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Design of Reconfigurable Manufacturing Systems

Journal of Manufacturing Systems, Vol. 29, No. 4, 2010

ARTICLE INFO

Article history:
Received 3 January 2011
Accepted 3 January 2011
Available online xxxx

ABSTRACT

This paper explains the rationale for the development of reconfigurable manufacturing systems, which possess the advantages both of dedicated lines and of flexible systems. The paper defines the core characteristics and design principles of reconfigurable manufacturing systems (RMS) and describes the structure recommended for practical RMS with RMS core characteristics. After that, a rigorous mathematical method is introduced for designing RMS with this recommended structure. An example is provided to demonstrate how this RMS design method is used. The paper concludes with a discussion of reconfigurable assembly systems.

1. Introduction

It is well known that Henry Ford's invention of the moving assembly line in 1913 marked the beginning of the mass production paradigm. Yet it is less known that mass production was made possible only through the invention of dedicated machining lines that produced the engines, transmissions and main components of automobiles. Such dedicated manufacturing lines have a very high rate of production for the single part type they produce, and they are very profitable when demand for this part is high. These dedicated transfer lines were the most profitable systems for producing large quantities of products until the mid-1990s.

The invention of NC, and later CNC in the 1970s [1], facilitated creation of flexible manufacturing systems (FMS) in the early 1980s. Stecke and Solberg were the first to formalize a mathematical solution for flexible systems [2]; already in 1981 they described the operation policies of FMS for a job shop consisting of nine machines interconnected by an automatic material handling mechanism [3]. Due to the high initial investment cost, however, close to twenty years elapsed before flexible manufacturing systems were able to penetrate the transportation powertrain industry, which is the largest market for FMS. At that time, in the 1980s and 1990s, the strategic goals of manufacturing enterprises were productivity, quality and flexibility [4].

In the mid-1990s, enhanced globalization and worldwide competition made it clear that FMS provide only a partial economic solution in a competitive market. The typical FMS serial structure used in industry (though not in job shops) facilitated changes in products manufactured, but it yielded a relatively slow production rate and did not provide the volume flexibility for responding to the unexpected changes in demand resulting from global competition. Cochran [5] noted that manufacturing system designs must be capable of satisfying a company's strategic objectives. When demand fluctuates, the strategic objective is to meet demand. This can only be accomplished by up-scaling or down-scaling the system's physical structure. But cost effective scalability through modifications in the system's physical cannot be accomplished with traditional FMS.

In response, in 1995 the University of Michigan submitted a proposal to NSF for establishing a research center on Reconfigurable Manufacturing Systems [6]. This paper explains the characteristics and principles of reconfigurable manufacturing systems (RMS) that were proposed in 1995, compares RMS structure with that of traditional flexible lines, and describes a mathematical method that facilitates RMS design. An example is provided to demonstrate how this RMS design method is used.

2. Manufacturing responsiveness is the challenge of globalization

Manufacturing companies in the 21st century face increasingly frequent and unpredictable market changes driven by global competition, including the rapid introduction of new products and constantly varying product demand. To remain competitive, companies must design manufacturing systems that not only produce high-quality products at low cost, but also allow for rapid

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doi:10.1016/j.jmsy.2011.01.001

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response to market changes and consumer needs. Responsiveness refers to the speed at which a plant can meet changing business goals and produce new product models. Reconfigurability is a novel engineering technology that facilitates cost effective and rapid responses to market and product changes.

Responsiveness enables manufacturing systems to quickly launch new products on existing systems, and to react rapidly and cost-effectively to:

1. Market changes, including changes in product demand.
2. Product changes, including changes in current products and introduction of new products.
3. System failures (ongoing production despite equipment failures).

All these changes are driven by aggressive competition on a global scale, customers who are more educated and demanding, and a rapid pace of change in product and process technology [7].

Although flexible manufacturing systems (FMS) do respond to product changes, they are not designed for structural changes [8] and therefore cannot respond to abrupt market fluctuations, such as varying demand and major equipment failures.

The speed of responsiveness is a new strategic goal for manufacturing enterprises. Although responsiveness has not yet been attributed the same level of importance as cost and quality, its impact is quickly becoming equally imperative. Responsiveness provides a key competitive advantage in a turbulent global economy in which companies must be able to react to changes rapidly and cost-effectively. Responsiveness can be achieved by installing a manufacturing system that has modest initial capacity and is designed to add production capacity as the market grows and to add functionality as the product changes.

A responsive manufacturing system is one whose production capacity is adjustable to fluctuations in product demand, and whose functionality is adaptable to new products. Therefore, two basic types of reconfiguration capabilities are needed in manufacturing systems—in functionality (some types of flexible manufacturing systems allow functionality changes) and in production capacity. Fig. 1 shows how the actual demand for Products A and B can differ from what was planned.

System production capacity must be adjusted to cope with fluctuations in product demand. This type of adjustment requires rapid changes in the system's *production capacity*, also referred to as system *scalability* [9].

Traditional manufacturing systems – both dedicated lines and FMS – are ill suited to meet the requirements dictated by the new competitive environment. Dedicated manufacturing lines (DMLs) are based on inexpensive fixed automation that produces a company's core products or parts over a long period and at high volume, as seen in Fig. 2. Each dedicated line is typically designed to produce a single part at a high rate of production achieved by utilizing all tools simultaneously. When product demand is high, the cost per part is particularly low. DMLs are cost effective as long as they can operate at full capacity, but with increasing pressure from global competition and over-capacity worldwide, dedicated lines usually do not operate at full capacity.

Flexible manufacturing systems (FMS) can produce a variety of products with a changeable mix on the same system. Typically, FMS consist of general-purpose computer-numerically-controlled (CNC) machines and other programmable forms of automation. Because CNC machines are characterized by single-tool operation, FMS throughput is much lower than that of a DML. The combination of high equipment cost and low throughput makes the cost per part using FMS relatively high. Therefore, FMS production capacity is usually much lower than that of dedicated lines (see Fig. 2).

3. RMS—a new class of systems

A cost effective response to market changes requires a new manufacturing approach. Such an approach not only must combine the high throughput of a DML with the flexibility of FMS, but also be capable of responding to market changes by adapting the manufacturing system and its elements quickly and efficiently. These capabilities are encompassed in reconfigurable manufacturing systems (RMS), whose capacity and functionality can be changed exactly when needed, as illustrated in Fig. 2.

Three features – *capacity, functionality*, and *cost* – are what differentiate the three types of manufacturing systems — RMS, DML and FMS. While DML and FMS are usually fixed at the capacity-functionality plane, as shown in Fig. 2, RMS are not constrained by capacity or by functionality, and are capable of changing over time in response to changing market circumstances.

When taking system cost versus capacity into consideration, the DML remains constant at its maximum planned capacity; an entire additional line must be built when greater capacity is needed. Pure parallel FMS are scalable at a constant rate (adding machines in parallel), as depicted in Fig. 3. But as Lee and Stecke stated [10], FMS are expensive: "FMS require large capital investment, and a large portion of this investment is committed at the early design stage". RMS are scalable, but at non-constant steps that depend on initial design and market circumstances.

Manufacturing equipment is reconfigurable if the answer to the following two questions is positive.

1. Was this manufacturing system or equipment designed so that its physical structure can be easily changed?
2. Was this manufacturing system or equipment designed for production or inspection of a particular part family?

Examples of changes in a system's physical structure include adding a new production resource rapidly and in a cost effective manner (e.g., a new CNC machine or conveyor extension), changing a tool magazine or changing the direction of an axis of motion.

FMS have the flexibility needed to switch between product variants in manufacturing, but are not as cost effective as DMLs. By contrast, a DML is marked by high productivity but no flexibility. A reconfigurable manufacturing system embraces the best qualities of both types. Not only is it cost effective with flexible production capabilities, but its structure also can be changed at both the system level and the machine level, so it can handle unexpected market changes [11].

DML design focuses on the specific part to be produced. Thus, if a part is not defined, a DML cannot be designed. By contrast, typical FMS are composed of CNC machines and are designed to manufacture any part (within an envelope). A process-planning procedure is needed to fit the processing of each specific part to the existing FMS. FMS design focuses on the machine rather than on the part, which is one reason for the waste and low production rates of FMS technology.

Borrowing from dedicated lines that are designed around a single part/product, RMS systems focus on families of parts, such as cylinder heads of car engines. Four-, six- and eight-cylinder engines have many differences, but they also have many more features in common. Focusing on the part family enables a designer to plan a system that accommodates different variations of the same part family with minimum alteration to the production scheme. This approach utilizes the high productivity of DML machine design,

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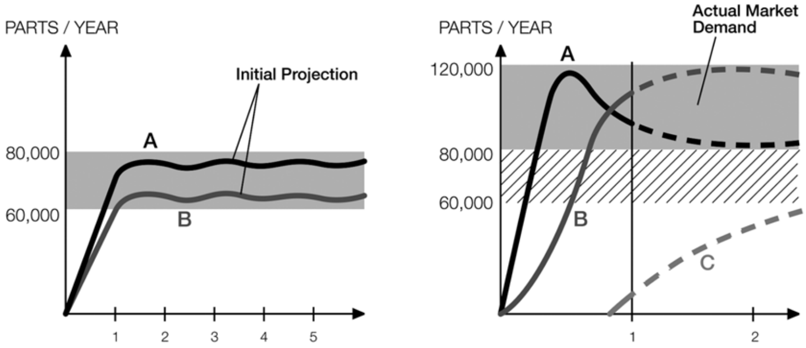

Fig. 1. Projection compared to actual product demand: Higher initial demand than expected for both products, and product C is introduced earlier than expected.

Table 1
RMS systems combine features of dedicated and flexible systems.

	Dedicated	RMS/RMT	FMS/CNC
System structure	Fixed	Changeable	Changeable
Machine structure	Fixed	Changeable	Fixed
System focus	Part	Part family	Machine
Scalability	No	Yes	Yes
Flexibility	No	Customized (around a part family)	General
Simultaneously operating tools	Yes	Possible	No
Productivity	Very high	High	Low
Cost per part	Low (For a single part, when fully utilized)	Medium (Parts at variable demand)	Reasonable (Several parts simultaneously)

and is much more economical than the general functionality of FMS.

As summarized in Table 1, Reconfigurable Manufacturing Systems (RMS) constitute a new class of systems characterized by adjustable structure and design focus.

A system built with changeable structure provides scalability and customized flexibility and focuses on a part family, thus generating a responsive reconfigurable system. The flexibility of RMS, though really only "customized flexibility", provides all the flexibility needed to process that entire part family.

Highly productive, cost effective systems are created by (i) part-family focus, and (ii) customized flexibility that enables the simultaneous operation of different tools [12]. RMS systems are designed to cope with situations where both productivity and system responsiveness are of vital importance. Each RMS system is designed to produce a particular family of parts. The main components of RMS for machining are CNC machines and Reconfigurable Machine Tools [13]. Reconfigurable controls integrated in an open-architecture environment that can coordinate and operate the CNCs and RMTs are critical to RMS success [14]. Therefore, a reconfigurable manufacturing system can be defined as follows [15]:

Reconfigurable Manufacturing Systems (RMS) are designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or regulatory requirements.

If the system and its machines are not designed at the outset for reconfigurability, the reconfiguration process will prove lengthy and impractical.

4. Characteristics and principles of reconfiguration

RMS are marked by six core reconfigurable characteristics, as summarized below [16].

Customization (flexibility limited to part family)	System or machine flexibility limited to a single product family, thereby obtaining customized flexibility
Convertibility (design for functionality changes)	The ability to easily transform the functionality of existing systems and machines to suit new production requirements
Scalability (design for capacity changes)	The ability to easily modify production capacity by adding or subtracting manufacturing resources (e.g. machines) and/or changing components of the system
Modularity (components are modular)	The compartmentalization of operational functions into units that can be manipulated between alternate production schemes for optimal arrangement
Integrability (interfaces for rapid integration)	The ability to integrate modules rapidly and precisely by a set of mechanical, informational, and control interfaces that facilitate integration and communication
Diagnosability (design for easy diagnostics)	The ability to automatically read the current state of a system to detect and diagnose the root causes of output product defects, and quickly correct operational defects

Customization, scalability and convertibility [17] are critical reconfiguration characteristics. Modularity, integrability and diagnosability allow rapid reconfiguration, but they do not guarantee modifications in production capacity and functionality. Customization, an essential RMS characteristic, is based upon design for a part family or a product family, a concept already mentioned by other

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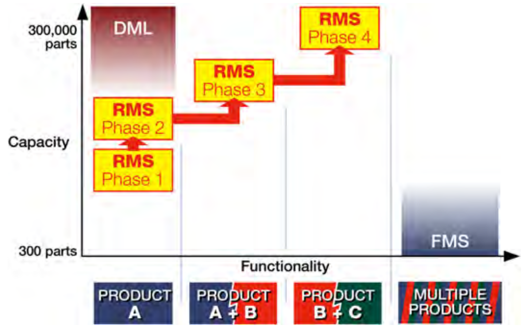

Fig. 2. Both DML and FMS are static; RMS are dynamic, with capacity and functionality changing in response to market changes.

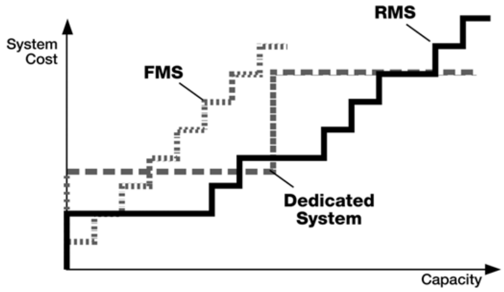

Fig. 3. Manufacturing system cost versus capacity.

researchers [18]. The six key RMS characteristics reduce the time and effort of reconfiguration, and consequently enhance system responsiveness. These characteristics can reliably reduce lifetime cost by enabling a system to change constantly during its lifetime, "staying alive" despite changes in markets, consumer demand, and process technology.

Reconfigurable manufacturing systems are designed according to reconfiguration principles [19]. Three of these principles (see Ref. [7], page 239) are intended to improve reconfiguration speed and consequently speed of responsiveness to (i) unpredictable external occurrences (e.g., market changes), (ii) planned product model changes, and (iii) unexpected intrinsic system events (such as an unexpected long machine failure). The more these principles are applicable to a given manufacturing system, the more reconfigurable that system is. These three principles are:

1. An RMS system provides *adjustable production resources* to respond to unpredictable market changes and intrinsic system events:
    - RMS capacity can be rapidly scalable in small increments.
    - RMS functionality can be rapidly adapted to new products.
    - RMS built-in adjustment capabilities facilitate rapid response to unexpected equipment failures.
2. An RMS system is designed around *a product family*, with just enough customized flexibility to produce all members of that family.
3. The *RMS core characteristics* should be embedded in the system as a whole, as well as in its components (mechanical, communications and control).

The environment of many manufacturing companies is characterized by unpredictable market changes. Changes in orders require altering the output capacity and processing functions of the manufacturing system. Reconfigurable manufacturing systems meet these requirements by rapidly adapting both their capacity and their functionality to new situations. Implementing RMS characteristics and principles in the system design leads to achieving the ultimate goal—to create a "*living factory*" that can rapidly adjust its production capacity while maintaining high levels of quality from one part to the next. This adaptability guarantees a high long-term profit-to-cost-ratio and rapid return on investment of reconfigurable manufacturing systems.

In large manufacturing systems production involves many stages. A product is partially processed in one stage and then transferred to the next, until all operations have been completed. A system's configuration can facilitate or impede its productivity, responsiveness, convertibility and scalability, and can also impact its daily operations. Multi-stage manufacturing systems can allow for several operational configurations, depending on how the machines are arranged in the stages and how they are connected via the material handling system. The following section offers a method for classifying configurations and uses it to compare the attributes of various configuration classes. It also discusses how Reconfigurable Manufacturing Systems (RMS) are configured and proposes a means for calculating the number of possible RMS configurations based on the number of machines in the system.

5. Classification of configurations

Classifying configurations requires determining the number of possible configurations when the daily demand, $\boldsymbol{Q}$ (parts/day), and the total machining time for the part, $\boldsymbol{t}$ (min/part), are given. In reality, machining times vary widely depending on the equipment involved, but, to begin we assume these are given.

The minimum number of machines, N, needed in the system is calculated by the equation

$$N = \frac{Q \times t}{\text{Min/day available} \times \text{Machine reliability}}. \tag{1}$$

The following calculations assume 100% reliability of all pieces of equipment (i.e., machine reliability = 1). The resulting number of machines calculated by Eq. (1) must be rounded to the next larger integer. For example, if 500 parts per day are needed and the processing time for each part is 9.5 min, at least five machines are needed in the system assuming working time of 1000 min/day.

In the general case the total number of configurations for N machines is huge. When plotted on a logarithmic scale, the number of configurations increases almost linearly with the number of machines, as shown in Fig. 4. The number of possible RMS configurations is much smaller, as indicated in the table in Fig. 4 [20].

Eq. (1) yields the minimum number of machines needed to meet the required demand. The next questions are: What is the best way to arrange and connect these machines? For example, should they be arranged in a serial line, a pure parallel system, or some combination? Which of all possible configurations is the most advantageous?

For example, in the case of five machines, the total number of possible configurations is 48. Fig. 5 shows 32 of these configurations. As shown in Fig. 4, the number of possible configurations increases exponentially with the number of machines. Having 80 or more machines coordinated into one system is not unheard of in the automotive powertrain industry. How can one possibly analyze the merits of so many possible configurations?

First, configurations are classified either as symmetrical or as asymmetrical, based on whether a symmetric axis can be drawn along the configuration. A configuration is then evaluated by its machine *arrangement* and *connections*. For example, configurations *a* and *b* have identical machine arrangements (one in stage 1, two in stage 2, and two in stage 3), but they differ because of different connections among the machines—configuration *b* uses cross-coupling between stages 2 and 3. The type of material handling system determines the connections of a configuration. Altogether,

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Number of machines	Number of possible configurations	Number of RMS configurations
2	2	2
4	15	8
6	170	32
8	2,325	128
10	**35,341**	**512**

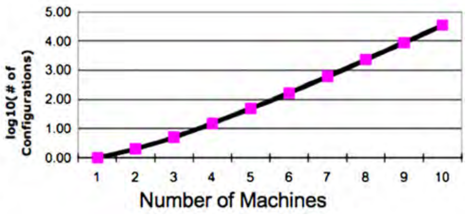

Fig. 4. Total number of system configurations for different numbers of machines.

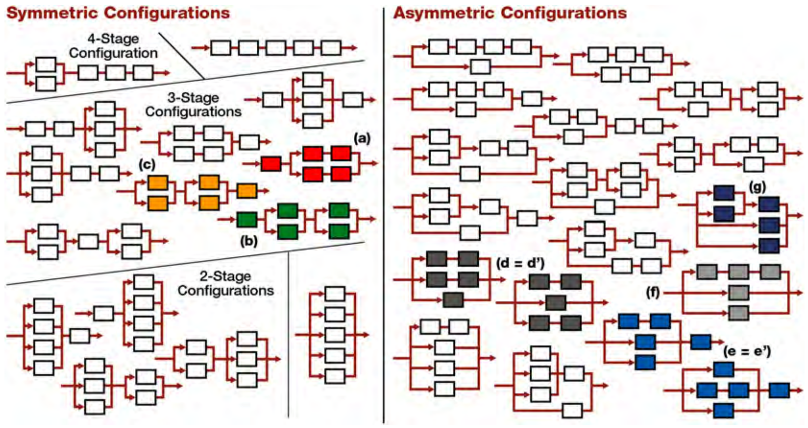

Fig. 5. Configurations with five machines.

a system with five machines may have 16 different symmetric arrangements (13 of which are plotted in Fig. 5). Fortunately, the designer will consider only symmetric configurations.

Asymmetric configurations add immense complexity and are not viable in real manufacturing lines, as explained below. The number of possible asymmetric configurations is much larger than of symmetric configurations—a total of 30 in the case of five machines (18 of them are plotted in Fig. 5). It is important to note that configurations d' and e' are defined as asymmetric (although they have a symmetric axis) because they may be positioned differently (as d and e). Similarly, according to reconfiguration science, the two configurations f and g in Fig. 5 are defined as asymmetric configurations, although they may be drawn as symmetric.

We would like to explain why asymmetric configurations are usually not suitable for real machining systems (though they may be suitable for assembly systems)? Asymmetric configurations may be sub-classified as (a) variable-process configurations or (b) single-process configurations with non-identical machines in at least one of the stages. Corresponding examples are shown in Fig. 6(a) and (b), respectively.

Variable-process configurations are characterized by possible non-identical flow-paths for the part. They therefore need several process plans and corresponding setups. For example, the system depicted in Fig. 6 has a number of possible flow-paths: $a–b–c–d–e$, $g–c–f$, $g–c–d–e$, etc. The process plan to be executed depends on the flow-path of the part being processed in the system. This is absolutely impractical because (1) designers will not go to the effort to design multiple process plans for the same part, and (2) different process plans and corresponding flow-paths increase part quality problems and make quality error detection more complicated.

Although the process planning is identical in each flow-path in the second class of asymmetric configurations, the machines are different in at least one stage. For example, in Fig. 6(b), machine b in stage 2 must be two times faster than machines a; machine d in stage 4 must be two times faster than machines c. In symmetric configurations, in contrast, the processing times of each machine in a particular stage are equal. Mixing different types of machines that perform exactly the same sequence of tasks in the same manufacturing stage is absolutely impractical. System designers should also not consider this class of configuration, due to their excessive complexity. The conclusion is:

It is more likely that in a real machining context, only symmetric configurations would be considered; these are always single-process configurations with identical machines in each stage.

Symmetric configurations may be further divided into three basic classes, as shown in Fig. 7.

A designer of manufacturing systems should consider only the following three classes:

I. *Cell configurations* are configurations consisting of several serial manufacturing lines (i.e., cells) arranged in parallel with no crossovers, as shown in Fig. 8. Cell configurations, commonly used in Japan, are simple.
II. *RMS configurations* are configurations with crossover connections after every stage, as shown in Fig. 9. A part from any machine in stage $\boldsymbol{i}$ can be transferred to any machine in stage $(\boldsymbol{i}+1)$. All machines and operations in every stage are identical. All three US domestic automobile manufacturers use these configurations in the machining of their powertrain components (a typical system may consist of 15 stages and 6 machines per stage).
III. Configurations in which there are some stages with no crossovers. This class includes combinations of the previous two classes.

Note that a mathematical model that minimizes inter-cell material handling costs for equipment layout in a single cell has been developed [21], but it has not been expanded to a system with several cells.

The sketch in Fig. 10 of a practical 3-stage RMS system with gantries that transport the parts illustrates the issue of RMS configuration. A spine gantry transfers a part to a small cell conveyor. The part then moves along the conveyor to a position where a cell gantry can pick it up and take it for processing in one

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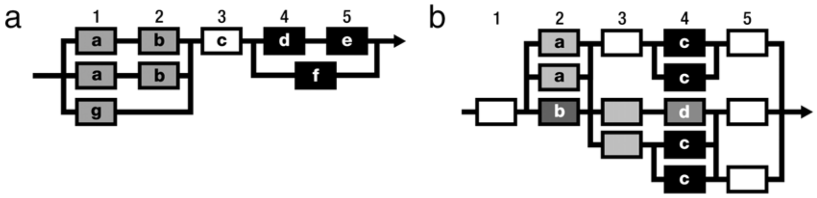

Fig. 6. Two classes of asymmetric configurations.

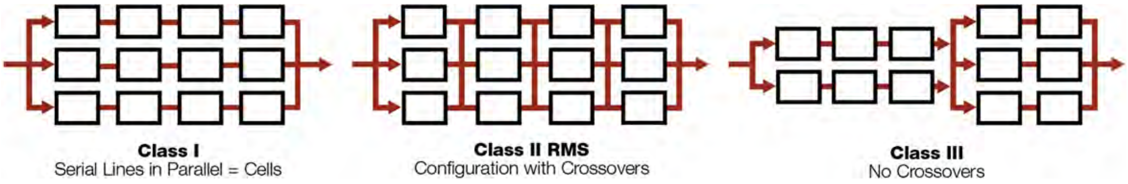

Fig. 7. Three classes of symmetric configurations.

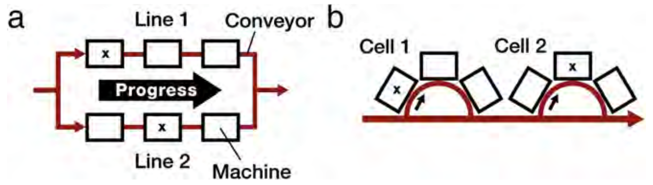

Fig. 8. Symmetric configuration of Class I—parallel lines, or cells. (If the two marked machines fail, the system production stops.)

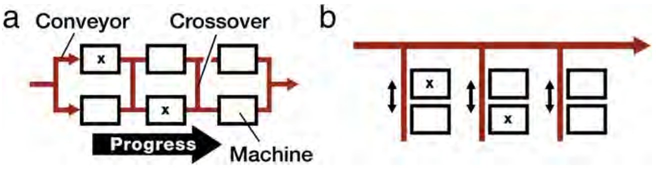

Fig. 9. Symmetric configuration of Class II—RMS configuration. (If the two marked machines fail, the system still has 50% production capacity.)

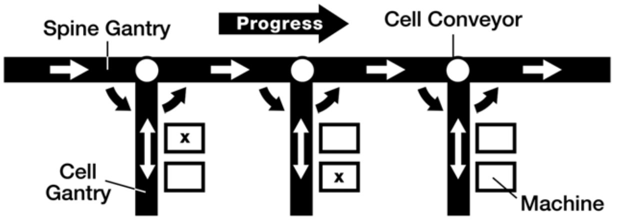

Fig. 10. A practical reconfigurable manufacturing system.

of the machines in its stage. When the part has been processed, the cell gantry returns the part to the conveyor, which moves the part to a position at which the next spine gantry can pick it up for processing in the next stage, and so on.

6. Comparing RMS configurations with cell configurations

Below we compare the two main practical configurations according to four criteria: investment cost, line-balancing ability, scalability options, and productivity when machines fail. For a more general analysis of the impact of configuration on system performance; see [22].

Capital investment. The configurations shown in Figs. 8 and 9 (or Fig. 10) have identical machine arrangements – three stages with two machines in each stage – but the connections are quite different in that they use different part handling devices, each requiring a different capital investment. The entire part handling system in Fig. 8 is simpler and has a smaller number of handling devices compared to the RMS system shown in Fig. 10. Thus, the capital investment in the RMS configuration is higher.

Line balancing. A major drawback of cell configuration is that it imposes severe limitations when balancing the system. For example, if just one product is produced, the processing time in all stages of the cell configuration must be exactly equal to be perfectly balanced. By contrast, to achieve a balanced RMS configuration only the following relationship needs to be satisfied

$$t_{s1}/N_{s1} = t_{s2}/N_{s2} = t_{si}/N_{si} \tag{2}$$

where N_{si} is the number of machines in stage i, and t_{si} is the processing time per machine in stage i. Therefore, in RMS configurations the number of machines per stage is not necessarily equal in all stages. The number of machines in the various stages of RMS configurations may be adjusted to provide accurate line balancing, which consequently yields improved productivity.

System scalability. RMS configurations are far more scalable than cell configurations. Adding one machine to one of the stages and rebalancing the system enables adding a small increment of capacity. In the cell configuration, a complete additional parallel line must be added to increase the overall system capacity. In markets with unstable demand, scalability represents an important advantage of RMS configurations.

Productivity. If machine reliability is low due to crossovers at each stage, an RMS configuration offers higher productivity than that of a cell configuration. As shown in Fig. 8, if machines in two different lines and at two different stages (marked with x) are down, the entire system is down (i.e., throughput = zero). For RMS, in contrast, under the same conditions – two machines not working (marked with x in Fig. 9) – throughput is still at 50%. So, RMS are more productive systems from the perspective of machine downtime. Nevertheless, the RMS material handling system is more complex, with its so-called “cell gantries” that enable crossovers (see Fig. 10). If one of the cell gantries is down, the entire RMS system will not work. In contrast, cellular systems with parallel lines do not contain cell gantries and are therefore more reliable from the material handling system perspective. The consequent critical question is therefore: When considering reliability, which configuration yields higher productivity?

A complete analysis of this problem is presented by Freiheit et al. [23,24]. In this analysis the number of machines per stage in the RMS configuration is equal in all stages. The RMS configuration has a spine gantry with reliability identical to that of the conveyors in Fig. 8. The analysis calculates tradeoffs between cell-gantry reliability and machine reliability.

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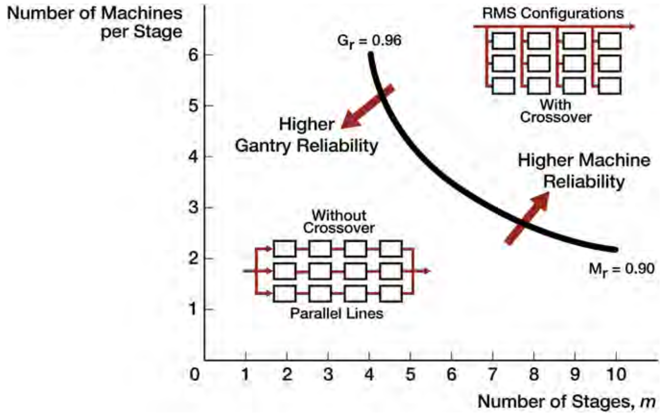

Fig. 11. Productivity comparison between parallel lines and RMS configurations.

Fig. 11 shows one typical result plotted for gantry reliability (or availability) of $\boldsymbol{G}_r = 0.96$, and machine reliability of $M_r = 0.90$. Our analysis revealed a borderline based on machine reliability and gantry reliability (which must always be better than the machine reliability). On the right-top side of the borderline, RMS with crossovers are preferred. For example, if the system has nine stages with four machines per stage, the RMS configuration will yield higher productivity than a parallel-line configuration. The parallel-line configuration is preferable when, for example, the system has nine stages with just two machines per stage (namely, two parallel lines with nine stages). The better the machine average reliability (e.g., 0.95), the larger the solution space for a parallel-line configuration (without crossovers), and vice versa.

The main conclusions of this analysis are:

- In large systems, with a large number of stages and machines per stage, the RMS configuration has higher productivity than the parallel-line configuration (i.e., cells).
- If machine reliability is very high, the cell configuration yields higher productivity.

The advantages of each configuration are summarized in the table below.

	Capital investment	Scalability	Line balancing	Productivity
Parallel lines	Lower			Higher for high machine reliability
RMS configuration		Much better	Much better	Higher in complex, large systems

7. Integrated RMS practical configurations

This section deals with two issues: (a) designing RMS systems with all six core characteristics, and (b) designing RMS systems that incorporate innovative reconfigurable machine tools (RMTs) and reconfigurable inspection machines (RIMs) into the configuration. These two innovations make RMS more productive and responsive.

Our starting point is the RMS configuration depicted in Fig. 12, representing a system already utilized in the powertrain industry. This three-stage system can produce two different parts simultaneously. A cell gantry serves all machines in a particular stage, bringing parts and loading them on the machines, and taking the finished parts and transferring them to a buffer (the circle in Fig. 12) located next to the main material handling system. This system is usually a gantry (called the spine gantry), but can also be a conveyor or several AGVs [25]. To balance the system sequence, all stages should have almost the same cycle time. In this figure, the cycle time for each of the two machines in stage 2 is approximately two-thirds of the cycle time for the three machines in stages 1 and 3. (In industry, the set of all machining tasks assigned to a stage is called an "Operation". Operations are usually assigned the numbers 10, 20, 30, etc., allowing for the addition of intermediate operations as needed over time, as in adding Operation 15. Here we prefer the term "stage".)

The system in Fig. 12 has four of the six core RMS characteristics:

Modularity: At the system level, each CNC machine is a module.
Integrability: Machines at the same stage are integrated via cell gantries, which, in turn, are integrated into a complete system by a conveyor or spine gantries or AGVs. (The circles in Fig. 12 represent buffers.)
Scalability: Machines can be easily added at each stage without interrupting system operation for long periods. From a system-balancing viewpoint, scalability begins at the stages that are already bottlenecks to reduce system cycle time.
Convertibility: It is easy to stop the operation of one CNC at a time and to reconfigure its functionality to produce a new type of part.

Scalability and convertibility enhance overall system performance. The system in Fig. 12, however, does not yet have the two remaining characteristics: *customization* (i.e., part family customized flexibility) and *diagnosability*.

As mentioned, implementing customized flexibility is critical to increasing productivity. Introducing this characteristic into a reconfigurable system is the key to enhance productivity, but how exactly can this be accomplished?

Let us assume that the milling tasks on the machined part can be separated from the drilling and tapping tasks and that milling can be assigned to different stages than drilling and tapping (i.e., performed in different stages in the system). The drilling and tapping tasks for a particular part α can be done very fast (at a dedicated machine speed) on a reconfigurable machine tool (RMTα) that is capable of drilling (or tapping) multiple holes simultaneously, on a particular part α in a single stroke—a single motion of the Z-axis. RMTα is customized to part α. Two RMTs, for two parts α and β are integrated into the configuration shown in Fig. 13. Namely, customization has been embedded into this system, resulting in a dramatic improvement in system throughput.

The sixth characteristic, diagnosability, can be embedded if the system includes in-process inspection resources that allow detection of quality defects in real time. In practice, this is implemented by installing reconfigurable inspection machines (RIMs) at a separate stage in the system, which allows the inspection to be conducted in a contaminant-free environment and can be bypassed if necessary, as shown in Fig. 13. Performing in-process diagnostics has a double advantage: it dramatically shortens the ramp-up periods after reconfigurations, and it allows rapid identification of part quality problems during normal production.

8. Calculating the number of RMS configurations

Professor Nam Suh laid out a theoretical framework for the design of large systems [26]. Yet as he himself wrote, "the goal is to develop a thinking design machine and create pedagogical tools for teaching". A few years later, Jacobsen et al. [27] recognized that "the design of a production system is a challenging activity". Yet the authors of this article did not propose a mathematical method or even a design procedure. Here we propose a practical mathematical method that engineers can easily utilize for designing reconfigurable manufacturing systems.

We have already seen that the minimum number of machines N required in the system can be easily calculated by solving

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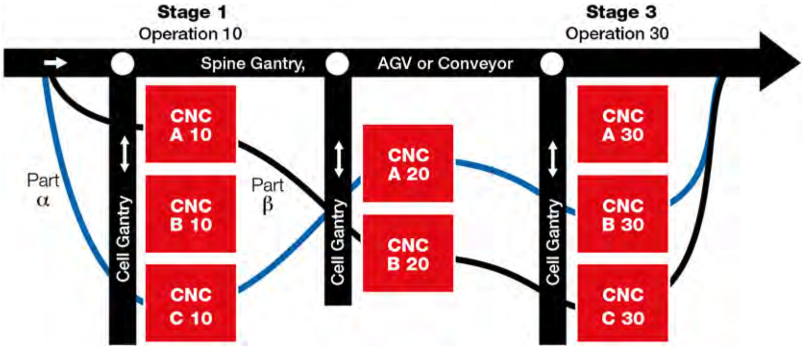

Fig. 12. Practical RMS configuration with three stages.

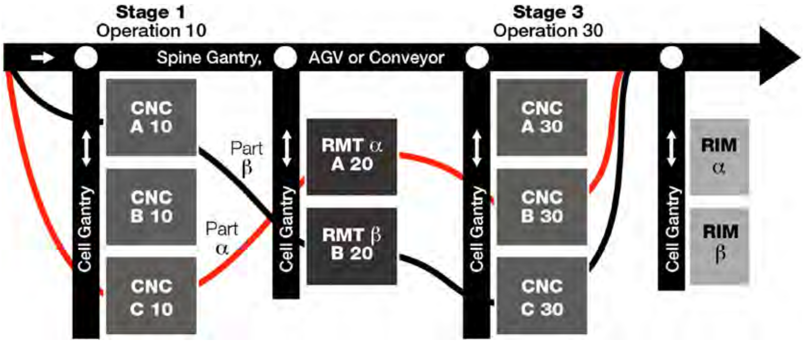

Fig. 13. RMS with integrated RMTs and RIMs.

Eq. (1). However, as shown in Fig. 5, the number of all possible configurations with N machines is enormous. After a thorough mathematical study of system configurations, we conclude the following:

Closed equations for calculating the number of configurations with N machines exist only for RMS-type configurations.

The basic equations for calculating the number of possible RMS configurations are given below. K, the number of possible RMS configurations with N machines arranged in *up to m* stages is calculated by:

$$\mathcal{K} = \sum_{m=1}^{N} \binom{N-1}{m-1} = 2^{N-1} \tag{3}$$

K, the number of possible configurations with N machines arranged in *exactly m* stages is calculated by:

$$\mathcal{K} = \left(\frac{(N-1)!}{(N-m)!(m-1)!}\right). \tag{4}$$

For example, for $N = 7$ machines arranged in up to 7 stages, Eq. (3) yields $K = 64$ configurations, and if arranged in exactly 3 stages, Eq. (4) yields $K = 15$ RMS configurations. The mathematical results of these two equations for any N and m may be arranged in a triangular format, known as a Pascal triangle, shown in Fig. 14.

The numerical value of each cell in the Pascal triangle is calculated as follows. The numerical value corresponding to N machines arranged in m stages is calculated by:

The value for N machines in m stages = (*the value for N* − 1 *machines in m* − 1 *stages*) + (*the value for N* − 1 *machines in m stages*).

For example, in Fig. 14, the cell of $N = 5$ and $m = 3$ shows 6, which is the sum of 3 + 3 of the previous line of $N - 1 = 4$ machines with 2 and 3 stages.

The triangle also allows the designer to immediately visualize the number of possible RMS configurations for N machines arranged in m stages. For example, there are 15 RMS configurations when 7 machines are allowed to be arranged in exactly 3 stages. In addition, the Pascal triangle allows the designer to immediately calculate the number of possible RMS configurations for N machines arranged between i stages and j stages $(i, j < N)$. This information is used in the following example.

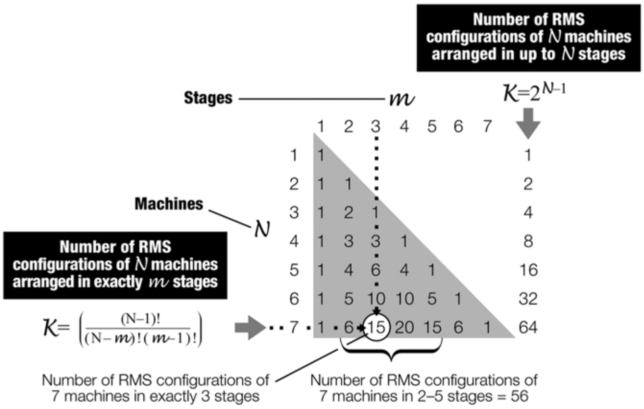

Fig. 14. The Pascal triangle is helpful in calculating the number of RMS configurations.

9. Example of system design

The following example demonstrates how the Pascal Triangle in Fig. 14 can be used to design a machining system with RMS configuration.

Raw parts are brought to a machining system after casting. The system contains many CNC machines that perform all machining operations required to finish the part, including milling, drilling, tapping, etc. A typical part of an automobile powertrain system is shown in Fig. 15. Note that the part has to be machined on several faces, and that there are more than 200 machining tasks required

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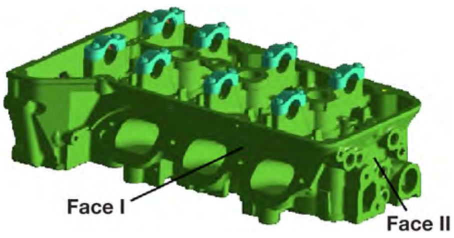

Fig. 15. An engine part after machining.

Fig. 16. Machining times.

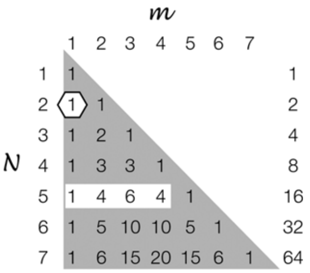

Fig. 17. Pascal triangle for the example.

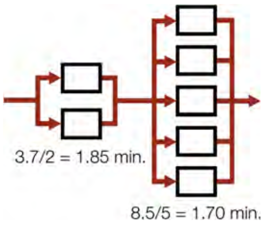

Fig. 18. Two stages.

to complete such a part, so it is impractical to include them all in this demonstration.

For simplicity, we consider a part that requires work on two faces only. Each face requires separate fixturing, and therefore the two faces must be machined using two separate setups. Our simplified example requires only five machining tasks to be completed. But even in this simple example, the analysis is tedious and lengthy. The methodical approach presented below is used to whittle down the range of possibilities and make logical decisions based on facts and data to determine the optimal system configuration.

The problem to be solved is defined as:

Design a machining system to machine a part that requires $\boldsymbol{t} = 12.2$ min *of machining time in five machining tasks. The execution times for the five tasks are given in* Fig. 16. *The required daily volume is* $\boldsymbol{Q} = 500$ parts/day.

The working time per day is 1000 min. Machine reliability is assumed to be 100%.

Solution: Producing 500 parts in 1000 min requires a cycle time of 2 min per part. The first step is to determine the minimum number of machines needed. Eq. (1) yields 6.1 machines. This number must be rounded to the next integer, so that $\boldsymbol{N} = 7$ machines.

According to Eq. (3), 7 machines and possible stages ranging from 1 to 7 yield 64 configurations to analyze. This large number of configurations can be reduced by considering the specific tasks. Since the part has only 5 machining tasks, the maximum number of stages can be 5. The part has two faces, each requiring a different set-up; therefore, the minimum number of stages must be 2. The Pascal triangle in Fig. 14 indicates that 7 machines in the 2–5 stage range have only 56 configurations.

But do we really have to compare all 56 configurations? The answer is no! If the part has two faces, we can divide the system into two sub-systems – one for Face 1 and the other for Face 2 – and then design two separate sub-systems. In the Face 1 sub-system, the machining time $\boldsymbol{t}$ is 3.7 min per part. According to Eq. (1) the required number of machines for Face 1 is 2.

$$N = \frac{500 \times 3.7}{1000} = 1.85 \Rightarrow 2 \text{ machines.} \tag{5a}$$

In the Face 2 sub-system, the machining time $\boldsymbol{t}$ is 8.5 min per part. According to Eq. (1) the required number of machines for Face 2 is 5.

$$N = \frac{500 \times 8.5}{1000} = 4.25 \Rightarrow 5 \text{ machines.} \tag{5b}$$

The Pascal triangle for these two sub-systems in Fig. 17 reveals only 15 possible configurations (rather than 56): one for Face 1, and 15 for Face 2.

The calculation yields: $1 \times (1 + 4 + 6 + 4) = 15$.

- If the system contains only two stages, there is only one possible configuration: stage 1 with two machines for Face 1, and stage 2 with five machines for Face 2.
- If the system comprises three stages, there are four possible configurations.
- For four stages there are six possible configurations.
- For five stages there are four configurations: stage 1 for Face 1, and 4 stages for Face 2.

The formula for calculating the number of machines in Eq. (1), however, is based on a perfectly balanced system, while the system here is not necessarily balanced. Therefore, several of these 15 possible configurations will not meet the demand of 500 parts per day. Our next step is to determine which of the configurations will not meet the demand and then to eliminate them.

- *For two stages* there is only one possible configuration, the one depicted in Fig. 18. In stage 1, one part is produced every 1.85 min (between the two machines), and in stage 2 one part is produced (between the five machines) every 1.7 min. Stage 1 is the bottleneck and dictates that the system cycle time is $t_{\max} = 1.85$ min. The number of parts per day is therefore: $Q = 1000/t_{\max} = 540$.
- *For three stages*, there are four possible configurations. However, only three of these satisfy the cycle time constraint of $t_{\max} \leq 2$ min. The three systems are depicted in Fig. 19. In these three cases, the cycle time is $t_{\max} = 1.85$ min.

  The fourth configuration (not shown) has only one machine in the third stage, which becomes a bottleneck with a cycle time of 3.3 min and cannot satisfy the required demand (a minimum cycle time of 2 min). Therefore, that configuration is unacceptable.

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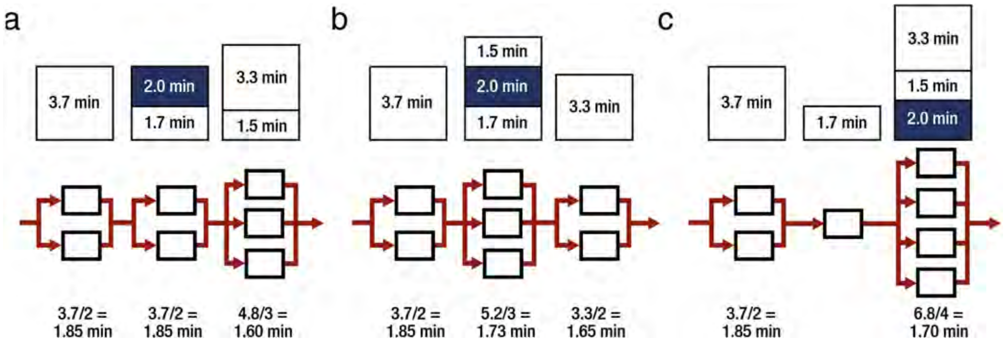

Fig. 19. Configurations with three stages.

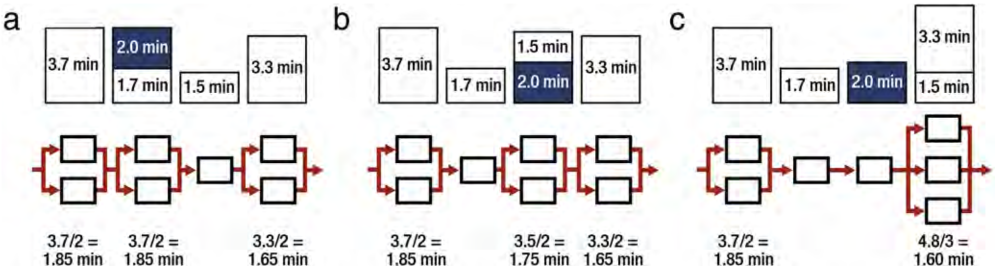

Fig. 20. Configurations with four stages.

- *For four stages* there are six possible configurations. However, three of them do not satisfy the cycle time constraint of $t_{\max} \leq 2$ min and have been eliminated from consideration. The three acceptable systems shown in Fig. 20 have a cycle time of $t_{\max} = 1.85$ min. The three eliminated configurations have only one machine in the fourth stage, which becomes a bottleneck with a cycle time of 3.3 min and cannot meet the required demand.
- *For five stages* there are four possible configurations, but only one of them (Fig. 21) is valid. The bottleneck in this configuration is in the third stage, which yields a cycle time of 2 min. In the other three five-stage configurations, only one machine is placed in the fifth stage, an arrangement that does not satisfy the required cycle time.

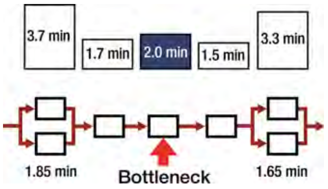

Fig. 21. A configuration with five stages.

Because of the cycle time requirement, the number of configurations is reduced from 15 to 8. Altogether, the number of possible RMS configurations to consider has been reduced from 64 to 8. Eight configurations is a manageable number to compare.

In order to make a final decision, the designer has to consider at least the following four factors (ranked by importance):

1. System throughput with reliability less than 100% (see next section).
2. Investment cost.
3. Scalability—the increment of production capacity gained by adding a machine.
4. Floor space, which may be roughly calculated by the configuration length (i.e., number of stages, m) times its maximum width (i.e., the maximum number of machines in a stage).

These factors are compared in Table 2.

The ranking is subjective and depends on the weight the designer (and the company) assigns to each factor (cost, scalability, etc.). We believe the designer will most likely favor (Rank = 1) the one shown in Fig. 19(b), to be further clarified at the end of the next section. Implementing configurations 19(b) meets the throughput requirement (500 parts/day), and the investment cost (machines and tooling) is acceptable. The configuration has a good scalability factor and will occupy a reasonable amount of floor space. Nevertheless, the facility layout to contain RMS should be considered in the final decision to minimize material handling costs.

The conclusions that may be drawn from this example are:

1. It is simple to calculate the minimum number of machines N needed in a system based on the total processing time per part and the required daily quantity.
2. The number of possible configurations is bounded by (i) the number of tasks needed on the part, and (ii) the number of faces on the part. This number is always smaller than 2^{N-1}.
3. The number of possible RMS configurations is reduced dramatically when the daily quantity requirement is taken into consideration.

10. Reconfigurable assembly systems

Product manufacturing consists of two main steps. First, components are fabricated using different methods, such as casting, machining, injection molding or metal forming. Second, these components are assembled or joined together using methods such as welding. Assembly systems comprising many stations for assembling a product are utilized in manufacturing virtually all types of durable goods, such as automobiles or office furniture. The product is fixed by clamps and transferred on the fixture through the assembly system [28]. Reconfigurable assembly systems are those that can rapidly change their capacity (quantities assembled) and functionality (product type, within a product family) to adapt to market demand. For example, Bair et al. described a reconfigurable assembly system designed to

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Table 2
Comparison of eight configurations in the example.

Configuration in figure	Stages *m*	Floor space	Throughput at $R = 100\%$	Cost	*RANK*
21	5	10	500	Low	7
20(a)	4	8	540	Med	6
20(b)	4	8	540	Med	5
20(c)	4	12	500	Med	8
19(a)	3	9	540	Med	**2**
19(b)	3	9	540	Med	**1**
19(c)	3	12	540	Med	**4**
18	2	10	540	*High*	**3**

Grey background = Best; Light grey background = very good result compared with alternatives.

produce different combinations of heat exchangers for industrial refrigerator systems [29].

Reconfigurable assembly systems should possess the characteristics of customization, convertibility, and scalability. Customization refers to designing a system for assembling an entire product family. For example, if each product in a family requires planar assembly, namely all parts are lying in a single geometric plane (e.g., printed circuit boards), the system may consist of SCARA-type robots [30]. Convertibility means that it is possible to switch quickly from the assembly of a certain product to the assembly of a different product in the product family. Designing fixtures that can hold all products in the family is needed to achieve a high level of convertibility. Scalability means the ability to change system throughput in a relatively short time to match demand.

There are three basic types of assembly systems: (1) manual assembly, carried out by human assemblers, usually with the aid of simple power tools; (2) assembly systems that combine human assemblers and automated mechanisms and robots, common in the assembly of mass-customized personal computers; (3) fully automated assembly systems for mass-produced parts, and particularly in hazardous environments such as welding auto body panels.

The first type, manual assembly, is the most reconfigurable assembly system since humans are very “convertible” and can easily adapt to new tasks when the line requires convertibility or scalability. If the system is scaled down, there are fewer people on the line and each person has to perform more tasks. Manual assembly is the norm in assembly of any complex products and especially in automotive final assembly and office furniture. However, as the system becomes scaled down dramatically, or as product variety becomes quite high in reconfigurable mixed-model assembly systems, assembly can become very complex. In manual assembly systems this complexity may cause human errors, and in turn impact system performance [31]. Therefore, in manual assembly there is always a limit on the number of product models that can be assembled during the same shift.

A key feature of reconfigurable assembly systems is a modular conveyor system that can operate asynchronously and be reconfigured to accommodate a large variety of component choices according to the product being assembled [32]. A reconfigurable conveyor allows quick rearrangement to alter process flow, adding or bypassing assembly stations according to the desired product. It also allows for serial–parallel configurations to balance the assembly line flow, as necessary to ensure even throughput.

Another feature that influences reconfigurability is system configuration. For example, traditional welding systems for automotive bodies have been designed using serial configurations. Although these serial lines offer a low level of convertibility and scalability, until recently other alternatives were not implemented. Advancements in controls and other technologies allow implementation of alternative system configurations, such as parallel and RMS configurations. These configurations offer improvements in convertibility and scalability, but their performance with regard to quality, particularly dimensional variation, must be studied for each type of configuration.

In designing configurations for assembly systems, the layout of stations and the assignment of assembly tasks to these stations are critical system design issues. When the assembled product consists of many parts, the assembly system grows in its size, and the development of a complete set of design solutions and their associated analysis of productivity and quality for each configuration becomes more difficult. Webbink and Hu pioneered a set of algorithms to quickly generate possible assembly system configurations and assign assembly tasks to these configurations [33]. Once all tasks are matched to configurations, performance parameters, such as productivity and quality, can be evaluated to select the configurations with the best performance.

Hu and Stecke studied a two-stage RMS configuration (similar to the one depicted in Fig. 9, but with two stages) [34]. They defined product quality both by its mean deviation and by 6σ level of variation, and examined it using compliant assembly variation simulation. This simulation uses both incoming part variation and tooling variation in its mathematical models to predict the level of variation of the final assembled product. This RMS configuration has four flow-paths. Because of the different levels of misalignment assigned to the tooling, the products passing through these four paths usually have four different local dimensional distributions. The result of a simulation of 10,000 cases is shown (see Fig. 22). The overall distribution is determined by the degree of misalignment.

11. Conclusions

Installing a new reconfigurable manufacturing system requires a large capital investment (e.g., a machining system for engine blocks may cost $150 million). Therefore, a systematic design approach such as the one proposed in this paper may save substantial money. Minimizing investment cost is important, but the issues of productivity and product quality are equally important since they will affect the operation cost. Several works that consider the effect of machine reliability on RMS daily operations have been published in the literature [35,36]. In recent years, global changes must also be predicted and considered when planning new systems [37].

A basic question is to determine the right time to consider building a new RMS system. The right time is when planning a new manufacturing system for a part family or a product family line with several variants that are expected to change in the next 10–15 years, and the market is volatile, making it hard to forecast demand [38]. The new system should be designed at the outset for reconfiguration, to be achieved by:

- Designing the system and its machines for *adjustable structure* that facilitates system scalability in response to market

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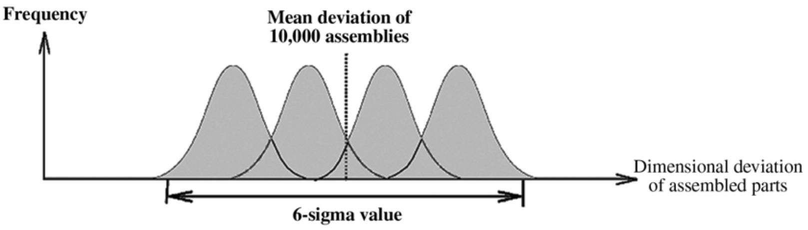

Fig. 22. The histogram of dimensional deviation for a 2 × 2 RMS assembly configuration.

demands and system/machine convertibility to new products. Structure may be adjusted (1) at the system level (e.g., adding machines), (2) at the machine level (e.g., adding spindles and axes, or changing angles between axes), and (3) at the control software (e.g., integrating easily advanced controllers).

- Designing the manufacturing system around the *part family*, with the customized flexibility required for producing all parts of this part family.

Product changes in multi-model production were not considered in this paper. Such considerations may optimize task-station assignments in mixed-model production, thereby reducing line changeover times and perhaps having some impact on RMS capital costs [39].

Nevertheless, the system design approach in this paper suggests that a new manufacturing system should be designed each time a new product is introduced. As life cycles of products become shorter and shorter, this approach is becoming ineffective. An effective solution should consider the evolution of products over multiple generations of models, and designing manufacturing system configurations that are cost effective for product evolution. This product–system co-evolution design approach constitutes a new direction of research that may enable quick product launches with smaller changeover costs for new products [40].

References

[1] Koren Y. Computer control of manufacturing systems. McGraw-Hill; 1983.
[2] Stecke KE. Formulation and solution of nonlinear integer production planning problems for flexible manufacturing systems. Management Science 1983; 29(3):273–88.
[3] Stecke KE, Solberg J. Loading and control policies for a flexible manufacturing system. International Journal of Production Research 1981;19(5):481–90.
[4] Son YK, Park CS. Economic measure of productivity, quality and flexibility in advanced manufacturing systems. Journal of Manufacturing Systems 1987; 6(3):193–207.
[5] Cochran DS, Arinez JF, Duda JW, Linck J. A decomposition approach for manufacturing system design. Journal of Manufacturing Systems 2001–2002; 20(6):371–89.
[6] Koren Y, Ulsoy AG. Reconfigurable manufacturing systems. Engineering Research Center for Reconfigurable Machining Systems. ERC/RMS report #1. Ann Arbor; 1997.
[7] Koren Y. The global manufacturing revolution—product-process-business integration and reconfigurable systems. John Wiley & Sons; 2010.
[8] Dupont-Gatelmand C. A survey of flexible manufacturing systems. Journal of Manufacturing Systems 1981;1(1):1–16.
[9] Spicer P, Yip-Hoi D, Koren Y. Scalable reconfigurable equipment design principles. International Journal of Production Research 2005;43(22):4839–52.
[10] Lee HF, Stecke KE. An integrated design support method for flexible assembly systems. Journal of Manufacturing Systems 1996;15(1):13–32.
[11] Landers R, Min BK, Koren Y. Reconfigurable machine tools. CIRP Annals 2001; 49:269–74.
[12] Koren Y, Ulsoy AG. Reconfigurable manufacturing system having a production capacity, method for designing same, and method for changing its production capacity. US patent no. 6,349,237. February 2002.
[13] Koren Y, Kota S. Reconfigurable machine tools. US patent no. 5,943,750. August 1999.
[14] Pritschow G, Altintas Y, Jovane F, Koren Y, VanBrussel H, Weck M. Open-controller architecture—past, present, and future. CIRP Annals 2001;50(2): 463–70.
[15] Koren Y, Heisel U, Jovane F, Moriwaki T, Pritschow G, Ulsoy AG, et al. Reconfigurable manufacturing systems. CIRP Annals 1999;48(2):6–12.
[16] Koren Y, Ulsoy AG. Vision, principles and impact of reconfigurable manufacturing systems. Powertrain International 2002;14–21.
[17] Maier-Speredelozzi V, Koren Y, Hu SJ. Convertibility measures for manufacturing systems. CIRP Annals 2003;52(1):367–71.
[18] Won Y, Currie KR. An effective *P*-median model considering production factors in machine cell-part family formation. Journal of Manufacturing Systems 2006;25(1):58–64.
[19] Spicer P, Koren Y, Shpitalni M. Design principles for machining system configurations. CIRP Annals 2002;51(1):276–80.
[20] Zhu XW. Calculating the number of possible system configurations. ERC/RMS report. 2005.
[21] Ariafar S, Ismail N. An improved algorithm for layout design in cellular manufacturing systems. Journal of Manufacturing Systems 2009;28:132–9.
[22] Koren Y, Hu SJ, Weber T. Impact of manufacturing system configuration on performance. CIRP Annals 1998;47:689–98.
[23] Freiheit T, Koren Y, Hu SJ. Productivity of parallel production lines with unreliable machines and material handling. IEEE Transactions on Automation Science and Engineering 2004;1(1):98–103.
[24] Freiheit T, Shpitalni M, Hu SJ. Productivity of paced parallel-serial manufacturing lines with and without crossover. Journal of Manufacturing Science and Engineering 2004;126(2):361–8.
[25] Um I, Cheon H, Lee H. The simulation design and analysis of a flexible manufacturing system with automated guided vehicle system. Journal of Manufacturing Systems 2009;28(4):115–22.
[26] Suh NP. Design and operation of large systems. Journal of Manufacturing Systems 1995;14(3):203–13.
[27] Jacobsen P, Pedersen LF, Jensen PE, Witfelt C. Philosophy regarding the design of production systems. Journal of Manufacturing Systems 2001–2002;20(6): 405–15.
[28] Camelio JA, Hu SJ, Ceglarek D. Impact of fixture design on sheet metal assembly variation. Journal of Manufacturing Systems 2004;23(3):182–93.
[29] Bair N, Kidwai T, Mehrabi M, Koren Y, Wayne S, Prater L. Design of a reconfigurable assembly system for manufacturing heat exchangers. In: Japan–USA flexible automation international symposium. 2002.
[30] Koren Y. Trajectory interpolators for SCARA-type robot. In: The 14th NAMRC, proceedings. 1986. p. 571–6.
[31] Hu SJ, Zhu XW, Wang H, Koren Y. Product variety and manufacturing complexity in assembly systems and supply chains. CIRP Annals 2008;57(1): 45–8.
[32] Hains CL. An algorithm for carrier routing in a flexible material-handling system. IBM Journal of Research and Development 1985;29(4):356–62.
[33] Webbink RF, Hu SJ. Automated generation of assembly system-design solutions. IEEE Transactions on Automation Science and Engineering 2005; 2(1):32–9.
[34] Hu SJ, Stecke KE. Analysis of automotive body assembly system configurations for quality and productivity. International Journal of Manufacturing Research 2009;4:117–41.
[35] Youssef AMA, ElMaraghy HA. Performance analysis of manufacturing systems composed of modular machines using the universal generating function. Journal of Manufacturing Systems 2008;27(2):55–69.
[36] Freiheit T, Shpitalni M, Hu SJ, Koren Y. Designing productive manufacturing systems without buffers. Annals of the CIRP 2003;52(1):105–8.
[37] Wang H, Kababji H, Huang Q. Monitoring global and local variations in multichannel functional data for manufacturing processes. Journal of Manufacturing Systems 2009;28(1):11–6.
[38] Koren Y. General RMS characteristics. Comparison with dedicated and flexible systems. Reconfigurable manufacturing systems and transformable factories, vol. I. Springer; 2006. p. 27–45.
[39] Nazarian E, Ko J, Wang H. Design of multi-product manufacturing lines with the consideration of product change dependent inter-task times, reduced changeover and machine flexibility. Journal of Manufacturing Systems 2010; 29(1):35–46.
[40] Ko J, Hu SJ. Manufacturing system design considering stochastic product evolution and task recurrence. ASME, Journal of Manufacturing Science and Engineering 2009;131.

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