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# Manufacturing system architecture for cost-effective mass-individualization

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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.

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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

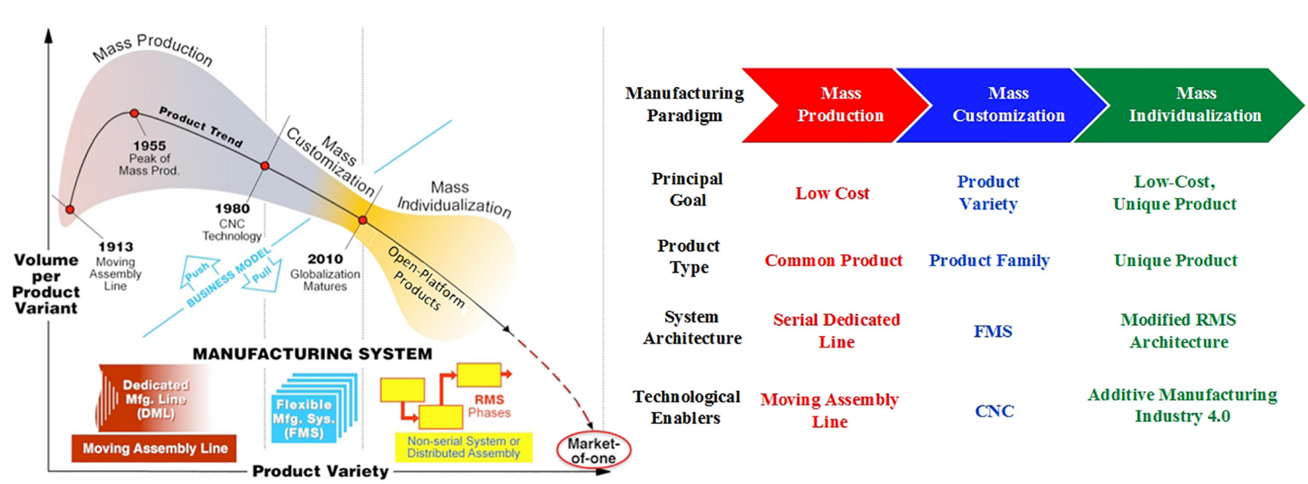


**Fig. 1.** The evolution of manufacturing paradigms (revised from [7]).