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REVIEW ARTICLE

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Reconfigurable manufacturing systems: Principles, design, and future trends

Abstract Reconfigurable manufacturing systems (RMSs), which possess the advantages of both dedicated serial lines and flexible manufacturing systems, were introduced in the mid-1990s to address the challenges initiated by globalization. The principal goal of an RMS is to enhance the responsiveness of manufacturing systems to unforeseen changes in product demand. RMSs are cost-effective because they boost productivity, and increase the lifetime of the manufacturing system. Because of the many streams in which a product may be produced on an RMS, maintaining product precision in an RMS is a challenge. But the experience with RMS in the last 20 years indicates that product quality can be definitely maintained by inserting in-line inspection stations. In this paper, we formulate the design and operational principles for RMSs, and provide a state-of-the-art review of the design and operations methodologies of RMSs according to these principles. Finally, we propose future research directions, and deliberate on how recent intelligent manufacturing technologies may advance the design and operations of RMSs.

Keywords reconfigurable manufacturing systems, responsiveness, intelligent manufacturing

1 Introduction

The world of manufacturing has changed dramatically in the last 100 years in response to economic and social circumstances. Driven by different requirements in various periods, manufacturing technologies and new paradigms have been introduced to address economic challenges, and respond to social needs. Facing the requirement of cost-effectiveness, Henry Ford invented the moving assembly line in 1913, which began the mass production paradigm. In the 1970s, the Japanese manufacturing industry started formulating lean manufacturing principles, and since then consistent product quality has been a major focal point. In the late 1970s, the development of computer numerical control (CNC) machines facilitated the creation of flexible manufacturing systems (FMS), which enabled producing a variety of products on the same manufacturing system [1].

Globalization that began in the 1990s transformed the competitive landscape. Manufacturing companies started facing unpredictable market changes, including rapidly varying product demand, and frequent introduction of new products. This made the design of manufacturing systems for new factories a major challenge, because it impacts the factory performance for many years after the factory design. It became essential that new factories should possess a new type of manufacturing system — A system designed for rapid responsiveness to unforeseen market surges and unanticipated product changes.

In response to this challenge, in 1995, Dr. Koren proposed designing factories with new system architecture that he called “reconfigurable manufacturing system.” The RMS has an open system architecture that enables adding machines to existing operational systems very quickly, in order to respond (1) rapidly, and (2) economically to unexpected surges in market demand [2]. Utilizing RMS enables building a “live” factory that its structure changes cost-effectively in response to markets and customers’ needs, so it can keep supplying products at competitive price for many years after the factory design.

In 1996, Dr. Koren’s proposal to form an “engineering research center for reconfigurable manufacturing systems” (ERC-RMS) was approved by the U.S. National Science Foundation (NSF). The ERC-RMS was established at the University of Michigan with a grant of 33 million USD for 11 years from NSF. Matching funds of 14 million USD

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were granted by industry and the State of Michigan. The center created the RMS science base and invented RMS technologies that were implemented in the U.S. automotive and aerospace industries, enhancing thereby the industry competitiveness.

It is worthwhile to note that the State of Michigan is home to notable inventions in manufacturing. In 1913, the first moving assembly line, invented by Henry Ford, was installed at the Ford Highland Park plant in Michigan. The second breakthrough invention was numerical control that was invented by John Parsons [3] in his company in Traverse City, Michigan. The recent innovation is the RMS. RMS is a new type of manufacturing system that can change its system structure and resources rapidly and cost-effectively, in order to possess "exactly the capacity and functionality needed, exactly when needed." Figure 1 illustrates how the inventions from Michigan have transformed the landscape of manufacturing paradigms.

The ERC-RMS has defined the key characteristics for RMS, and invented patents and software packages that have provided the basis for developing new reconfiguration technologies. The developed technologies have been successfully implemented in U.S. automotive companies —Ford, General Motor, and Chrysler — which have increased their system responsiveness [4] and created substantial economic value for these firms [5]. RMS is not only an open-architecture manufacturing system that can respond to the challenges of globalization [6], but also one that boosts productivity, enhancing thereby the competitiveness of manufacturing enterprises. RMS can also achieve agility and sustainable manufacturing [7,8].

In this paper, we formulate the principles that guide the design and operations of RMS. According to these principles, we review and evaluate the state-of-the-art RMS design issues presented in the literatures. Possible future developments of RMS are discussed as well.

2 RMS characteristics and principles

The three main goals of all manufacturing systems are cost, product quality, and responsiveness to markets. Responsiveness is achieved by designing manufacturing systems for upgradable capacity and modifiable functionality. Comparing RMS with other types of manufacturing systems from the perspective of these goals, highlights the advantages of RMS.

2.1 RMS combines advantages of dedicated lines and flexible systems

In the last decades of the 20th Century the manufacturing industry utilized two types of common manufacturing systems: Dedicated manufacturing lines (DMLs) and FMSs. DMLs are designed to enable mass production of a specific product at a very low cost and very high throughput. FMSs are designed to enable production of any product (confined within a geometric envelope), but compared with DMLs their throughput is very low.

The DML is designed with fixed automation that produces the company's core product at a very high rate. During the production, many tools can operate simulta-

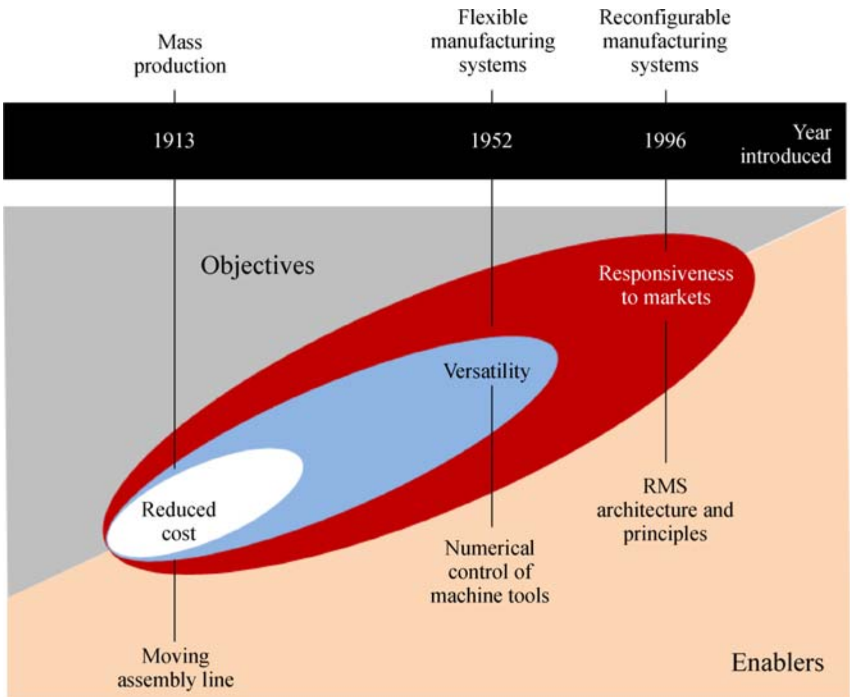

Fig. 1 Manufacturing inventions initiated in Michigan

neously on every machine in the line, leading to extremely high system throughput. The DML structure is fixed and cannot be changed neither to increase the throughput nor to produce a different product. If the market requires higher throughput, the DML cannot supply the full demand and the firm loses sale opportunities and consequently may lose market share. If the market requires a different product, the DML is useless and must be scrapped.

By contrast, FMSs possess general flexibility that can produce a variety of products, but their production is by far more expensive than producing on DMLs. The FMS consists of general-purpose CNC machines and other forms of programmable automation. By contrast to a DML machine on which many tools operate simultaneously, each CNC machine uses a single tool during its operation. Therefore, the throughput of FMS is by far lower than that of DML (for the same investment cost). The main drawbacks of FMS are the high investment cost (on both machines and tooling) and the relatively low throughput. Due to the high investment on CNC equipment, and the large number of cutting tools in the system, producing high volumes on FMS becomes a significant economic issue.

The main advantage of RMS is that its functionality and capacity can be changed (1) rapidly and (2) cost-effectively. It is a feature that neither a DML nor an FMS possesses. The throughput of RMS is higher than the FMS throughput, but it is lower than that of a DML (for the same investment cost). The RMS is designed around producing a family of parts (e.g., cylinder heads, which are manufactured in reconfigurable machining systems) or products (e.g., engines, which are assembled in reconfigurable assembly systems), so its flexibility is by far higher than that of a DML. A thorough comparison of these three types of manufacturing systems is presented in Ref. [9], and their comparison with adjustable manufacturing systems is presented in Ref. [10].

2.2 Core characteristics and principles of RMS

The RMS is defined as follows: An RMS is designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust its production capacity and functionality within a part family in response to sudden changes in market or regulatory requirements.

The RMS possesses six core characteristics that are summarized in Table 1.

The six core RMS characteristics reduce the time and cost of reconfiguration, thereby enhancing system responsiveness. They are widely implemented today in the automotive, aerospace, food and beverage industries in the U.S. Based on these RMS core characteristics, the following RMS principles are formulated.

RMS principles:

1) Design manufacturing system capacity for cost-effective adaptation to future market demand (scalability);

2) Design the manufacturing system for adaptation to customer's new products (convertibility);

3) Design optimally embedded product quality inspection into manufacturing systems (diagnosability);

4) Design the manufacturing system around a product family (customization);

5) Maximize system productivity by reconfiguring operations and reallocating tasks to machines;

6) Perform effective maintenance that jointly maximizes the machine reliability and the system throughput.

The first four are system design principles that utilize the characteristics of "modularity" and "integrability" to enable cost-effective design. For example, at the system level, every machine is a module and the integration is done with material handling systems (e.g., a gantry or a conveyor). Principles 5 and 6 are system operational principles that improve the system productivity and reliability. Based on Principle 5, the ERC-RMS created system-balancing software that was implemented in 22 factories of General Motors and Chrysler and generated substantial savings. For example, Mr. Brian Harlow, VP Chrysler reported: "By using the ERC-RMS line-balancing software, Chrysler succeeded in saving 10% of the operating costs on engine assembly lines in the Mack

Table 1 Core characteristics of RMS

Characteristic	Interpretation
Scalability (design for capacity changes)	The capability of modifying production capacity by adding or removing resources and/or changing system components
Convertibility (design for functionality changes)	The capability of transforming the functionality of existing systems and machines to fit new production requirements
Diagnosability (design for easy diagnostics)	The capability of real-time monitoring the product quality, and rapidly diagnosing the root-causes of product defects
Customization (flexibility limited to part family)	System or machine flexibility around a part family, obtaining thereby customized flexibility within the part family
Modularity (modular components)	The compartmentalization of operational functions into units that can be manipulated between alternative production schemes
Integrability (interfaces for rapid integration)	The capability of integrating modules rapidly and precisely by hardware and software interfaces

Avenue Engine Plant in Detroit, which is extremely significant."

Mathematical definitions have been proposed for the RMS key characteristics [11], especially for scalability [12], convertibility [13], and an integrated multi-attribute reconfigurability index [14]. These characteristics and principles are applied to the design of different types of reconfigurable manufacturing systems, including machining systems, fixturing systems, assembly systems, and material handling systems [15,16], by using various models [17–20] and methodologies [21,22].

2.3 Examples of reconfiguration technologies

In order to illustrate the RMS core characteristics, three examples of reconfiguration technologies — machine, inspection, and system — are presented below.

2.3.1 Reconfigurable machine tools

Reconfigurable machine tools (RMTs) are designed for a specific range of operational requirements, and can be rapidly converted from one configuration to another. The design of the RMT is usually focused on a specific part family, and should be rapidly adjustable to changes in its structure and/or operations to manufacture various parts of that part family. The world-first patent on RMT was issued in 1999 [23].

Figure 2(a) shows an arch-type RMT that was built by the ERC-RMS and exhibited in 2002 at the International Manufacturing Show in Chicago. It was designed to drill and mill on inclined surfaces in such a way that the tool is perpendicular to the surface. This RMT is reconfigurable to five angular positions of the spindle axis ranging from –15° to 45° at steps of 15°, and the reconfiguration from one angle to another takes less than 2 min. It was utilized to mill and drill engine blocks at angles of 30° or 45°.

2.3.2 Reconfigurable inspection machine

The reconfigurable inspection machine (RIM) represents a class of in-process inspection machines that can be reconfigured to fit the inspected part geometry. The world-first patent on RIM was issued in 2003 [24].

Figure 2(b) shows an example of an RIM that is composed of a precision conveyor moving the part along one accurate axis of motion within an array of electro-optical devices, such as digital or line scanning cameras, and laser-based sensors. Depending on the part that is being measured, the location and number of sensors in the RIM can be reconfigured to fit the geometry of the inspected part. The RIM depicted in Fig. 2(b) was configured to measure cylinder heads. On one side of the part there are two laser sensors; on the other side there are additional three laser sensors as well as an accurate computer-vision system.

In 2006, General Motors installed an RIM that was developed by the ERC-RMS at its engine plant in Flint, Michigan. This RIM utilized machine vision to efficiently detect small surface pores (<1 mm) on engine blocks at the line speed to inspect each part. Utilizing the RIM has significantly improved the quality of the product and greatly reduced the number of recalls because of noisy engines.

2.3.3 Reconfigurable manufacturing system

A typical RMS integrates CNC machines and several RMTs that are utilized to manufacture a family of products, as well as product quality inspection machines that inspect the product during its manufacturing (i.e., not only at the end of the production line). The structure of an RMS is easily changeable to enable adding more production resources. The option of reconfiguration by adding production resources should be planned at all levels,

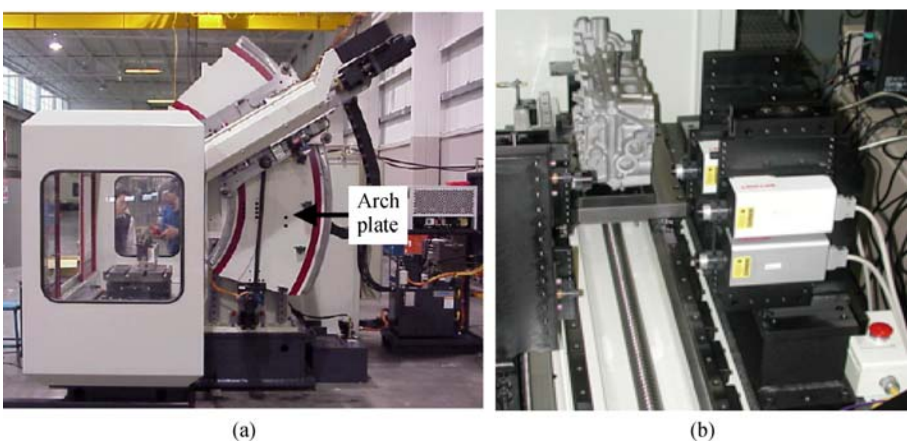

Fig. 2 Reconfiguration machine tool (RMT) and reconfigurable inspection machine (RIM) developed at the ERC-RMS. (a) RMT; (b) RIM

hardware, software and controls, to enable adding machines, in-line inspection stations, gantries, etc. The world-first patent on RMS was filled in 1998 [25].

The Ford Windsor Engine Plant that was designed and built in 1998–2000 contains about 120 CNC machines that are arranged in a reconfigurable system architecture that consists of 20 stages, with 6 machines per stage (as shown in Fig. 3) [26]. Ford Motor Co. called this system: "Flexible, reconfigurable manufacturing system." Flexible because the CNC machines can produce multiple product variants.

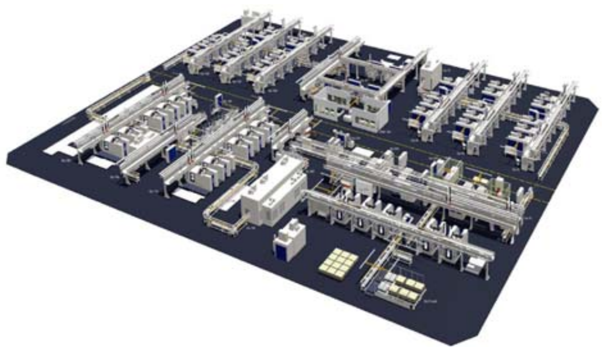

Fig. 3 Ford Winsor Engine Plant with CNC machines [26]

Note that, at the system level, each CNC machine is a module, and its function can be converted when a new type of part is required to be manufactured by the system. At each stage of the system, there are multiple parallel CNC machines that are integrated into the system by using gantries to load and unload the CNCs. Furthermore, all the stages in the system are integrated into one large system by overhead gantries that transport parts between the stages. This system possesses the characteristic of diagnosability by including in-line inspection stations that are located next to critical machining stations. This system is scalable, namely, it is easy to add machines to the system to increase the system capacity. Actually, since 2000, the Ford plant went through three reconfigurations in which capacity was added. Note that, if the CNCs in some stages were replaced by RMTs that can process a certain part family, then the customization characteristic would be implemented.

The RMS principles are widely used in the design of reconfigurable machines [27], machining systems [15], and assembly systems [16]. Next, we review the related research problems in system-level design and operations. Different from other general reviews [11,15,16,22], this paper reviews the design and operations of RMSs according to the principles that we have formulated in Section 2.2.

3 Design and operations of reconfigurable manufacturing systems

The designer of a manufacturing system has to determine: 1) The system configuration — the way that machines are arranged and interconnected in the system; 2) the equipment — the number and type of machines, the material handling system, and the in-line inspection equipment; 3) the process planning — assigning operations to each machine in the system.

3.1 Selecting the system configuration

The performance (e.g., throughput) and characteristics (e.g., scalability) of the manufacturing systems significantly depend on the system configuration [28]. We elaborate here on three types of manufacturing system configurations: Serial production lines, parallel systems, and reconfigurable manufacturing systems. The system type should be carefully determined at the system design stage because once determined, it cannot be changed in the future.

Depending on the business goals of the manufacturing enterprise, four major performance metrics should be considered and prioritized when selecting the system configuration:

1) Investment cost;

2) Throughput resilience to machine failures;

3) Speed of responsiveness to markets (i.e., increasing throughput to match future higher demand);

4) Level of consistency in product quality in mass production environment.

Traditional configurations of manufacturing systems are mainly of two types: Pure serial lines that consist of dedicated or flexible machines, and pure parallel systems that are composed of CNC machines. The drawbacks of serial machining lines are the high sensitivity of their throughput to machine failures, and the lack of responsiveness to changing markets. The parallel configurations are not sensitive to machine failures, and can easily increase their throughput by adding more machines in parallel. However, parallel configurations are very expensive because: 1) Each machine must be capable of performing all the production tasks, which significantly increases the capability of each machine and consequently its cost, and 2) the total tooling cost in the system is expensive (the tool magazine of each machine must include all tools needed to produce the part). Because of these drawbacks, parallel systems are rarely found in practice.

For large machining systems, there are two types of configurations that are commonly used in industry: 1) A configuration that consists of several serial lines arranged in parallel (SLP), and 2) RMS configuration that consists of several stages, where each stage consists of multiple parallel identical machines (usually CNCs or reconfigurable machines). The schematic layouts of the SLP and RMS configurations are shown in Fig. 4. Both systems in Fig. 4 have the same number of machines.

The principal difference between SLP and RMS configurations is that RMS has crossover connections that enable operating the three machines in each stage in a parallel mode. In practice, a gantry that operates in each stage enables these connections. The gantry loads and unloads parts to or from each machine in that stage. The cost of these gantries makes the RMS more expensive than the SLP configuration. However, the two major advantages of RMS are: 1) Resources (e.g., machines) can be added very quickly and cost-effectively, enabling thereby high speed of response to changing markets; 2) if the gantries availability is higher than the machine availability, the throughput dependency on machine failures in RMS is smaller than that in serial lines.

Freiheit et al. [29] developed a model that compares the throughput of SLPs and RMSs. It proves that the RMS configuration has a higher throughput for large systems (i.e., systems with more stages or more machines per stage). Gu [30] extended the analysis to systems with buffers, and showed that RMS is advantageous when small buffers are added to the system. In addition to throughput, Koren et al. [31] compared the performance of SLP and RMS configurations from other perspectives, including cost, responsiveness, and consistency in product quality.

Moreover, in an RMS configuration, each stage may not necessarily have an identical number of machines. Therefore, practically, for the same number of machines there are more RMS configurations than SLP configurations. Various complex optimization problems have been formulated for selecting the optimal RMS configuration. For example, Youssef and ElMaraghy [32] proposed a procedure for modeling and optimization of multiple-aspect, multi-part RMS configurations, with several future reconfiguration plans considered. Dou et al. [33] built an optimization program that determines the system configuration, the type of machines, as well as the operations assigned to each stage. Goyal et al. [34] developed algorithms to choose the optimal RMS configuration based on the reconfigurability and operational capability of RMTs.

Note that for reconfigurable assembly systems, determining the optimal configuration is more complicated than that in reconfigurable machining systems. Webbink and Hu [35] studied how the assembly system configuration can be generated given the number of assembly stations. Benkamoun et al. [36] reviewed the main strategies dealing with the variety and product change in assembly system design.

3.2 Utilizing the RMS principles to design and operate the system

We elaborate below on how the six RMS principles are utilized to optimize the system design and its operations.

3.2.1 Capacity planning by utilizing Principle 1

Capacity means the maximum number of products that a manufacturing system can produce annually. Designing the capacity of a new system is a major challenge in an environment of future unpredictable market changes. If in the future the market demand becomes lower than the system capacity, machines will stay idle, which consequently causes a huge capital loss. And if the future demand is higher than the capacity, the firm will lose sale opportunities, and consequently may lose market share.

To build a factory with a large manufacturing system may take two to three years, and then it is operational for 12 to 25 years. The designed capacity of the new manufacturing system is critical to the factory future profitability, but the enterprise business unit provides its forecasting for a projected demand for the next years (e.g., up to 8 years) with statistical data. How can this forecasting be utilized to design an optimal manufacturing system?

The RMS provides an economical response to this challenge. The RMS is built according to *Principle 1: Design manufacturing system capacity for cost-effective adaptation to future market demand*. Various models have been developed to determine the optimal capacity at the system design stage, as well as the potential capacity expansion strategies in the future. For example, Narongwanich et al. [37] investigated the optimal capacity

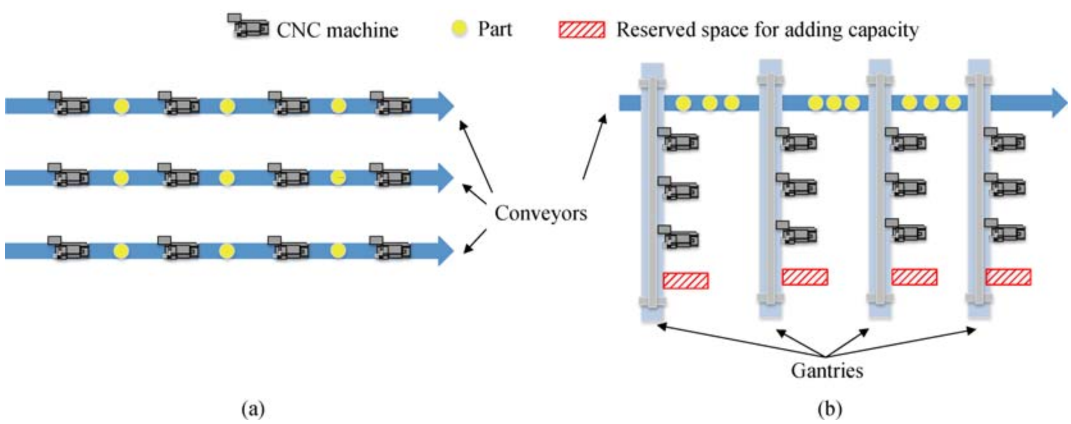

Fig. 4 Schematic layout of (a) SLP configuration and (b) RMS configuration

portfolio of a firm that utilizes two types of systems — a dedicated manufacturing system (DMS) and an RMS. As Ford VP, Mr. Krygier, reported in Ref. [27], Ford utilized their models in justifying purchasing an RMS for the new Windsor Engine Plant. Deif and ElMaraghy [38] considered the capacity-planning problem for an RMS where the cost function incorporates the physical capacity-based cost as well as the cost associated with the reconfiguration process. Gyulai et al. [39] studied the capacity-planning problem for an assembly system in order to decide whether a certain product should be assembled on a dedicated or on a reconfigurable line, or it should be outsourced. Renne [40] developed a genetic algorithm and Monte Carlo simulation based model to design a hybrid manufacturing system composed of dedicated, flexible and reconfigurable machines. Asl and Ulsoy [41] developed the capacity investment and adjustment policy for a reconfigurable manufacturing system by using stochastic optimal control and feedback control approaches, where the capacity can be added to the system or removed from the system at a cost. Spicer and Carlo [42,43] simultaneously considered the investment and operational costs for an RMS by considering system reconfiguration, and developed heuristic policies to determine the optimal system configurations at the design stage.

3.2.2 Functionality planning by utilizing Principle 2

In addition to the capacity, the system functionality is another critical factor in developing system reconfiguration policies. The system functionality focuses on changing the system from manufacturing one product to another of the same product family. It requires consequent changes in the process planning and the configuration.

The RMS is designed according to *Principle 2: Design manufacturing systems for adaptation to customer's new desires*. This principle requires designing systems with the core characteristic of convertibility, which can effectively transform the RMS to produce a new product. Maier-Speredelozzi et al. [13] pioneered the mathematical definition of the convertibility measure for manufacturing systems.

The RMS may contain both dedicated resources for specific products, as well as flexible resources for multiple products. Van Mieghem [44] studied the optimal investment ratio between dedicated and flexible capacities, where the "dedicated" and "flexible" capacity in this research means the capacity that can be used to produce one specific product or multiple products, respectively; namely, this study is from the product viewpoint. Ceryan and Koren [45] extended the model to a multi-stage problem and studied the optimal investment strategy for a system that manufactures two products. Matta et al. [46] formulated the reconfiguration problem of production systems by using a dynamic programming approach, and proposed the optimal reconfiguration policy to react to product changes. Bryan et al. [47] developed a mathematical model to study the co-evolution of product and the manufacturing system.

Note that, in the capacity and functionality planning problems of RMSs, ramp-up is an important consideration when developing system reconfiguration policies. It is defined as "the time interval it takes a newly introduced or just reconfigured production system to reach sustainable, long-term levels of production, in terms of throughput and part quality, considering the impact of equipment and labor on productivity" [2]. The RMS has unique characteristics that allow high-resolution scalability and rapid responsiveness, which reduce the ramp-up period. Matta et al. [48] investigate the impact of ramp-up period on the reconfigurable policy, by considering both capacity expansion and reduction. Niroomand et al. [49] built a mathematical programming model to discuss about how different reconfiguration characteristics (e.g., the time needed for reconfiguration and the ramp-up period) impact the design of manufacturing systems.

3.2.3 Maintaining product quality by utilizing Principle 3

Maintaining product quality is a critical consideration when designing manufacturing systems. Each machine has a tolerance, and the dimensional deviation from the norm accumulates as the part moves along the system. In a serial line there is only one production route, and therefore the range of the dimensional deviation is small. The number of production routes in a serial-lines-in-parallel configuration is equal to the number of lines, which is small. However, in the RMS, the number of possible production routes is very large. Assuming there are n stages, and m parallel machines in each stage, there are m^n production routes. The RMS built at Ford Windsor Engine plant has 6 machines in a stage and about 20 stages, so that the number of possible routes is huge (i.e., around 3.6×10^{15}). The designer should be aware of the huge number of routes issue in RMS, and pay prime attention to the product quality issue.

The large number of production routes causes two problems. First, it increases of the variation of the product dimensional quality. Second, if there is any abnormal machine in the system, it is extremely difficult in the RMS case to trace that machine by just inspecting the quality of the final product. Therefore, the system designer should pay attention to the quality of the products in an RMS by implementing *Principle 3: Design optimally embedded product quality inspection into manufacturing systems*. If there are any quality issues detected by in-line inspection stations, the system should be able to locate the root-cause quickly, and take suitable actions (e.g., preventive maintenance).

Stream-of-variation (SoV) [50,51], a method based on the state-space model that is utilized in control system, has been developed to systematically analyse the quality propagation in multi-stage manufacturing systems, in order to identify the root-cause and reduce the product variation. Monte Carlo simulation methods can also be used to analyze the product variation [52]. Based on the SoV model, Kristianto et al. [53] developed a two-stage programming model to investigate the reconfiguration problem of RMS. In addition to the SoV model, Abad et al. [54] developed an algebraic expression to represent the quality stream in more complex configuration, such as mixed-model assembly systems.

In order to measure the product quality in-line, it is recommended to integrate RIMs into the RMS. When designing the system configuration, experts should decide on the critical locations where RIMs should be installed. Moreover, a return conveyor can be added into the RMS to route back parts that need to be reprocessed. Figure 5 illustrates the design of an RMS with inspection stations and a return conveyor. Optimizing the number and location of the inspection stations is an important issue that should be investigated in the future. On the one hand, reducing the frequency of inspection decreases the system capital cost; on the other hand, increasing the number of in-line inspection stations reduces the number of parts rejected because of quality loss.

3.2.4 Formulating a product family by utilizing Principle 4

In order to reduce the cost and improve the system efficiency, RMSs are designed according to *Principle 4: Design the manufacturing system around a product family*. For utilizing RMSs, products are grouped into families, each of which requires its own system configuration. The system is configured to produce one product family. The system can produce every product within this product family with high efficiency, and it can be done without reconfiguring the system (or with simple alternation). Once the current product family is phasing out, the system is reconfigured to produce another product family, and so forth [55]. Therefore, finding the similarity between products and forming the right product family improve the system efficiency.

A product family consists of products that share similarities. In order to formulate the product family, a similarity index could be established to measure the similarity between different products. Kimura and Nielsen [56] developed a framework for the relationship between product functionality and manufacturing resources. Their framework yields to a design method for product family structure, which realizes the required product functional variety with efficient utilization of manufacturing resources. Abdi and Labib [57] proposed a novel “reconfiguration link” that incorporates the tasks of determining the product families and selecting the appropriate family at each configuration stage. An analytical hierarchical process (AHP) model is used while considering both market and manufacturing requirements, which is illustrated by a case study in Ref. [58]. Galan et al. [59] also used the AHP method to build the similarity matrix among different products, by considering the product requirements such as modularity, commonality, compatibility, reusability, and demand. Based on the similarity matrix, the average linkage clustering algorithm was applied to formulate the product families. In addition, an analytical network process (ANP) model is proposed by Abdi [60] to incorporate all the outlined decisive factors and major criteria and elements influencing the product family formation and selection. Battaïa et al. [61] developed a combinatorial optimization problem for part family formation and configuration design in reconfigurable machining systems.

On the operational level, operation-scheduling problems are studied that optimize the sequence of producing different products, in order to improve the system

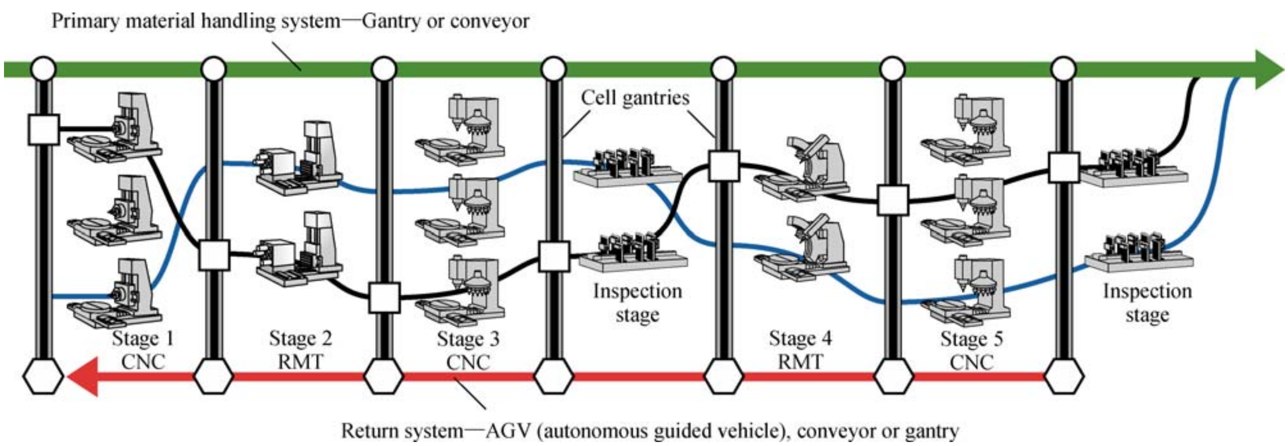

Fig. 5 A futuristic RMS configuration with RIMs and a return conveyor

efficiency. The operational sequence should also be considered in analyzing the similarities of products and determining the product families. For example, Goyal et al. [62] developed an operation sequence based BMIM (bypassing moves and idle machines) similarity coefficient that utilizes several concepts in set theory, such as the longest common subsequence (LCS), and the minimum number of bypassing moves and the quantity of idle machines. Wang et al. [63] further combined LCS and the rest of the operation to construct the shortest composite super-sequences. These similarity coefficients are used as the basis for part clustering and family formation.

In addition to machining systems, the concept of product family formation has been applied to assembly systems [64] and disassembly systems [65].

3.2.5 Process planning and line balancing by utilizing Principle 5

Process plan specifies the components and operations that are needed to manufacture a workpiece into a part or a product. The process planning in an RMS requires the consideration of multiple product families, or multiple product generations.

Effective process planning can reduce the reconfiguration cost, improving thereby the system efficiency. For example, Azab and ElMaraghy [66] proposed the idea of "reconfigurable process planning," and formulated it as an integer-programming problem. Azab et al. [67] used simulated annealing method to sequence the machining operations in order to reduce the system idle time. Bensimaine et al. [68,69] investigated the process-planning problem in RMS by developing optimization algorithms for different objectives.

Each time that the system has to manufacture a new product, a new process plan is needed. It includes the sequence of all operations needed to complete the product. The operations should be distributed among the machines in the system in order to balance the system according to *Principle 5: Maximize system productivity by reconfiguring operations and reallocating tasks to machines*. A new process plan is needed each time that machines are added to the system to increase the system capacity. The objective is to make as close as possible equal operation times on each machine or stage in the system in order to balance the system, which maximizes the system throughput.

Transfer line balancing problem has been extensively studied in the literature. In an RMS environment, various models and methods have been developed to formulate and solve the line-balancing problem. For example, Wang and Koren [12] developed an optimization algorithm based on genetic algorithm (GA) that determines simultaneously at which stage to add machines, and how to rebalance the modified system (by shifting operations among stages) in order to maximize throughput. This algorithm was adopted by General Motors to be used in practice. In industrial utilizations several practical constraints were imposed, such as the tasks precedence relationship, and the product facets on which a specific operation is needed. Borisovski et al. [70] also used the GA method as well as a set-partitioning model [71], to solve the line-balancing problem in RMS, with the objective of minimizing the set-up times. In addition, Essafi et al. [72] studied the line-balancing problem in an RMS consisting of mono-spindle head CNC machines. Makssoud et al. [73] developed an optimization problem in order to minimize the reconfiguration cost of an RMS. They formulated the problem as a mixed integer-programming problem in order to consider the compromise between introducing new equipment and reusing old one. Delorme et al. [74] studied the line-balancing problem in RMS to deal with the trade-offs between the cost and productivity.

Moreover, the control system needs to be developed for enabling task reallocation and system rebalancing. For example, da Silva et al. [75] proposed a control architecture based on the Petri nets, service-oriented architecture, and holonic and multi-agent system techniques, in order to design the control system in an RMS that considers reconfiguration in functionality and production capacity.

3.2.6 Optimizing maintenance operations by utilizing Principle 6

In order to improve the system reliability and the product quality, maintenance needs to be performed. According to an ERC-RMS survey conducted at the U.S, and European automotive and machine tools industries [76], maintenance is ranked second of all the cost factors. Hence, utilizing an effective maintenance policy is a very important operational decision.

Although maintenance policies have been extensively studied in the literature, most of the studies focus on single machines. The literature on maintenance policies in large manufacturing systems, especially in RMSs, is very limited. On the system level, maintenance policies should be developed according to *Principle 6: Perform effective maintenance that jointly maximizes the machine reliability and the system throughput*. System-level maintenance decision-making is complex because of the following reasons [77]: 1) There are different types of maintenance policies (e.g., inspection, preventive maintenance, corrective maintenance), and all have to be addressed simultaneously at the system level; 2) multiple sources of information should be integrated, from machine level (e.g., health states of machines) to system level (e.g., buffer contents, throughput requirement, and the availability of maintenance personnel). The maintenance decision-making in large manufacturing systems addressed in the literature includes maintenance resource allocation [78], maintenance opportunity identification [79–81], and maintenance scheduling [82].

Note that in RMSs, although all the parallel machines in the same stage perform the same operations, the health condition of each machine may be different. In addition, the maintenance policies in RMS should be considered jointly with the reconfiguration process. These factors cause the maintenance decision-making problem to be even more difficult.

Due to the complexity of the problem, most maintenance policies in RMSs are developed by using simulation-based approaches. For example, Zhou et al. [82] developed an integrated reconfiguration and age-based maintenance (IRABM) policy and applied it to an RMS. Xia et al. [83] considered the RMS maintenance opportunities, and proposed a reconfigurable maintenance time window (RMTW) method to make real-time schedules for system-level opportunistic maintenance, which can respond rapidly to various system-level reconfigurations. Considering the operation process rebuilding of manufacturing/operation systems, Xia et al. [84] proposed a dynamic interactive bi-level (i.e., machine and system) maintenance methodology to satisfy rapid market changes. These proposed policies are more cost-effective than the conventional preventive maintenance policies. However, compared to other RMS issues, the maintenance decision-making problem is insufficiently explored in RMSs.

4 Future research trends

In the current age of intensified globalization, manufacturing enterprises are facing now more competitive pressure than 20 years ago, when RMS was introduced. The challenges of unpredictable market demand, shorter product life cycles, greater product variety, lower production costs, and higher environmental regulations, have all intensified. To retain "sustainable competitiveness" [85], possessing reconfigurability becomes even more important: In addition to rapid responsiveness and lower cost, a higher reconfigurability can lead to a better environmental performance [86]. Moreover, based on the recent technologies in "Industry 4.0", the development of RMS and modern manufacturing systems is entering a new era. In this section, we propose several potential future research trends, and deliberate on how the advances in recent technologies can improve the design and operations of RMS.

4.1 Concurrent design of product, manufacturing systems, and business strategies

The product development process of a manufacturing enterprise involves the decision-making on the following three aspects [6]: 1) The product characteristics subject to cost and engineering constraints; 2) the manufacturing systems that produce the product, including the system configuration, the selected machines (e.g., functionality, power, accuracy, ranges, and number of axes), and the process parameters (e.g., task precedence, task type, access direction, dimension, accuracy and power needed to perform the task); and 3) the business strategy, or marketing strategy, such as the prediction of sales, the determination of the product price, and the decision on when to introduce a new product into the market. The objectives from these different aspects are usually coupled, but sometimes competing. For example, from manufacturing perspective, it is preferable to reduce the product complexity; however, such reduction may result in a product that is less desirable in the marketplace. Therefore, a joint consideration is needed to solve the trade-off, and concurrent design methods should be developed. Most of the current literatures are focused on only one aspect of the design problem, and some studied the joint decision-making on the development of the product and manufacturing system [46,62,63]. However, new research is needed on integrating the business objectives into the engineering decision-making process. Michalek et al. [87] considered the concurrent design problem that balanced the marketing and manufacturing objectives in a production line. The design problem was decomposed into various sub-problems. The optimal design solution should not only determine the optimal manufacturing systems, but must also develop the product evolution strategy as well as the long-term marketing strategy.

Note that, the concurrent design problems are challenging because of the multiple factors that need to be considered simultaneously. Note that even if just the manufacturing system itself is considered, complex problems, such as joint process planning and line balancing [5,88], or joint process planning and scheduling [69,89,90], must be developed. Such complicated design optimization problems are usually formulated as mathematical programming problems where heuristics need to be developed to find the solution. Renzi et al. [91] reviewed non-exact meta-heuristic and artificial intelligence methods that were applied to solve such RMS design problems. In the future, more complex comprehensive design methods that integrate the business objectives into the engineering should be formulated. Furthermore, a generic design method that synthesizes the different design aspects is still in need [22].

We elaborate below on two topics that require comprehensive studies in product-system-business design strategies.

1) The role of the cooperate culture in developing product-system-business strategies. Cooperate culture have a profound impact on the system design; it is an emerging area that we call "social-engineering." The product-system-business design problem is very challenging when these factors are considered. For example, a dilemma may rise between the marketing and the

manufacturing departments of a manufacturing enterprise: The former requires products that are more desirable by the market, while the latter prefers to manufacture less complex products, which, in turn, will reduce their price and make them affordable to buyers. To resolve this dilemma, future research should be conducted on the relationship between the enterprise management structure and the firm working culture.

Cooperate culture can affect the system design and operation strategies. For example, Koren et al. [92] investigated how the corporate culture (e.g., the reaction time to urgent maintenance request) may affect the selection of the system configuration, and pointed out that a different corporate culture may explain why the U.S. and Japan prefer different system configurations.

2) The potential advancement of the equipment and operations. RMSs can achieve high system sustainability due to its capability of producing multiple generations of products. However, in order to improve the system efficiency during its entire lifecycle, one should consider not only the current state-of-the-art technology but also how technology may evolve in the future. For example, more reliable machines, innovative control technology, new sensors may impact the optimal system design (e.g., system configuration). For example, as pointed out in Ref. [29], with higher machine availability, an SLP configuration has a higher throughput than the RMS configuration.

4.2 Improving the effectiveness and efficiency of real-time operational decision-making

Compared to the production planning problem, the real-time operational decision-making for RMSs is limited in literature. The main challenge is the complexity of the system, and the requirement of an efficiency of the developed strategy/algorithm that can be used in real time.

As mentioned above, maintenance decision-making is very complicated; it is even more complicated when the maintenance and production scheduling problems are jointly considered. For example, based on the product requirement and the health condition of machines, how to optimally perform maintenance, and at the same time, choose the production routes by using the machines that are not under maintenance? Such problems are very complicated, especially when the decision is needed in real-time. Most of traditional analytical and decision-support tools are unable to deal with such a level of complexity, or they can only deal with such complexity very inefficiently.

The effectiveness and efficiency of real-time decision-making can be improved by applying intelligent manufacturing techniques, such as multi-agent systems [93], cloud manufacturing [94], digital manufacturing [95] and cyber physical systems [96]. For example, He et al. [93] developed a novel mechanism that enables manufacturing resources to be self-organized cost-efficiently within structural constraints of a make-to-order manufacturing system for fulfilling customer orders.

Next, we discuss on how the big-data techniques and cyber physical manufacturing system techniques can improve the design of RMSs. Based on the advanced monitoring and analytics capabilities, more effective and intelligent maintenance and production-scheduling decisions can be made in real-time.

1) The rapid development of sensor technologies and data analytics methods has significantly improved the prognostics and diagnostics capabilities of manufacturing systems, and thus driven the systems' continuous improvement. In today's manufacturing systems, more data are collected from machines and processes, which are analysed and provide better knowledge of the system status, including both on-line status and offline characterization. Moreover, the computing capabilities that are aided by the cloud-based approaches are advancing rapidly. Such capabilities enable the development and deployment of more efficient prognostics and diagnostics techniques [94], including online monitoring [97,98], remote monitoring [99], anomaly detection [100] and remaining useful life prediction [101], in manufacturing systems. Future research is needed on developing of flexible or reconfigurable condition monitoring systems [102], which can integrate several decision-support tools such as data collection, feature selection, and sensor allocation.

2) The recent development of the cyber physical manufacturing systems has the potential to solve these challenges. Monostori et al. [96] reviewed the key techniques in cyber physical systems (CPSs), and illustrated how it could be implemented in the manufacturing environment with several case studies. A CPS has two components, physical and cyber, that are interconnected. The cyber system deploys a "digital twin" of the real system, which can be considered as a mirrored image of the real machines and operations [103]. While the real system operates in the physical world, the digital twin operates in the cloud platform, simulates the health condition of each individual machine in the system, and continuously records and tracks machine conditions, energy consumption, product quality, and all kinds of information. Data-driven models and algorithms can be developed [104], which can be further integrated into the simulation model, together with physical knowledge. With ubiquitous connectivity offered by cloud computing technology, the cyber system will be able to provide better accessibility of machine condition for factory managers. More importantly, simulation on the digital twin will enable optimal decision-making, such as evaluating alternative maintenance and production scheduling policies. Once optimal or near-optimal solutions are found in the cyber system, they will be executed in the physical system to improve its operation.

4.3 From mass customization to mass individualization

Today, customers' requirements become more versatile and personalized. Contributed to the development of technologies in additive manufacturing and 3D printing [105], the personalized products can be manufactured cost-effectively, which transfers the manufacturing paradigm from mass customization to mass individualization. In this new paradigm, open-architecture products will be developed [106]. One key challenge for mass individualization is the huge number of possible modules that need to be assembled into a complex product. Therefore, the manufacturing system (an assembly system in this case) should be able to produce a large number of different models, and should be a reconfigurable assembly system (RAS).

The characteristics and principles of RMS that are introduced in Sections 2 and 3 can be implemented to improve the design and operations of RAS. However, the design and operations of such RAS is more complicated than that of a traditional RMS for machining. For example, the RAS should be scalable to supply more variants of demand, and be convertible to accommodate various variations and new products. The design topics of an RAS also include modelling systems that couple complex interaction among different machines, line balancing, and production scheduling, etc. [107]. In addition, new metrics are needed to quantitatively measure the complexity of the system configuration and the products.

New system layout for contemporary RAS should be developed in order to improve the system efficiency and reduce the operational cost. For example, Fig. 6 shows a hexagon layout of conceptual RAS for the final assembly of personalized auto interiors [106,108]. Each small square represents a station where a particular component is assembled. When the process proceeds via different routes, different combinations of components can be installed, making different product variants. Some stations in the systems are shared by multiple product variants. For example, for the system in Fig. 6, station 1E is shared by three product variants (I, II, and IV), and there are 13 stations (i.e., 1D, 1F, 2C, 3A, 3D, 3F, 4C, 4D, 4E, 4F, 5C, 6C, and 6F) that are shared by two product variants. To meet the demand requirement, popular components will require more than one assembly station. Such configuration enables freely variable assembly routes to produce the personalized product quickly and at low cost.

To make mass individualization a reality and to confront with the complexity brought by the huge variety offered by this paradigm, a RAS should combine the advantages of both robots and humans. The recent development of collaborative robot systems [109–111] may offer a way to improve the efficiency and adaptiveness of RASs.

The robot has a high precision and repeatability, while the human is more adaptive, and can deal better with complex tasks and unexpected situation. The cycle time of the robot is fixed, but the time needed for a person to complete the task is not fixed, especially when complex tasks are involved. A serial assembly line is not a cost-effective solution for utilizing robot-human assembly tasks in large volumes. Therefore, for utilizing effectively collaborative man-robot tasks in high-volume assembly, an RAS with either the configuration depicted in Fig. 4(b) or the configuration in Fig. 6 should be designed and deployed.

5 Conclusions

RMS is a new type of manufacturing system that focuses on enhancing the system responsiveness to fluctuating markets and enabling rapid and cost-effective competition in environment of volatile markets. In this paper, we have introduced the concept and architecture of RMS, and explained how it differs from other manufacturing systems such as DML and FMS. We defined the RMS characteristics and its principles, and brought up examples to illustrate them. Based on the principles, the RMS-related research in the literature is reviewed, which provides guidance for the design and operations of RMSs. We have also discussed

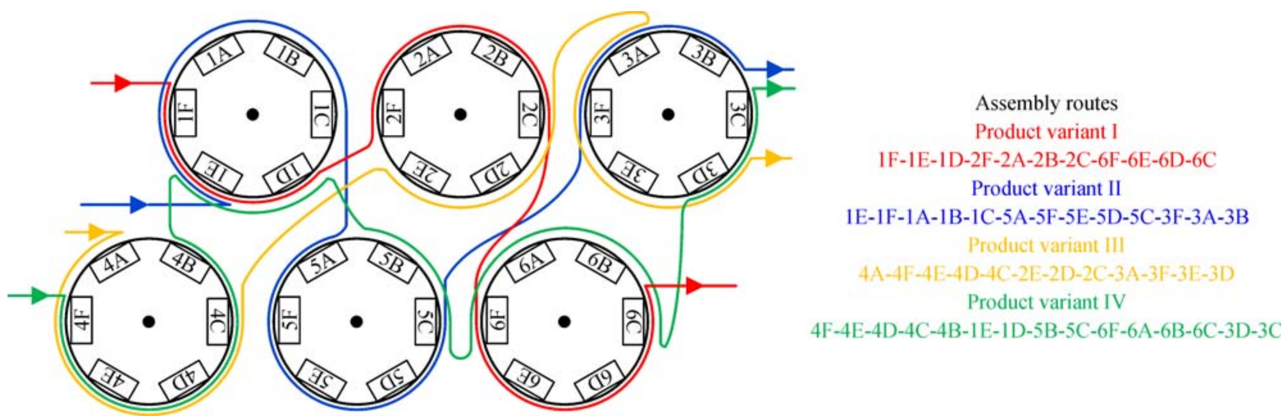

Fig. 6 A conceptual layout of a reconfigurable assembly system

the role of intelligent manufacturing technologies in enhancing RMS performance, and how recent development of advanced diagnostics and cyber physical manufacturing systems can facilitate the design and operations of RMS. Future research should be conducted on the concurrent design of the product-system-business strategies utilizing the RMS concept and principles, as well as for more effective methodologies for real-time RMS operations, for both machining and assembly systems.

We believe that RMS has already played a vital role in the evolution of manufacturing systems, and, integrated with other novel techniques, will continue to revolutionize the future development of modern manufacturing systems.

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