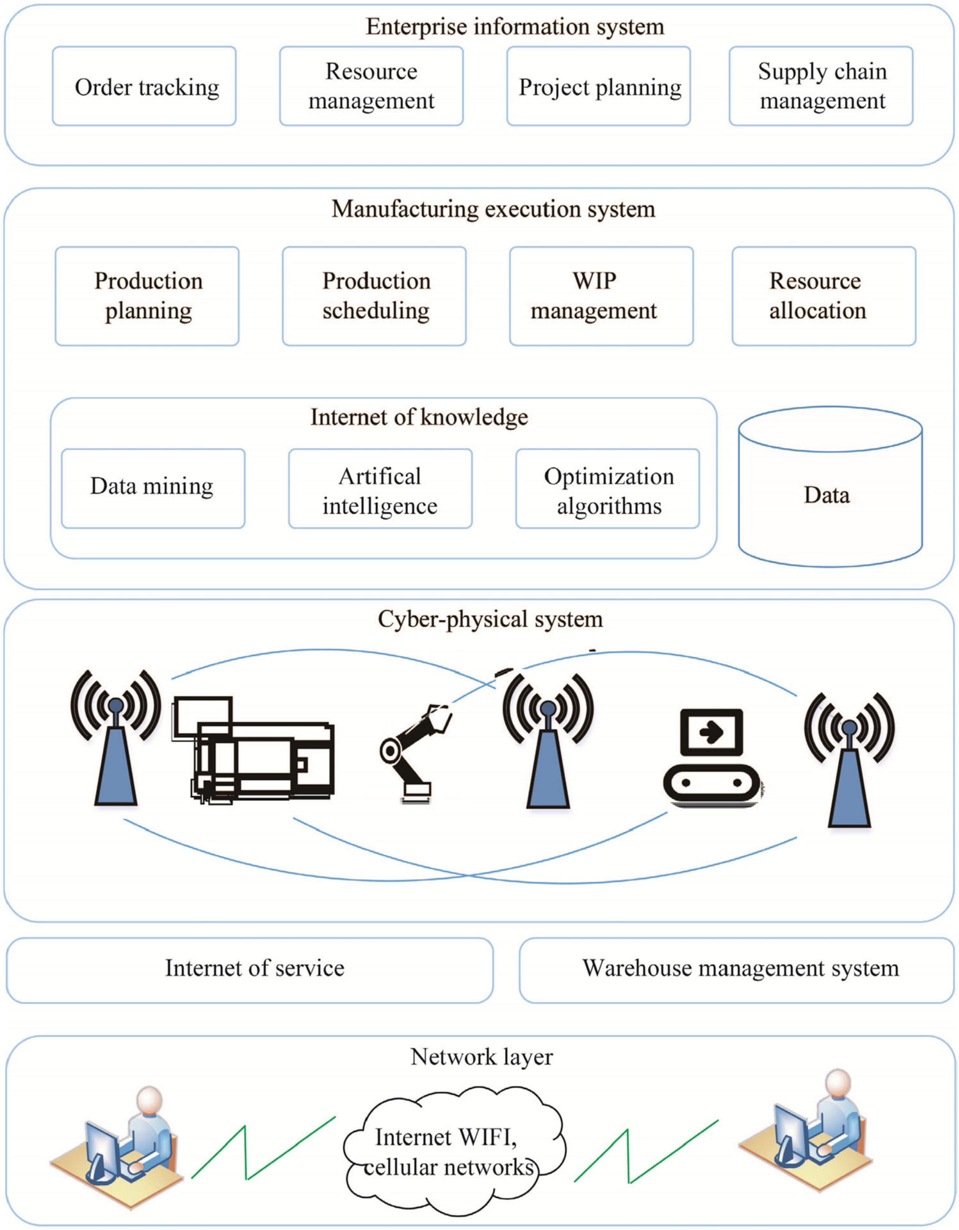

Fig. 3 Framework of MPP system

consumption, as well as manufacturing progress. MES is the comprehensive system that controlls all the activities occurring on the shop floor. It begins with all the various orders from the EIS and other planning sources, and then builds the products in the most effective, low cost, expedient, and high-quality way possible.

4.5 Enterprise information system

While MES primarily supports operational decisions, EIS supports strategic decisions. EIS is designed for order processing, supply chain and inventory management, human resources, and customer relationship management. EIS can aid management of resources across an entire business, ensuring greater efficiency and improved competitiveness. Because of the complex, continually varying environment on the shop floor, the scheduling needs to account for a level of variation that is typically beyond the scope of the planning system, EIS and MES must communicate and act as a seamless whole to allow the manufacturing industry to meet the dynamic demands coming from regulators, customers, suppliers, and even internal staff.

4.6 Warehouse management system

A warehouse is an essential component for linking the upstream (production) and downstream (distribution). The basic operations in the warehouse are to receive stock keeping units (SKUs), store the SKUs in storage locations, retrieve SKUs from storage locations, and ship the completed orders to customers. The performance of these operations not only affects the productivity and operation costs of a warehouse, but also the whole supply chain. WMS is adopted to satisfy increasing customer demand in terms of responsiveness, cost effectiveness and flexibility. WMS is responsible for allocating warehouse resources, such as SKUs, forklifts, and warehouse staff members efficiently and effectively to enhance productivity and reduce the operation costs of the warehouse.

5 Industry examples

Many industries have started to work towards MPP implementation. Some industrial models are described below.

5.1 Dell model

Dell relies on the Internet to produce various parts and personalized products based on the preferences of customers. Consumers can make their own choices on important computer features. Dell receives their orders and deposits, and the product is assembled within a few days, and sent to the hands of consumers. The result of this business model is the elimination of two, namely the elimination of inventory, the elimination of intermediaries. China's average inventory of many products is up to several months, while Dell's average inventory is only 5 d. Dell's leaders claim that in one year or two, the average inventory will be further reduced to 2−3 d. The cost of merchandising is very low, and Dell will transfer most of the cost savings to consumers. It makes more people be able to customize it directly to Dell. Dell's various parts of the demand are very large, which are not produced by Dell itself. Outsourcers produce these parts economically owing to MP and the cost to supply parts to Dell is naturally low. It further strengthens the Dell's cost and price advantages [24].

5.2 Red collar model

Red collar group (RCG) is a Chinese garment company, which specializes in clothes manufacturing and brand marketing. It is a pioneer in the development of a model of MPP in the garment industry. The practice of customer to manufacturing (C2M) makes it popular in China. RCG creates a cross-border C2M e-commerce platform, which supports the direct interaction between local production and global customers, and shares real-time data and information in the whole business process. The characteristic of the platform has built a new commercial civilization: everyone is designer, customer, operator, and entrepreneur. The needs of global customers are very different. Personalized needs have become a fashion. The consumption pattern of perfection, simple, cheap, and fast has been dominated in customer sovereignty. RCG produces the personalized products in the way of industrialization, which utilizes digitalization, IoT, data analysis, IoS, automation, and artificial intelligent technology to build the C2M exchange surroundings. In this way, customer demand could be achieved by the simplest, the most convenient and the most pleasant way [25].

5.3 Harley-Davidson (H-D) model

Only H-D brings the exclusive parts, processes, and expertise together so one can build a one-of-a-kind H-D motorcycle. As a century-old brand of motorcycle enterprises, H-D motorcycle has a very classic brand, but has encountered many challenges. They found that their users were getting older, and the younger generation needed more personalized bikes, for example, to refractor the existing model. H-D has made the strategic change from MCP to MPP, which means they will provide personalized custom services for all users. However, a motorcycle may have tens of thousands of spare parts, and personalization is not so simple. They reformed the existing factories and reduced the areas of the factories from 140 000 m^2 to 60 000 m^2 with fully flexible, automated, and modern production lines. The number of employees could be dramatically reduced by 50%. More importantly, the production line reformed through the Industry 4.0 concepts, such as IoT, CPS, smart sensors, M2M communication, DM technology, makes smart manufacturing feasible. One production line can produce different types of motorcycle models and achieve mass personalized production [26].

5.4 Madshus

In order to meet market demand of the mass personalization, the Norwegian Ski Company, Madshus, has developed an empower system, which is embedding NFC RFID inlays in its champion series, not only to track WIP progress at its factory, but also to ensure retailers sell the right skis to a customer and provide buyers with product and usage information. Madshus Empower is changing the way skis are built, purchased, and enjoyed. The unique information of each ski is loaded into the global digital database

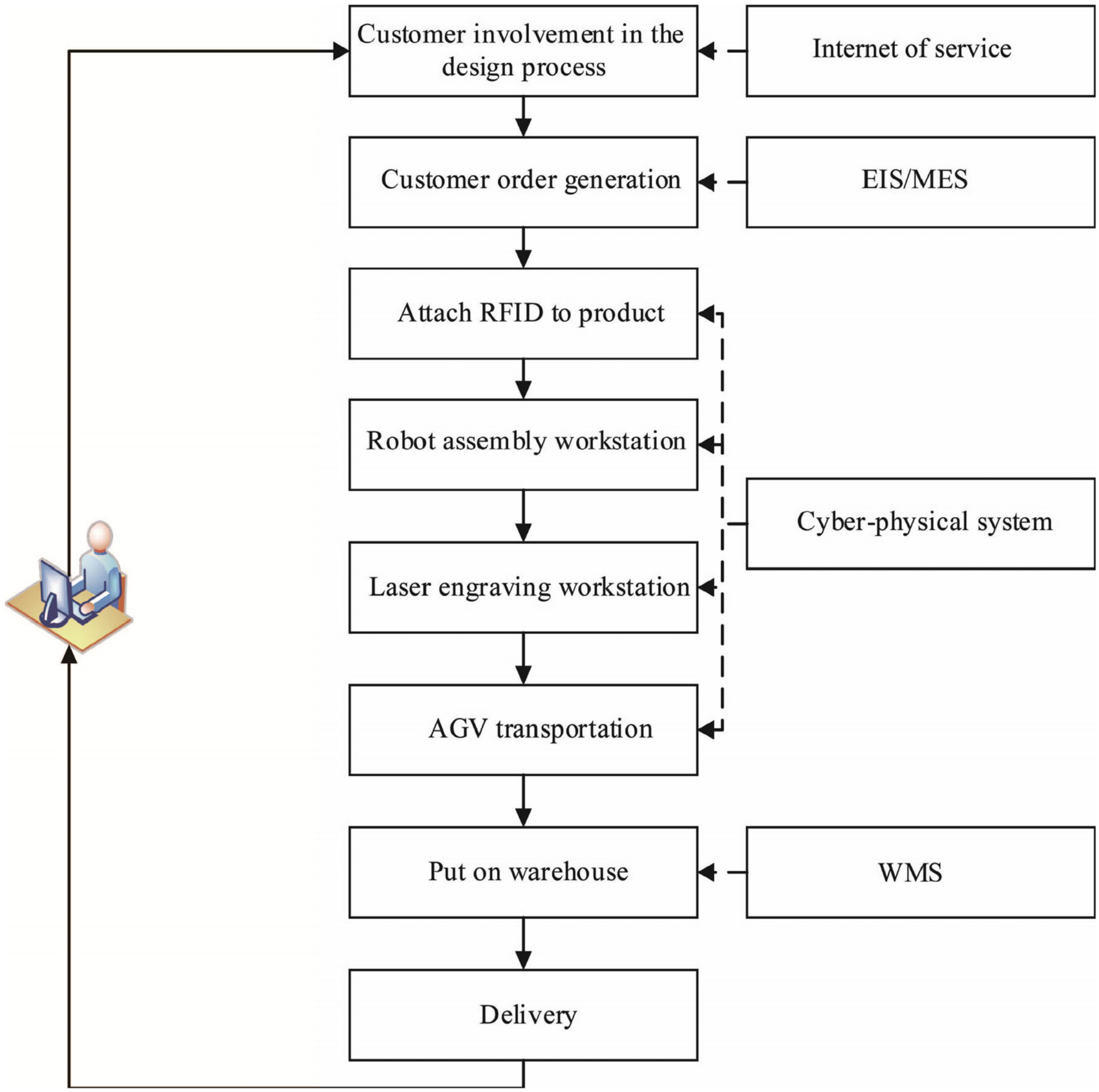

Fig. 4 Operating procedure of MPP system

which allows customers to choose the perfect pair of skis based on their specific profile [27]. It consists of three components:

(i) Measurement. Empower technology enables the customers to find the perfect ski for their specific physical profiles. At retail, after the customer's measurements are entered, the Empower tablet display enables the perfect pair of skis to be chosen for the specific customer by matching the customer's weight, height, and ski ability to the ski length, camber height, and flex. When the Empower skis are purchased and the Madshus Empower app is downloaded, the customer is allowed to construct a similar profile via the application. By inputting the customer's key specifications, e.g., height and weight, the Madshus Empower app can ensure that the customer retains accurate information about how to adjust the ski performance before going on the snow.

(ii) Identification. After building the skier profile, it is easy to identify the right pair of skis. Madshus Empower application enables the customer's quiver to always be at their fingertips after the customer has uploaded the skis into this app. When the perfect pair is chosen, the embedded wax assistant can then help the customer make fine-tuned adaptations to the wax pocket, making ski prep simple every time.

(iii) Optimization. With development of technology, it is time to get the personalized service to a higher level. The customer is enabled by the Madshus Empower application's embedded GPS to match the choice of ski to main training data. It keeps track of the mean

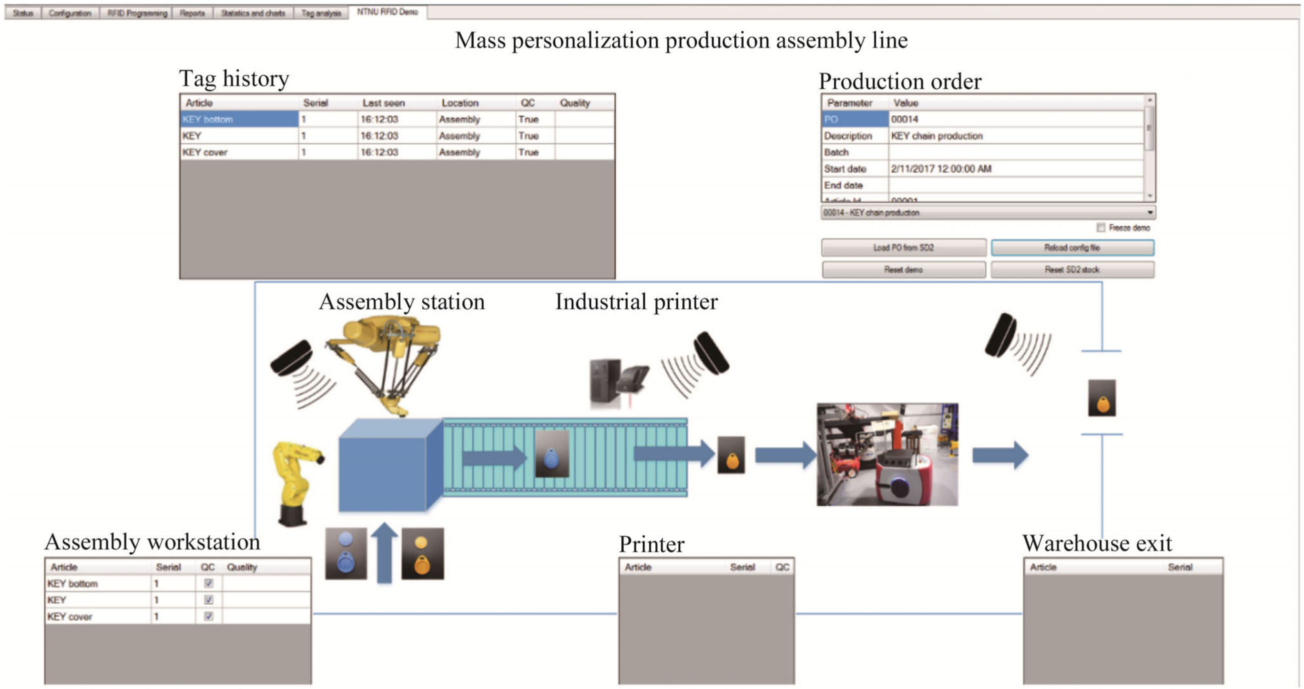

Fig. 5 RFID based MPP system

speed, entire length, and additional specific characteristics needed to log training days.

6 Lab case

An RFID enabled smart factory was set up by Shanghai Polytechnic University (SPU) in cooperation with the Knowledge Discovery Laboratory (KDL) at the Norwegian University of Science and Technology (NTNU). The keychain is produced in the smart factory to demonstrate MPP using the concept of Industry 4.0. As shown in Fig. 4, there are eight steps to produce the personalized key chain.

Firstly, through the IoS, each customer decides the color and shape of the keychain. Moreover, the customer can print his or her name on the keychain to satisfy their unique individual requirements. Secondly, all this information is transferred to EIS for customer order generation. The EIS is responsible for order tracking, resource management, project planning, and supply chain management. MES begins with all the various orders from the EIS system and then builds the products in the most effective and efficient way possible. Next, the CPS will execute the customer order.

The procedure of keychain production is as follows. Firstly, the serial robot selects the materials, including a bottom, a cover, and an RFID tag, from the shelf, and puts them on the workbench equipped with a parallel robot. Secondly, the bottom, the cover, and the tag are assembled by the parallel robot. Thirdly, the finished keychain will then be put on the conveyor belt which can transfer the keychain to the printer workstation. The printer engraves personalized information on the key ring based on the information read from the RFID tag. Finally, the AGV delivers the keychain to the warehouse. All the processes above can be tracked and displayed in an RFID system as illustrated in Fig. 5. At each workstation, the assembly and the printer, the RFID reader antenna can read the tag. From the moment the tag is attached to the keychain, the product can be identified and tracked using RFID.

The functions of the RFID system are as follows. When the keychain is detected by the reader antenna installed at the assembly workstation, the RFID information will be displayed on the assembly list box. When the keychain arrives at the printer workstation, the printer list box will show the corresponding RFID information and the information in the assembly list box is cleared. This is the real-time tracking of RFID tags and all the RFID information during the production is displayed in the history list box and stored in the database of the RFID system for further research.

In this case, mass personalization is realized via the active participation of the individual customer in the design process. Based on the proposed MPP framework, the personally unique keychain with the customer's name engraved is produced efficiently and effectively. The main components of Industry 4.0, such as CPS, IoT, and IoS are integrated into the manufacturing process. This lab case also indicates that Industry 4.0 enables MPP.

7 Conclusion and future research

With the growing amount of ICTs, the concept of mass customization cannot keep up with individual demand and provide personalized services. Meanwhile, the technological concepts of Industry 4.0 will enable a whole new form of personalization. In order to bridge the gap between mass customization and mass personalization, a framework for MCP based on the concept of Industry 4.0 is proposed in this paper. The emerging technologies of IoT, CPS, IoS, and RFID are integrated into the framework to realize the MPP. A lab case about the production of personalized keychain is implemented to demonstrate MPP using the concept of Industry 4.0. The results show that mass personalization can be achieved by the proposed MPP framework. Future research will focus on improving the smart factory in SPU to build a personalized bicycle.

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