Chapter 3

General RMS Characteristics. Comparison with Dedicated and Flexible Systems

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3.1 Introduction

At the end of the 20th Century, manufacturing entered a new era in which all manufacturing enterprises must compete in a global economy. Global competition increases customers' purchasing power, which, in turn, drives frequent introduction of new products and causes large fluctuations in product demand.

To stay competitive, manufacturing companies must use systems that not only produce their goods with high productivity, but also allow for rapid response to market changes and consumer needs. A new manufacturing capability that allows for a quick production launch of new products, with production quantities that might unexpectedly vary, became a necessity. Reconfigurable manufacturing systems (RMS), offer this capability.

Reconfigurability is an engineering technology that deals with design of production machines and manufacturing systems for cost-effective, rapid reconfigurability to quickly respond to market changes. If the system and its machines are not designed at the outset for reconfigurability, the reconfiguration process will prove lengthy and, therefore, impractical**.** The RMS is, therefore, a responsive manufacturing system whose production capacity is adjustable to fluctuations in market demand and whose functionality is adaptable to new products.

The RMS concept of a living, evolving factory that quickly adapt to new products and changing market demands was introduced at the Engineering Research Center of the University of Michigan (UM) in the mid 1990s. Subsequently, RMS enabling technologies were developed at both the UM and in Europe and Canada. RMS is being recognized today as a necessary tool for increasing productivity and sustaining profits despite of abrupt global market changes.

A typical RMS may include an array of flexible equipment, such as CNC machines, and special reconfigurable equipment – machine tools, robots, and in-process inspection machines. RMS may have two levels of reconfigurability: (1) In the arrangement and connections of machines at the system level, and (2) in some of the system's machines that are reconfigurable. Both levels are designed according to a set of principles, and possess special characteristics that are called RMS Core Characteristics: Modularity, Integrability, Customization, Scalability, Convertibility, and Diagnosability.

3.2 The Challenge

Every manufacturing enterprise, and, in turn, its manufacturing systems, should have three goals: Produce at low cost, enhance product quality, and possess capabilities for rapid responsiveness. Reconfigurable systems are focused on achieving the third goal – responsiveness, and achieving it at low cost and rapid time.

As we will show, manufacturing systems that use reconfigurable components and architectures can offer a much greater benefits to manufacturers than traditional manufacturing systems. These include adjustable rates of productivity and flexibility, along with new tools for designing systems and getting production up and running are a hallmark of reconfiguration design that improve the time-to-market and provide production at precisely the quantities needed, and at the lowest possible cost.

3.2.1 Traditional Manufacturing Systems

Current manufacturing systems, that are mainly dominated by dedicated and flexible systems, are not able to meet the market responsiveness requirements at reasonable cost, as explained below.

Dedicated manufacturing lines (DML), or transfer lines, are based on fixed automation and produce a company's core products or parts at high-volume. Each dedicated line is typically designed to produce a single part (e.g., specific engine block) at high production rate. When the volume is high, the cost per part is relatively low. Therefore, DMLs are cost effective as long as market demand matches the supply; but with increasing pressure from global competition, there are many situations in which dedicated lines do not operate at full capacity, and thereby create losses. Of course, producing product variety is impossible with a DML, and therefore their role in modern manufacturing is decaying.

Flexible manufacturing systems (FMS) consist of computer numerically controlled (CNC) machines and other programmable automation and can produce a variety of products on the same system [1]. Despite this advantage, however, our survey shows that flexible systems have not been widely adopted, and many of the manufacturers that bought FMSs are not pleased with their performance [2]. Drawbacks of FMSs are that they require more expensive machines than DMLs, and because of the single-tool operation of CNC machines, the production rate of FMSs is very small compared with their DMLs counterparts. In addition, the production capacity of FMSs is usually lower than that of dedicated lines, and they are not designed for a quick change in their capacity, namely, they are not responsive to market changes.

The comparison between the two systems, shown in Table 1, identifies key limitations in both types of systems.

The challenge of coping with large fluctuations in product demand cannot be solved with dedicated lines that are not scalable. So much so that quite often opportunities to supply a larger demand of a product are ignored even though the available production capacity for another product remains largely underutilized. A

Table 1 Comparison between DML and FMS

DML	FMS
Limitations: • Not flexible – *for a single part* • Fixed capacity – *not scalable*	**Limitations:** • Expensive • Slow – single-tool operation
Advantages: • Low cost • Fast – multi-tool operation	**Advantages:** • Convertible • Scalable capacity

study [3] carried out on a manufacturer of components for the car industry has shown that the average utilization of DML transfer lines available was only 53%. The reason for this low average utilization is that some products in the early stages of introduction, or at the end of their life cycle are required, but in lower than optimal volumes. Even products in the mature phase do not always reach the production volumes forecast when the dedicated manufacturing line was designed.

Conversely, DMLs also fail when demand goes above the design capacity. If a product's popularity exceeds all market expectations, or when new uses are found for existing products, the DML is powerless to respond. This challenge is theoretically met by flexible manufacturing systems that are scalable, especially when designed with multi-axis CNC machines that operate in parallel. Despite this advantage, however, a recent survey shows that flexible systems have not been widely adopted, and many of the manufacturers that bought FMSs are not pleased with their performance [2].

Drawbacks of Flexible manufacturing systems The high cost of FMS is one of the major reasons for the low level of acceptance or satisfaction with FMS. Why is FMS expensive? Unlike DML stations, CNC machines are not designed around the part nor around the part family. Rather, general-purpose CNCs are built around a standard operational envelope, designed even before the manufacturer determines the product to be built. Only when the standard CNCs were selected to constitute a system, process planning is undertaken to adapt the machines and the process to the part. Since the machine builders do not know the specific use of the machine when they design the machines, flexible systems and their machines are constructed with all possible functionality built in. The full functionality is often underutilized and constitutes a capital waste. It is also a common assumption that FMS should be able to produce (1) any part (within the machine envelope), (2) at any mix of parts, and (3) in any sequence. This approach increases cost since it requires a parallel system structure for FMS that utilizes high-power, general-purpose 5-axis CNCs with a very large tool magazine and multiple sets of tools – a very expensive solution.

3.2.2 The Need for Responsiveness

Responsiveness is an attribute enabling manufacturing systems to quickly launch new products on existing systems and to react rapidly and cost-effectively to

1. Market Changes
2. Customer's Orders
3. Government regulations (safety and environment)
4. System failures (keep production up despite equipment failures).

Market changes include

- Changes in product demand
- Changes in current products
- Introducing new products.

These changes are driven by aggressive economic competition on a global scale, more educated and demanding customers, and a rapid pace of change in process technology [4]. To survive in this new manufacturing environment, companies must be able to react to changes rapidly and cost-effectively. This can be done by a manufacturing system that is designed for changing production capacity as market grows, and adding functionality as product changes.

Figure 1 shows an example where the actual demands for Products A and B are different from what was planned. The manufacturing system was planned for capacity (i.e., maximum production) of 80,000 units annually. But it so happened that the initial demand for product A was higher than expected, which created a temporary sale loss. The production of product B could supply demand only in the first year, which means a permanent loss afterwards, unless capacity is added quickly. This type of changes requires rapid reconfiguration in the system *production capacity*, namely system scalability. To capture the opportunity, the system scalability must be done quickly and cost-effectively.

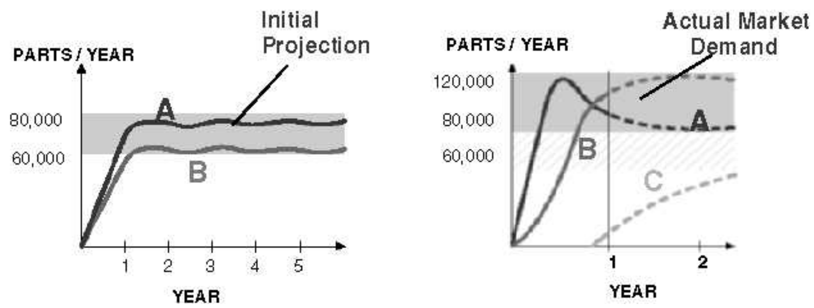

Fig. 1 Projected vs. actual product demand comparison

3.3 RMS – A New Class of Systems

A cost-effective response to market changes requires a new manufacturing approach that not only combines the high throughput of DML with the flexibility of FMS, but also is able to react to changes quickly and efficiently. This is achieved by designing systems according to two principles:

- Design of a system and its machines for **adjustable structure** that enable system scalability in response to market demands and system/machine adaptability to new products. Structure may be adjusted at the system level (e.g., adding machines) and at the machine level (changing machine hardware and control software).
- Design of a manufacturing system around the **part family**, with the customized flexibility required for producing all parts of this part family. (This reduces the system cost.)

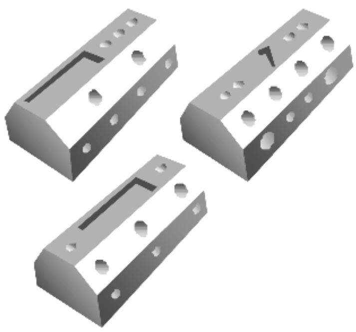

Fig. 2 Example of a part family

Accordingly, a definition of a reconfigurable manufacturing system that captures the essence of these principles is as follows.

> **A Reconfigurable Manufacturing System (RMS) is a system 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**

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

3.3.1 RMS —The Best of Both Worlds

A system designed according to these principles constitutes a new class of systems – a Reconfigurable Manufacturing System (RMS**)**. The RMS is designed to cope with situations where both productivity and the ability of the system to react to change are of vital importance. The invention of the RMS is documented in US Patent #6,349,237 [5].

As summarized in Table 2, building a system with adjustable structure, scalability, and flexibility focused on a part family creates a responsive reconfigurable system. Highly productive, cost-effective systems are created by (i) part-family focus and (ii) customized flexibility that enables the operation of simultaneous tools (similar to a dedicated machine). The flexibility of RMS, although it is indeed just "customized flexibility," provides all the flexibility needed to process the part family, and therefore is less expensive than the general flexibility of FMS.

Table 2 Comparison of system features (Dedicated vs. RMS vs. FMS)

	Dedicated	**RMS/RMT**	**FMS/CNC**
System Structure	Fixed	**Adjustable**	Adjustable
Machine Structure	Fixed	**Adjustable**	Fixed
System focus	Part	**Part Family**	Machine
Scalability	No	Yes	Yes
Flexibility	No	Customized	General
Simultaneously Operating Tool	Yes	Yes	No
Productivity	High	High	Low
Lifetime Cost	**Low** for a single part, when fully utilized	**Medium** or production at me lium-to-high volume new parts and vari- able demand during system lifetime	**Reasonable** for simultaneous production of many parts (at low volume); otherwise – **High**

In summary, RMS embraces the best qualities of DML and FMS systems, For instance, borrowing from dedicated lines that are designed around a single part/product, RMS focuses on families of parts, cylinder heads for example. Between four-, six-, and eight-cylinder models there are many differences, but they also have many common features. Focusing on the part family enables the designer to plan a system that accommodates different variation of the same part family with a minimum of alteration to the production scheme. This approach utilizes the high productivity of DML machine design and is much more economical than the general functionality of FMS.

3.3.2 Comparison of Manufacturing Systems

Traditional manufacturing systems can hardly meet the requirements dictated by the new, competitive global environment. Dedicated manufacturing lines (DMLs) as we have described, are based on inexpensive fixed automation and produce a company's core products or parts at high volume and for a long run time (see Figure 3). Therefore, the FMS production capacity is usually lower than that of dedicated lines and their initial cost is higher as depicted in Figure 3. While DML and FMS are limited in capacity-functionality, RMS capacity and functionality change over time as the system reacts to changing market circumstances.

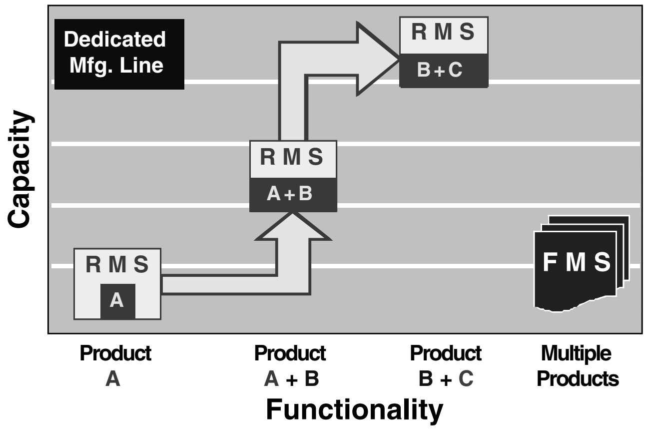

Fig. 3 Comparison of capacity and functionality allocation: DML, FMS and RMS

Figure 3 does not express the capital cost associated with changing the system capacity or functionality. Figure 4 depicts the system-cost versus capacity for DML, FMS, and RMS.

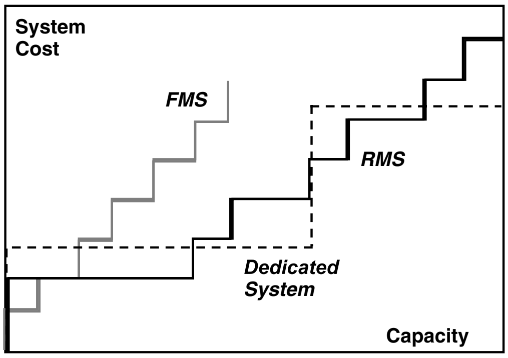

Fig. 4 Manufacturing system cost versus capacity (or production rate)

The DML has a constant capital cost up to its maximum planned capacity, and then an expensive, additional line must be built. This added line doubles the capacity, which in many cases is not needed, and therefore it is a questionable addition. The FMS is scalable at a constant capacity rate of small cost-increments expressing adding more machines in parallel. The RMS is scalable, but at a non-constant capacity rate that depends on the initial design of the RMS and the changing market circumstances.

The conclusions are that if the dedicated line is always producing at least 75% of its maximum capacity, it is the most economic solution if product changes are not accounted for. If only small quantities are needed, then a parallel-type FMS is the most economical. If larger quantities are needed and the market uncertainty is high, then RMS is the most cost-effective solution.

3.3.3 RMS Operation

To cope with the short windows of opportunity for new products, computer-aided design (CAD) has dramatically reduced product development times during the last decade (Figure 5, top). However, such design methodologies do not exist for the manufacturing system itself, and therefore its design time remains lengthy. Manufacturing system lead-time (i.e., the time to design and build or reconfigure the manufacturing system, and to ramp-up to full-volume, high-quality production) has now become the bottleneck.

Brief windows of opportunity can be captured, with major economic savings, if the lead-time of manufacturing systems can be reduced. Reduced lead-time can be achieved through the rapid design of systems that are created from modular components, or by the reconfiguration of existing manufacturing systems to produce new products, as depicted in Figure 5, bottom [5].

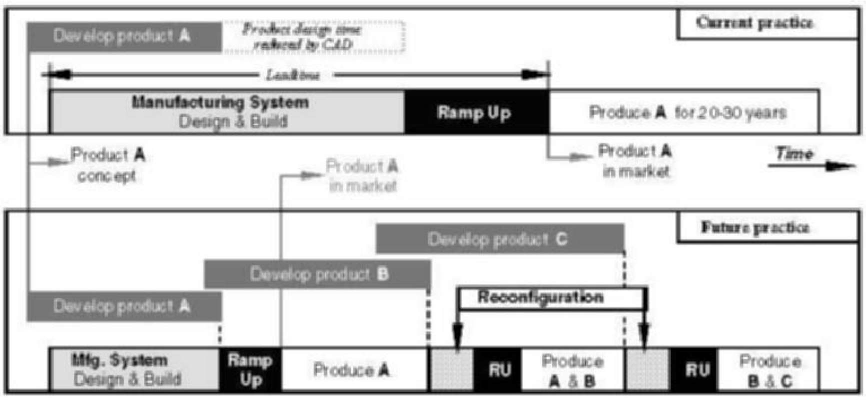

Fig. 5 Frequency of product introduction: current vs. future practice

In order to produce new products and accommodate required changes in existing products, new functions must be added to the manufacturing system through reconfiguration. This type of reconfiguration (i.e., adding manufacturing *functions*) is also needed for accommodating government regulations and integrating new process technology (such as new sensors, more reliable machine elements, etc.).

If designed correctly, many reconfiguration periods will occur during the lifetime of a reconfigurable system. To make reconfiguration successful, short Ramp Up (RU) phases are critical to bring the system back on line quickly. There are systematic methods, such as the Stream-of-Variations [6], to reduce ramp-up period by efficient root-cause analysis of the whole system.

A different type of reconfiguration is needed to adjust the system production rate in order to cope with the fluctuations in product demand and mix caused by changing market conditions.

In summary: A responsive manufacturing system is one whose production capacity is adjustable to fluctuations in product demand, and whose functionality is adaptable to new products. The RMS is a new class of responsive manufacturing systems.

3.4 Enabling Technologies and Reconfiguration Characteristics

In 1996, the National Science Foundation established an Engineering Research Center for Reconfigurable Manufacturing Systems to explore and describe the science that underlies reconfigurable manufacturing. Since that time the Center has defined a range of RMS principles and characteristics, and invented a range of patents that provide the basis for developing new reconfiguration technologies and processes. These basic enabling technologies and characteristics that make systems reconfigurable are discussed below.

3.4.1 RMS Enabling Technologies

The common denominator for existing dedicated and flexible systems is their use of fixed hardware and fixed software. For example, only part programs can be changed on CNC machines, but the software architecture or the control algorithms cannot. In recent years, however, two technologies that are necessary enablers for reconfiguration have emerged: in software, modular, **open-architecture controls** that aim at allowing reconfiguration of the controller [7]; and in machine hardware, **modular machine tools** that aim at offering the customer more machine options [8, 9, 10]. These emerging technologies show a trend toward the design of systems with **reconfigurable hardware** and **reconfigurable software**, as depicted in Figure 6 [11].

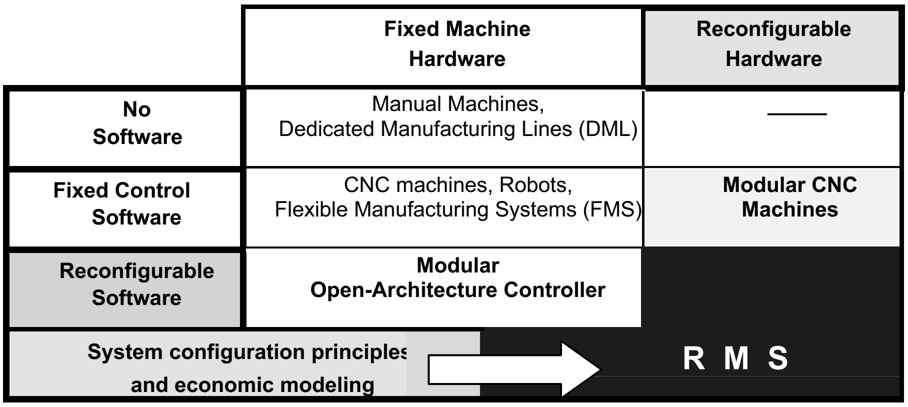

Fig. 6 Classes of manufacturing systems; RMS combines reconfigurable hardware and software, and is designed from systems perspective

Reconfigurable hardware and software are necessary but not sufficient conditions for a true RMS. The core of the RMS paradigm is an approach to reconfiguration based on system design combined with the simultaneous design of open-architecture reconfigurable controllers with reconfigurable modular machines that can be designed by synthesis of motion modules [11, 12].

RMS design not only combines reconfigurable hardware with reconfigurable software, but also includes systems perspective and economic modeling. The ultimate goal of RMS is to adopt a systems approach in the design of the manufacturing process that allows

(1) Reconfiguration of the entire system
(2) Reconfiguration of machine hardware
(3) Reconfiguration of control software.

With such design, the system capacity and functionality are not fixed but change over time in response to market demand, The RMS paradigm also influences a whole new generation of reconfigurable machines that allow cost-effective reconfiguration for scalability and/or functionality.

Similar to flexible systems, reconfigurable manufacturing systems are equipped with automated part handling and tool supply systems. The structure of the part (i.e., workpiece) handling system significantly influences the productivity and reliability of reconfigurable manufacturing systems.

When the production plan of a new product is added, the system functionality adjusts to handle it. We summarize this attribute by the phrase:

Exactly the functionality and capacity needed … Exactly when needed.

The reconfigurable manufacturing system allows flexibility not only in producing a variety of parts, but also in changing the system itself. Both the systems and the reconfigurable machines must be designed at the outset to be reconfigurable, by utilizing the technologies discussed above and by possessing specific characteristics.

3.4.2 RMS Core Characteristics

Reconfigurable systems must be designed at the outset using hardware and software modules that can be integrated quickly and reliably. Otherwise, the reconfiguration process will be both lengthy and impractical. Achieving this design goal requires a RMS that possesses the several key characteristics: Modularity, Integrability, Customization, Scalability, Convertibility, and Diagnosibility. These characteristics apply to the design of whole production systems, as well as the machines, their controllers, and their control software. They may also be applied to manpower resources, and ultimately to the enterprise as a whole. We elaborate below on these key characteristics.

Modularity: In a reconfigurable manufacturing system, all major components are modular (e.g., structural elements, axes, controls, software, and tooling). When necessary, the modular components can be replaced or upgraded to better suit new applications. Modules are easier to maintain and update than whole machines, thereby lowering life-cycle costs over current systems [8]. New compensation and calibration algorithms can be readily integrated into the machine controller, resulting in a system that continuously evolves for greater accuracy. Selection of basic modules, and the way they are connected, must allow for the creation of systems that can be easily integrated, diagnosed, customized, and converted.

Integrability: While there are hundreds of machine tool builders in the world, only about a dozen of them are capable of supplying fully integrated flexible machining systems for high-volume production (above 200,000 units annually). The reason is the lack of system integration methodologies. To aid in designing reconfigurable systems, a set of system configuration and integration rules must be established. Such rules were developed for configurable computing [13]. In the machining domain these rules should allow designers to relate clusters of part features and their corresponding machining operations to machine modules, thereby enabling product-process integration. In addition, machine controls and processing units must be designed for integration into a system.

Customization: This characteristic drastically distinguishes RMS from FMS and DML, and allows a reduction in system and machine cost. It enables the design of a system for the production of a part family, rather than a single part (as produced by DML) or any part (FMS). “Part family” means, for example, several types of engine blocks or several types of microprocessors, or all types of Boeing 747. In the context of RMS, a **part family** is defined as all parts (or products) that have similar geometric features and shapes, the same level of tolerances, require the same processes, and are within the same range of cost. The definition of the part family must ensure that most manufacturing system resources are utilized for the production of every member part. Customized flexibility means that the dominant features of the part family being manufactured will determine the overall machine configuration and system configuration. It allows the utilization of multiple tools (e.g., spindles in machining or nozzles in injection molding) on the same machine, thereby increasing productivity at reduced cost without compromising flexibility. Customized control is achieved by integrating control modules (e.g., user-developed process models, special compensation algorithms, diagnostics that match the system type, discrete event control, and simultaneous control of multiple spindles) into generic controller platforms. The benefits of such customization are improved productivity, accuracy, up-time, and machine life.

The characteristic of customization, or customized flexibility, provides substantial economic benefit by enhancing productivity at low cost. Dedicated lines are *customized* hardware lines built with precisely the functionality needed to produce a specific product. Therefore, they can take advantage of using *multiple tools* – tools that cut or drill the part simultaneously, and thereby achieve high productivity. On the other hand, CNC machines, that are the cornerstones of FMS, are designed as multi-axes, general-purpose machines that use a *single tool* that can be manipulated in different directions to allow for *general flexibility*. However, not all these axes-of-motion and tool manipulation capability are needed in the production of each member of the part family. By contrast, reconfigurable machines can be designed with several active tools cutting simultaneously, like a DML, but be able to produce a whole part family like an FMS. Thus both the productivity of DMLs, and the FMS's ability to handle part variety (with in the part family) are achieved in RMS.

Convertibility: System convertibility may have several levels. At the machine level conversion is needed when switching production between two members of the part family and may require switching spindles (e.g., from low-torque high-speed spindle for aluminum to high-torque low-speed spindle for titanium), or manual adjustment of passive degrees-of-freedom [14]. Machine conversion at this daily level must be carried out quickly to be effective (e.g., 1 to 10 minutes). To achieve this, the RMS must contain advanced mechanisms that allow for easy conversion between parts, as well as sensing and control methods that enable quick calibration of the machines after conversion. A higher level of convertibility may include adding functions to machines (e.g., expanding the size of a tool magazine, or adding a rotary table to a 3-axis CNC), or even adding machines to expand the range of system functionality to produce new parts.

Scalability: Scalability of the system capacity is the counterpart characteristic of convertibility. Scalability may require adding spindles to a machine to increase its productivity, or even adding machines to expand the overall system capacity as a given market grows.

Diagnosability: Diagnosability has two aspects: detecting machine failure and identifying the causes for unacceptable part quality. The second aspect is critical in RMS. As production systems are made more reconfigurable, and their layouts are modified more frequently, it becomes essential to rapidly tune the newly reconfigured system so that it produces quality parts. Systematic measurement methods were developed to help identify the sources of product quality problems in the production system rapidly, and to correct them by utilizing control technologies, statistics, and signal processing techniques [6].

There is a relationship between the characteristics and the system goals of enhancing responsiveness and productivity and reducing life-cycle cost, as shown in Table 3. Modularity, integrability, convertibility, and diagnosability reduce the reconfiguration time and effort, and thereby enhance system responsiveness. Except of modularity, the other five characteristics contribute to a reduction in the system lifetime cost, by enabling it to change faces during its lifetime and "stay alive" despite changes in markets, consumer's demands and process technology. Building a modular system may be more expensive because of the added cost of the interfaces. If, however, modular components become commodities, then economies of scale may reduce the overall system cost.

Table 3 RMS characteristics support system productivity and cost

	Reconfigure time	**Productivity**	**Life-cycle cost**
Modularity Components are modular	•		
Integrability Interfaces for rapid integration	•		•
Customization Flexibility limited to part family		•	•
Scalability Designed for capacity change		•	•
Convertibility Designed for functionality change	•	•	•
Diagnosability Designed for diagnostics	•	•	•

3.4.3 Sufficient and Necessary Conditions for RMS

Having a system or a piece of equipment with reconfigurable hardware and reconfigurable software are necessary but not sufficient conditions for a true RMS. This statement, which may be contrary to the common thinking, is correct if one keeps in mind the goal of a reconfigurable system or a reconfigurable machine (see Sec. 5 below). The reconfigurable hardware and software should be designed for convertibility and/or scalability, which are the goals of RMS – *Exactly the functionality and capacity needed, exactly when needed*. In addition, in order to reduce costs, the design of the system and several of its machines should be focused on a part family; namely, the characteristic of Customization should be embedded in the design of a reconfigurable equipment and reconfigurable system.

Analyzing the relationship between the RMS six core characteristics and the RMS definition in Sect. 3.3, one can define two sufficient conditions for the existing of a RMS:

- A system that possesses the characteristics of Customization and Scalability is a RMS
- A system that possesses the characteristics of Customization and Convertibility is a RMS

However, contrary to the common thinking, Modularity is not a necessary or sufficient condition for RMS, since nor capacity neither functionality changes are guaranteed with modularity. The likelihood that a modular structure will enable functionality or capacity changes is high, but it is not guaranteed. Therefore, the following statements are valid:

- A manufacturing system that possesses the characteristics of Modularity and Integrability has high likelihood to be a RMS
- The characteristics of Modularity, Integrability and Diagnosability reduce the system reconfiguration time and its ramp-up time

To conclude, the characteristics of Customization, Scalability and Convertibility are essential RMS characteristics, while the other three – Modularity, Integrability and Diagnosability – are supporting characteristics that make the RMS conversions efficient in terms of reconfiguration time as shown in Table 3.

3.4.4 Reconfiguration Principles

Reconfigurable manufacturing systems are designed and operate according to a set of basic principles given below. The first three principles are the core principles that define a reconfigurable system. The others are secondary principles that assist in designing a cost-effective RMS.

1. The RMS contains adjustable production resources to respond to imminent market needs.
   - The RMS capacity is rapidly scalable in small, optimal increments.
   - The RMS functionality is rapidly adaptable to the production of new products.
2. The RMS is designed around a part/product family, with just enough customized flexibility needed to produce all members of that family.
3. To enhance the responsiveness of a manufacturing system, RMS core characteristics should be embedded in the whole system as well as in its components (mechanical, communications and controls).
4. The RMS contains an economical mix of flexible and reconfigurable equipment with customized flexibility, such as reconfigurable machines

whose functionality and productivity can be readily changed when needed (See Sect. 3.5).

5. In general, systems with a large number of alternative routes to producing a part are more reconfigurable, but they require higher investment cost in tooling and in material-handling systems.
6. The RMS possesses hardware and software capabilities to respond cost-effectively to unpredictable events (market changes and machine failure).

The more of these principles are applicable to a given manufacturing system, the more reconfigurable that system is. Implementing these principles in the system design enables achieving the ultimate goal – to create a "**living factory**" that is able to rapidly adjust its production capacity while maintaining high levels of quality from one part to the next.

3.5 Reconfigurable Machines

Reconfigurable machines (RMs) are machines whose structures can be changed to provide alternative functionality or/and upgradeable capacity on demand (Principle 1). They are always designed around the common characteristics of part families (Principle 2). The RM can be either returned to its original state, or further modified to provide yet other new functionality or production capacity as needed. The Engineering Research Center at the University of Michigan has built two reconfigurable machine tools, two reconfigurable inspection machines, and a reconfigurable assembly machine.

3.5.1 Reconfigurable Machine Tools

While there might be major differences between various engine cylinder heads, for example, the basic configuration of all of them is quite similar. A reconfigurable machine tool (RMT) can therefore be designed to perform the necessary machining operations on all the members of the part family with reconfiguration to the machine tool itself [14]. That means that the RMT can cost-effectively produce a whole family of parts, even part styles that haven't been called for yet, with equal precision and reliability [15].

There are two basic objectives in RMT design. These objectives are

(1) To increase the production rate for the machine by adding machining devices (…exactly the capacity needed), and
(2) To adapt the functionality of the machine by changing its geometry to fit the production of a new member of a family of parts (…exactly the functionality needed).

Accordingly, there are two types of RMTs as depicted in Figure 7.

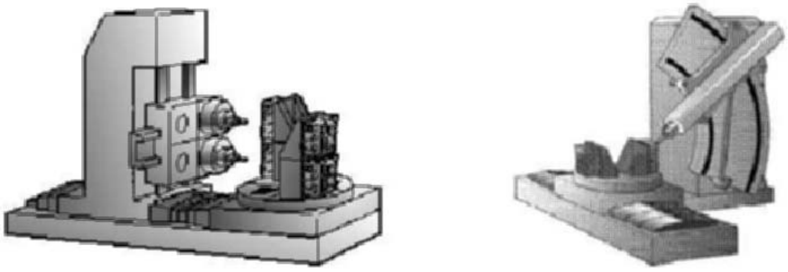

Fig. 7 Capacity-changing RMT (a, left) and functionality-changing RMT (b, right) [artwork: Rod Hill]

The capacity-changing RMT in Figure 7a possesses the characteristics of Modularity (each spindle is a module), Integrability (the spindle holders provide rapid mechanical-electrical integration), Customization (flexibility just for horizontal drilling), and Scalability (adding up to four spindles). The functionality-changing RMT in Figure 7b possesses two characteristics: Customization (a family of parts with inclined surfaces), and Convertibility (rapid changing the angle of the Z axis).

The RMT paradigm is driven primarily by economic considerations. Rather than build a multi-spindle dedicated machine, a manufacturer should be able to initially purchase a single-spindle CNC machine and then add spindles to it and cut several parts at the same time, when market demand justifies the investment (Adjustable Capacity RMT). Also, rather than invest in a highly complex, general-purpose CNC machine tool, it is more economical to have a simpler machine with enough functionality to produce just a part family without buying a lot of extra unused functionality (Adjustable Functionality RMT). Purchasing just the capacity and functionality needed to produce a part family gives RMTs an advantage. A prototype of an adjustable functionality RMT that was designed and built at the ERC at the University of Michigan is shown in Figure 8.

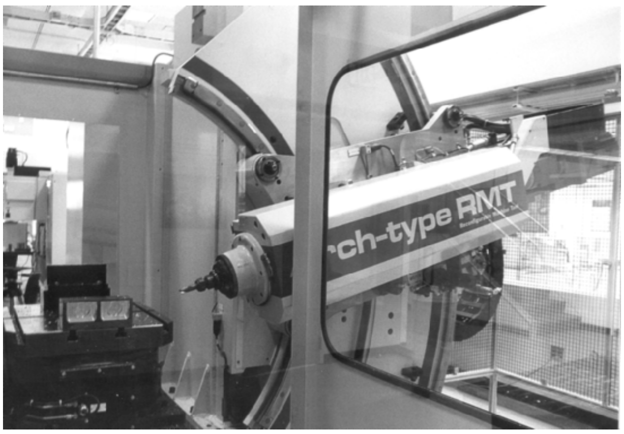

Fig. 8 Functionality-changing RMT prototype (ERC at UM)

3.5.2 Reconfigurable Inspection Machines

Many critical parts of the automobile, such as engine blocks and cylinder heads, are produced with precision machinery at a high rate of 100 parts per hour. But what happens when the drilling and milling tools of the machines are worn, or a tiny chip of their sharp edge is broken? Then the performance of the engine deteriorates quickly, which in turn may cause, for example, a noisier engine than planned or adding oil to the engine in shorter intervals than scheduled. Consequently, the customer is disappointed and the manufacturer may lose reputation. In order to identify and minimize the occurrence of these types of failure modes the current state of practice is to measure the machined parts by a relatively slow Coordinate Measuring Machine (CMM) – a measurement that takes about 3 hours. If a bad dimension is identified, the production line is stopped and the problem is fixed. But during these 3 hours about 300 engines were produced – part of them with the defects resulting in deteriorated performance. Either these engines are identified and scraped or the consumer gets a deteriorated product.

The Engineering Research Center for Reconfigurable Manufacturing Systems (ERC/RMS) has developed a Reconfigurable Inspection Machine (RIM) that utilizes new non-contact sensor technologies to measure within 30 seconds features associated with a family of cylinder heads of automobile engines [16]. As shown in Figure 9, the part moves along a single axis motion stage while optical sensors configured on both sides of the part are scanning its features.

Because of the short measuring time, the RIM is capable of inspecting each part on a real time basis directly on the machining line (1005 inspection), and thereby identifies machining problems immediately. As a result, the customer gets a better product and the manufacturer avoids scrap, which in turn increases the overall system productivity.

The RIM can be reconfigured in a relatively short period of time in order to accommodate a variety of feature measurement applications including surface flatness, profile, precise hole location, and surface porosity (which may cause oil leaks). A Human Machine Interface and Database have been developed to facilitate the measurement process as well as the analysis and sharing of the data that is generated. The knowledge base that has been derived using the RIM is currently being utilized in the development of a prototype industrial version of the RIM to be used in an industrial partner's manufacturing facility.

3.6 Summary

Global economic competition and rapid social and technological changes have forced manufacturers to face a new economic objective: **manufacturing responsiveness** (i.e., adaptation of the manufacturing system to market conditions). To respond to these challenges a new type of manufacturing system, a Reconfigurable Manufacturing System, has been developed. RMSs are quite different than current manufacturing technologies (i.e., dedicated manufacturing lines and flexible

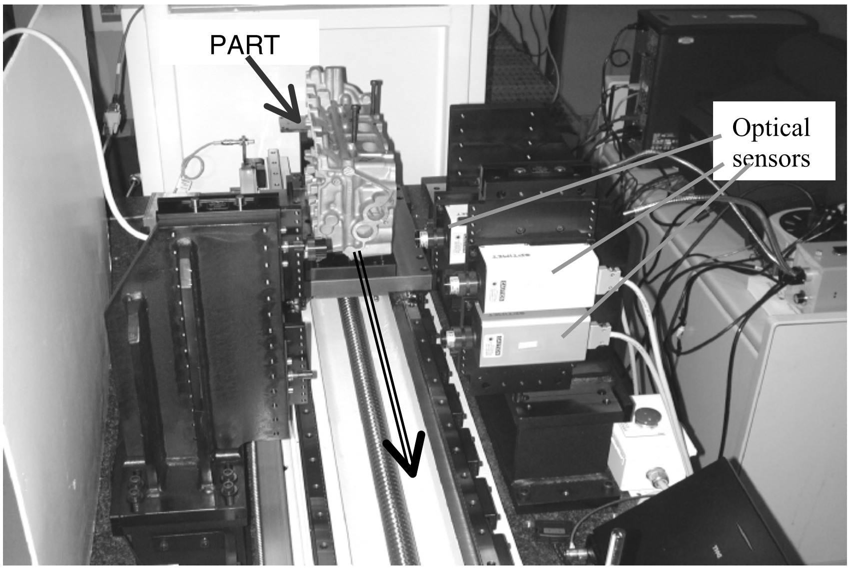

Fig. 9 A reconfigurable inspection machine (ERC at UM)

manufacturing systems) in that they are designed from the outset with adjustable resources in order to provide exactly the capacity and functionality needed, exactly when it is needed. For this reason **Design for Reconfigurability** is recently emerging as an important new trend in designing manufacturing systems.

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