Manufacturing Letters 16 (2018) 44–48

Contents lists available at ScienceDirect

Manufacturing Letters

journal homepage: www.elsevier.com/locate/mfglet

Manufacturing system architecture for cost-effective mass-individualization

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ARTICLE INFO

Article history:
Received 22 December 2017
Received in revised form 3 April 2018
Accepted 21 April 2018
Available online 23 April 2018

Keywords:
Mass-individualization system architecture
Reconfigurable manufacturing system
Market-of-one products

ABSTRACT

Globalization and social networks are dramatically changing the producer-buyer landscape. Consumers have an increasing desire to buy unique products that precisely reflect their individual preferences and needs. Therefore, approaching the era of mass-individualization in which Market-of-One products are manufactured economically is inevitable. This emerging paradigm brings engineering challenges in designing new manufacturing systems that produce large quantities of individualized products at relatively low cost.

We propose a new manufacturing system architecture that satisfies the production requirement for the mass-individualization paradigm. In the proposed system, individualized products can be manufactured cost-effectively, making them affordable for the general public. Operational challenges of the proposed system are highlighted.

1. Evolution of manufacturing paradigms

Driven by the social and economic needs in different historical periods, the landscape of manufacturing paradigms has witnessed several major changes in the last century. In 1913, Henry Ford invented the moving assembly line, where a single product could be produced at high throughput and very low cost. This invention symbolizes the start of the mass production paradigm. The development of computer numerical control (CNC) [1] and flexible automation technologies in the late 1970s facilitated the creation of flexible manufacturing systems (FMSs), which enabled a manufacturing system to produce a larger variety of products, forming thereby the mass-customization paradigm [2,3].

A sequence of global events during the 1990s and early 2000s (e.g., the creation of NAFTA and the European Union, and the admission of China to the WTO) initiated the globalization era [4], and, in turn, enhanced the expansion of the mass customization paradigm. Globalization has resulted in (1) an increased frequency at which new products with shorter lifecycles are introduced, and (2) a higher demand for more customized products.

In response to these challenges, Koren coined the term “Reconfigurable Manufacturing System” in his 1995 Engineering Research Center proposal to the US National Science Foundation (NSF).[1] There he proposed the RMS architecture and defined RMS as a manufacturing system, which has “exactly the production resources needed, exactly when needed.”

A few years later Koren headed an international team that wrote a keynote paper on RMS [5], which he presented at the CIRP 1999 General Assembly. This paper became CIRP’s highest cited paper, which signifies the considerable international impact of RMS.

RMS enables building a “live” factory that can quickly and cost-effectively respond to the changing customer needs. The RMS invention [6] has brought about rapid responsiveness to market changes to quickly satisfy customers’ desires, thereby enhancing the mass-customization paradigm.

The increasing maturity of globalization and the popularity of social networks (e.g., Facebook) in the last decade have been dramatically changing the producer-buyer relationships. Consumers nowadays have an increasing desire to buy unique products that reflect their individual preferences or urgent needs (e.g., original decorative art, or bone replacement produced by additive manufacturing). If money were not a constraint, any individualized product could be designed and manufactured; but the reality is that only the rich can afford such products. The challenge is to produce individualized products at a reasonable cost, so the middle class can afford them, and consequently individualized products will be manufactured in large quantities for the benefit of society. This scenario defines the emerging mass-individualization

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[1] The NSF granted $33 million (over 11 years) to develop the RMS science base and its implementations.

https://doi.org/10.1016/j.mfglet.2018.04.002
2213-8463/

paradigm [7–10], in which "market-of-one" products could be produced at a cost similar to that of mass-customized products.

The challenging question is: How to produce individualized products in large quantities at a reasonable cost? Certainly, a critical technology that enables the cost-effective realization of individualized products is additive manufacturing [11,12]. However, many individual products require metal parts, at least for their mechanical interface (e.g., a special car accessory). Therefore, to produce a "Mass" of individualized products, the additive manufacturing machines should be integrated into a manufacturing system that also contains other operations (e.g., milling, assembly), enabling thereby the simultaneous production of a variety of individualized products cost-effectively.

A critical technology for fulfilling this requirement is the manufacturing system architecture – an architecture that integrates the various manufacturing operations and thereby optimizes the whole production process for a variety of products manufactured simultaneously, which, in turn, reduces the production cost. Furthermore, the recent development of Industry 4.0 technologies can significantly increase the system intelligence, facilitating system-level operational decision-making and process optimization [13].

For each manufacturing paradigm introduced in the 20th Century, distinct system architectures have been originated to fulfill the goal of the paradigm. Fig. 1 summarizes the three manufacturing paradigms, their principal goals, product types, system architectures, and prime technology enablers.

To reduce the product cost in the mass-production era, dedicated manufacturing lines (DMLs) were introduced. DMLs consist of dedicated machines that are connected in serial, and can produce a single product at extremely high throughput, and consequently at low cost. However, a DML can produce only one product, and its system structure is fixed; once the DML is built, it is practically impossible to change the system capacity and functionality.

To achieve the product variety goal of the mass-customization era, flexible manufacturing systems (FMSs) consisting of CNC machines were introduced. Nevertheless, FMSs are expensive, and thus are usually not a practical option for large manufacturing systems.

Combining the advantages of both DML and FMS, the RMS architecture and its mathematical base have been developed [14]. Based on the RMS architecture for high-volume manufacturing, we propose an original system architecture for cost-effective manufacturing of mass-individualized products. This system can produce unique products at a reasonable cost, facilitating thereby the vision of Market-of-One products for a considerable number of buyers.

2. RMS architecture for high-volume manufacturing

Traditional RMSs for high-volume manufacturing focus on improving the system's responsiveness to changing markets, and its sustainability in producing several generations of products at high throughput. As shown in Fig. 2, a traditional RMS architecture consists of multiple stages connected in serial, where each stage is composed of identical parallel machines that perform identical operations. These machines may be CNC machines, reconfigurable machines, or inspection machines. The machines are integrated by means of gantries (one per stage) and a forward conveyor (or gantry) that moves the parts through the system. Buffers are built between the stages. This material handling system provides the RMS architecture with a high level of flexibility [15].

In order to respond rapidly and cost-effectively to the changing market demand and customers' needs, RMSs should be designed to contain six core characteristics: *Scalability, convertibility, customization, modularity, integrability, and diagnosability*. The RMS architecture enables the integration of these characteristics in the system. The characteristic of scalability, which enables rapid responsiveness to abrupt market changes, is the most critical characteristic in the traditional RMS for high-volume production [16]. Scalability is integrated into the system by reserving special space, which enables adding new CNCs very rapidly, thereby substantially reducing the ramp-up time for capacity expansion [17].

The principles that guide the design and operations of traditional RMSs have been vividly formulated in [18]. The design of the initial RMS is extremely critical for the system lifetime profitability. Various models and optimization algorithms have been developed to solve the optimal configuration selection problem for the traditional RMS [19–21].

3. A new RMS architecture for mass-individualization

The main challenge in producing a variety of individualized products is that the variation of the cycle time increases dramatically, which consequently decreases the efficiency of the traditional RMSs. To address this challenge, we present a new system architecture that can fulfill the requirements of the mass-individualization paradigm – that is, an architecture that can

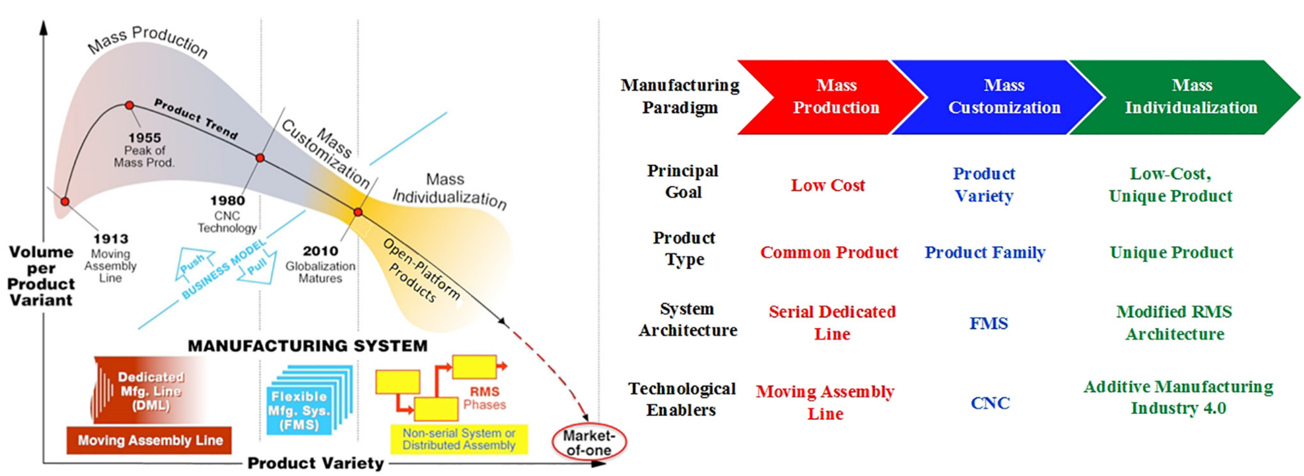

Fig. 1. The evolution of manufacturing paradigms (revised from [7]).

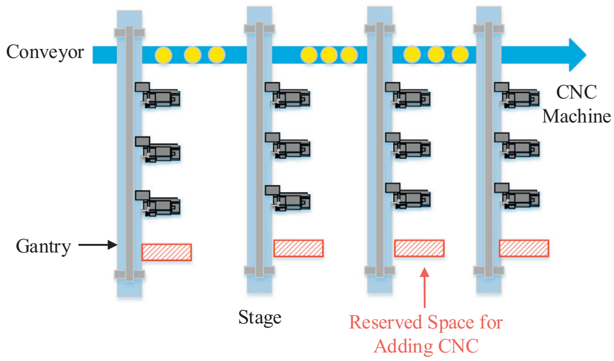

Fig. 2. RMS architecture for high-volume manufacturing.

provide a low-volume/high-mix production at affordable costs. This architecture is modified based on the traditional RMS so it also possesses the six core RMS characteristics.

One example of the proposed architecture is depicted in Fig. 3, where Stage A contains CNC milling machines, Stage B additive manufacturing machines, Stage C another type of CNC machines, Stage D inspection machines, and the assembly of the various parts is done in Stage E either by people, or by human-robot collaboration. In this example, four different product variants are produced simultaneously.

The main architectural difference between the traditional RMS (Fig. 2) and the proposed architecture for mass-individualization (Fig. 3) is the addition of the return conveyor (or return gantry) that can transfer the parts backwards. By implementing both the forward and return conveyors, the products can be processed in extremely flexible routings, substantially improving the system efficiency and resource utilization. Moving the parts backwards is useful if a part that is processed on CNC C2, for example, needs to be transferred to CNC A2 for further processing (i.e., Product III), or if a part fails inspection and correction is needed (e.g., Product IV is detected by the inspection station D3 to be nonconforming, and is then sent back to Stage C via the return conveyor for reprocessing).

A major challenge in the effective utilization of the proposed system is developing scheduling algorithms that maximize the utilization of each machine. The optimal operation sequences may bypass stages or enter one stage more than once, by utilizing both the forward and return conveyors. Assume for example that Product I requires two additive manufacturing processes, which take 20 min and 10 min; while Products II, III, and IV require one additive manufacturing operation each, taking 20, 20, and 10 min, respectively. One can assign the two 10-min tasks of Products I and IV to additive manufacturing machine B1, and the three 20-min tasks of Products I, II, and III to the other three machines in Stage B, respectively, so that each machine in Stage B has an equal processing time, and the machine utilization can be maximized. If the manufacturer has a large number of orders, each of an individual product, the scheduling problem will become extremely complicated and heuristics need to be developed.

Table 1
Comparison of the two RMS architectures.

	RMS for High-Volume Manufacturing	RMS for Mass-Individualization
Returning Conveyor	No	Yes
Product routing	Fixed	Flexible
Machines (in the same stage)	Identical	Identical or Different
Cycle time	Fixed	Large Variations
Buffer capacity	Small	Large
Buffer release policy	First-In-First-Out (FIFO)	Flexible

In addition to having the returning conveyor and flexible product routing, the proposed system architecture for mass-individualization is different from traditional RMS architecture in the following two aspects: (1) Machine and cycle time. Because the mass-individualized products require individualized operations and are produced at low volume, the machines at every stage in the new architecture are not necessarily identical – these machines should be of the same type, but may be scaled or reconfigured to fit a specific market and customers' needs [22]. (2) Buffer capacity and release policy. The large variation of the processing time for individualized products increases the product waiting time in the system. To accommodate this, buffers with relatively large capacities are required in the proposed architecture. Moreover, different from traditional RMSs where each buffer has the same contents and the "First-in-First-Out" (FIFO) release policy can be applied, the buffers in the new architecture contain different products, for which innovative release policies should be developed.

A comparison between the two RMS architectures is summarized in Table 1.

The proposed system architecture is particularly advantageous when manufacturing individualized mechanical or decorative products, where the metal parts are manufactured by the CNCs and the individualized parts are manufactured by using additive manufacturing. For example, such systems can manufacture individualized car interior configuration where various modular components are integrated [23]. Another example is a decorative fountain for a small garden, where each buyer requires a different fountain depending on the buyer's taste and the garden size. The decorative part of the fountain can be produced by additive manufacturing.

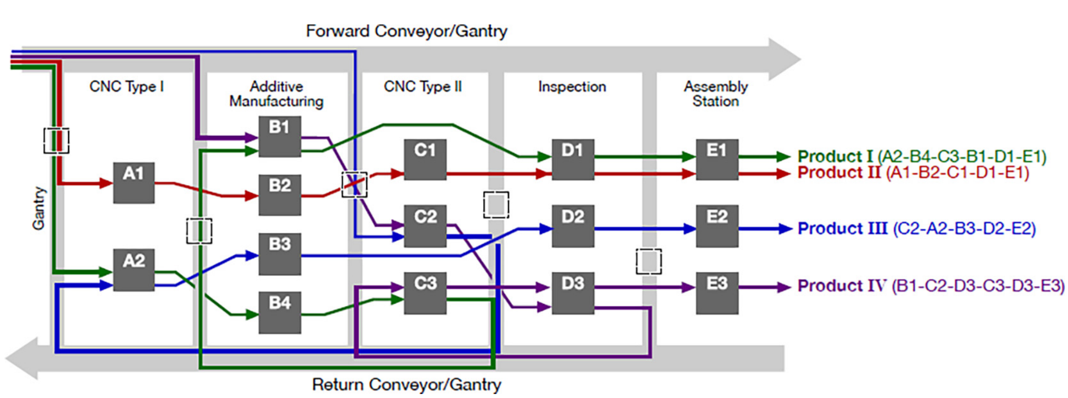

Fig. 3. An RMS architecture for Mass-Individualization production.

4. Optimizing production operations in mass-individualization RMSs

In the mass-customization paradigm, the design of the initial traditional RMS is extremely critical for the system lifetime profitability. The operational principles, however, are relatively straightforward and are focused on improving the system productivity and reliability, which can be achieved by implementing optimal line balancing algorithms [16,24] and by applying efficient maintenance policies [25–29].

By contrast, the initial design of our proposed system for mass-individualization is not critical for the system lifetime profitability given that space for adding new machines is reserved. The main goal of the new mass-individualization system is maximizing resource utilization, which enlarges the manufacturing firm profit. Minimizing the waiting time in buffers is only a secondary goal, if the delivery time is not critical. To achieve this goal requires developing innovative algorithms that address several operational challenges, such as:

(1) **Process Planning:** The new architecture requires an intelligent process planning algorithm that considers the following factors: (a) the product requirement (e.g., urgency and priority of the order); (b) the task precedence constraints for each product; (c) the availability and capability of machines/stations; and (d) the processing time on the machines and the travelling time on both the forward and return conveyors. Based on such information, the algorithm should simultaneously determine (a) at which order to produce the products, (b) the optimal operation sequence for each product, and (c) the optimal production routes, when considering multiple products that are simultaneously produced.

(2) **Real-Time Scheduling:** Developing an efficient production scheduling algorithm is extremely challenging, especially because of the large number of product variants to manufacture and the large variation of the processing time of different products (particularly in the additive manufacturing and assembly stages). Moreover, the scheduling algorithms should react efficiently to unexpected events (e.g., machine/conveyor failures, rush orders) in the system; and should be jointly considered with maintenance scheduling [30]: When one machine is down for maintenance, one can utilize both the forward and return conveyors to reallocate the tasks that are initially assigned on it to other machines in the system.

(3) **Adaptive Control of the Part Routing Traffic:** The product traffic on the forward and return conveyors, as well as the processing time on the different machines, should be coordinated to achieve the overall optimal operation of the entire system. Therefore, for this system a sophisticated part routing algorithm should be developed based on control theory [31]. For example, adaptive control principles that change the processing speed during production [32,33] can be implemented to maximize the throughput. Furthermore, cross-coupled control principles that coordinate the speed of operations among machines [34] can be utilized to optimize the system's overall utilization.

Due to the complexity of the new system architecture and product requirement, the operational problems are significantly more complex than that in traditional RMSs. Models and algorithms that are developed for mixed-model assembly systems [35] may shed light on the optimal operations in the new system. In addition, Industry 4.0 technologies, such as Internet of Things and Cyber Physical Systems [36], may be utilized to facilitate the operational decision-making in the new system architecture.

5. Conclusion

New manufacturing paradigms evolve in response to changing market requirements. Each paradigm requires its own manufacturing system architecture. Observing the emerging mass-individualization paradigm, new system architecture should be developed to cost-effectively produce mass-individualized products. This paper proposes a new manufacturing system architecture for mass-individualized products that is based on the traditional RMS architecture, with a return conveyor that enables cost-effective manufacturing of small-volume, individualized products. The major challenge is the development of system operational algorithms so that the overall production cost is minimized.

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