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Reconfigurable Machining Systems

Reconfigurable Manufacturing Systems

by

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RECONFIGURABLE MANUFACTURING SYSTEMS

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Creating the new manufacturing paradigm –
– Exactly the capacity and functionality needed, exactly when needed

Manufacturing of consumer goods is the foundation of the US economy (see Fig. 1). But, to stay competitive in the 21st Century, manufacturing companies must possess a new type of manufacturing system that is very responsive to global markets; a system whose production capacity is adjustable to fluctuations in product demand, and which is designed to be upgradable with new process technology needed to accommodate tighter product specifications. Current systems, even so called flexible manufacturing systems, do not have these characteristics. Cost-effective, reconfigurable manufacturing systems, whose components are reconfigurable machines and reconfigurable controllers, as well as methodologies for their systematic design and diagnostics, are the cornerstones of this new manufacturing paradigm. The manufacturing paradigm termed "reconfigurable manufacturing" will have as big an impact as mass-production and lean-manufacturing have had. Maybe bigger.

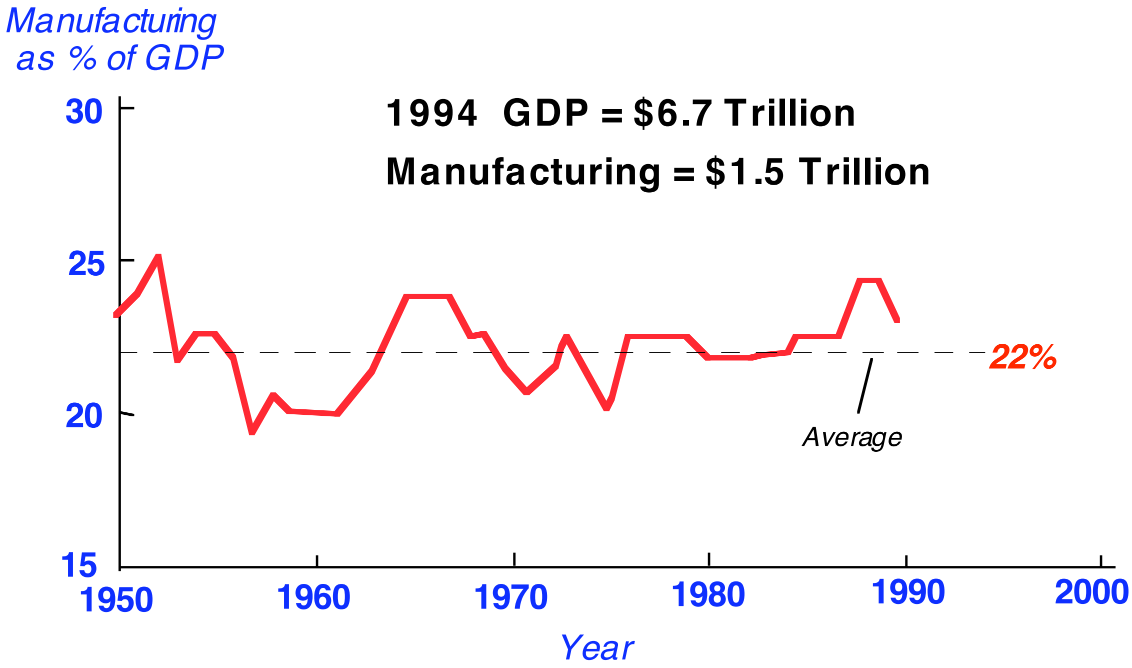

Figure 1. Despite assertions that the USA is becoming a service economy, manufacturing has consistently accounted for about 22% of GDP (*Source:* US Bureau of Labor Statistics).

The Changing Manufacturing Environment

Medium and high-volume manufacturers in the U.S. are now facing new market conditions characterized by: (i) short windows of opportunity for new products, and (ii) large fluctuations in product demand. To cope with the need for quick introduction of products, computer-aided design (CAD) and concurrent engineering methods have dramatically reduced product development times during the last decade (see Fig. 2a). Noteable examples include the design of the Boeing 777 and the Chrysler Neon. The production system lead time (i.e., the time to design and build the production system, and to ramp-up to full-volume, high-quality production) has now become the bottle neck. Reducing lead time for manufacturing systems that produce the new products provides major economic savings (see Fig. 2b), and is the critical objective for responding to short windows of opportunity.

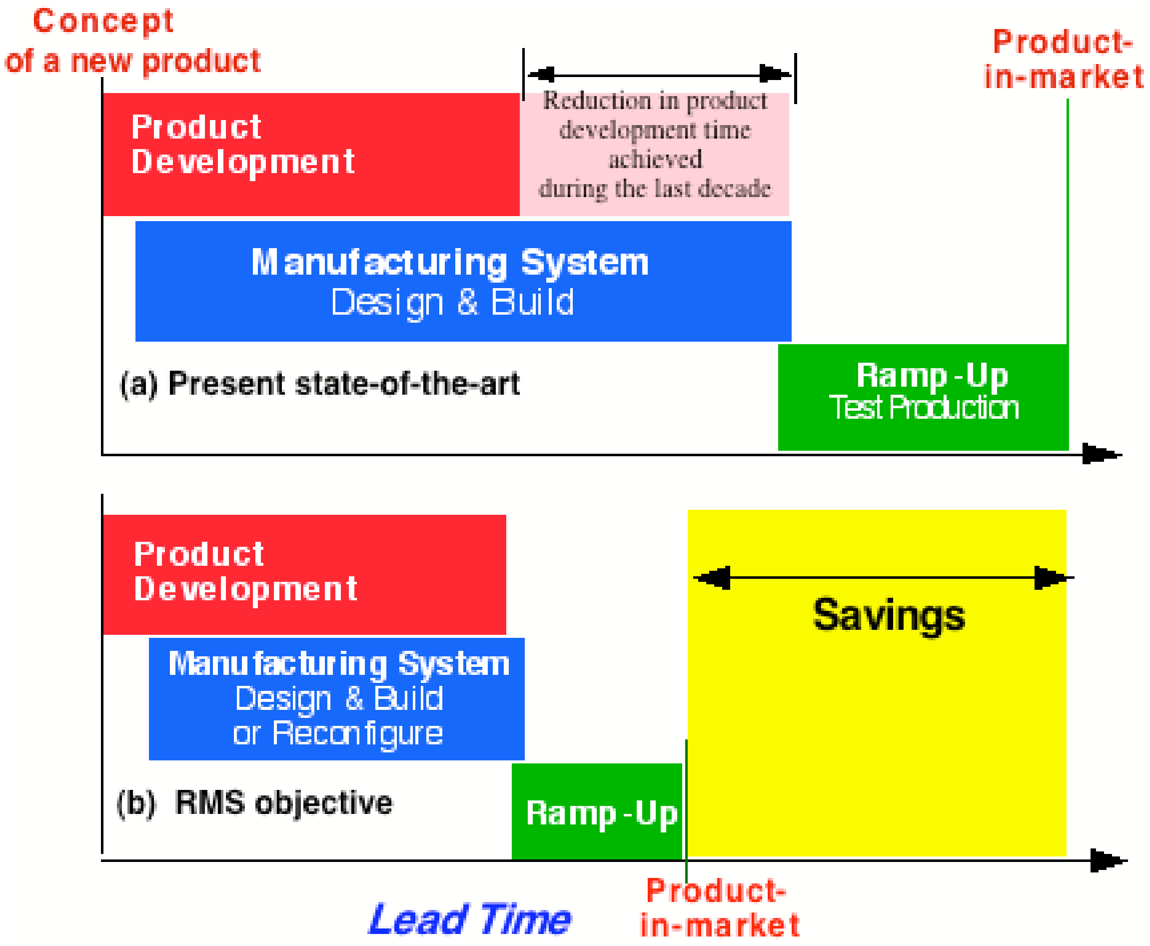

Figure 2. Lead time includes the time required to design and build (or reconfigure) the manufacturing system, as well as the time required for ramp-up (after installation) to full volume production at the required quality. The success in dramatic reduction of product development time achieved during the last decade, must now be repeated for manufacturing systems to achieve real economic savings.

The design of manufacturing systems is more challenging than that of developing CAD for products since it also requires optimally matching the dominant geometric product features to machine modules and designing the systems such that they can produce the required product demand and the needed product mix on a single system.

The second challenge — coping with large fluctuations in product demand — can be theoretically solved by utilizing flexible manufacturing systems (FMSs) that have the ability to produce a variety of products. However, these systems have not been widely adopted, and two-thirds of the manufacturers that bought FMSs are not pleased with their performance.[1] The main reasons for the low level of acceptance or satisfaction are: (i) FMS is expensive, (ii) it utilizes inadequate system software since developing user-specific software is exteremely expensive, (iii) takes a long time to ramp-up a new system (there are cases of two years), and (iv) the systems are subject to rapid obsolescence.

The most troubling problem is the high risk of an expensive flexible production system becoming obsolete. Because advances in software, computers, information processing, controls, high-speed motors, linear drives and materials sometimes occur in cycles as short as one year, today's most efficient production system can become inefficient, and even obsolete, almost as soon as it goes on-line. Furthermore, if the FMS is already producing at full capacity, adaptation to market growth is not an option. Addressing these limitations as well as the new market conditions require a new manufacturing approach that enables:

1. the launch of new product models to be undertaken very quickly
2. addition of incremental manufacturing capacity as the market grows
3. new developments in manufacturing technology to be utilized in production

These new manufacturing systems must be rapidly convertible to the production of new products and be designed to produce them in unpredictable quantities. As the following example illustrates, such systems do not exist today.

In the winter of 1996 the manufacturing lines producing a luxury car for a major automotive manufacturer were half-idle because of low demand for these cars. At the same time, an unexpected demand for trucks made by the same manufacturer exceeded supply by some 20%. Building new manufacturing lines for trucks to supply the additional demand was viewed by the company management as a high-risk investment. The best solution would be to reconfigure the car manufacturing lines to produce trucks for a limited time. However, today's technology does not allow such a change in manufacturing line functionality. The next best solution could be to rapidly increase the production capacity in the truck plant by 20%. But, again, today's manufacturing systems are not designed for the addition of incremental capacity. The potential economic benefit of reconfigurable manufacturing systems in such cases is enormous.

Definition of Reconfiguration and its Importance

A Reconfigurable Manufacturing System (RMS) is one designed for rapid adjustment of production capacity and functionality, in response to new circumstances, by rearrangement or change of its hardware and software components.

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[1] P. Heytler and A.G. Ulsoy, *Survey on Flexible and Reconfigurable Manufacturing Systems*, ERC/RMS Technical Report #5, 1997.

Components may be machines and conveyors for entire production systems, mechanisms for individual machines, new sensors, and new controller algorithms. New circumstances may be changing product demand, producing a new product on an existing system, or integrating new process technology into existing manufacturing systems. Table 1 summarizes several scenarios that require reconfiguration and their corresponding modes of reconfiguration. Unlike FMS, a new RMS for a new product (first row in Table 1) is installed with just the functionality needed for this product and therefore is less expensive. When an additional new product is introduced, the system functionality is upgraded (2nd row). To be competitive, it is critical that the reconfiguration modes in Table 1 be achieved rapidly and cost-effectively.

Table 1 Scenarios requiring reconfiguration

Driver for Reconfiguration	Reconfiguration Mode
New Product (new system)	Design of a New Reconfigurable System
Add New Product (original product is phasing out; new product is ramping-up; both produced on existing system)	Add or Change Functionality
Changing Product Demand (existing products on existing system)	Change Incremental Production Capacity
Improved Quality or Productivity Requirements	Integrate New Process Technology into Existing System
New Product (discard existing product; reuse existing system components)	Integrate Reusable Existing Modules with New Modules

As seen in Table 1 (3rd row), one of the reconfiguration modes is the integration of new process technology. Why is the ease of process integration so important? Let us elaborate on one example. Some 25 years ago drivers had to add engine oil every 1000 miles. Today, such a need does not exist. This improvement is attributed to process technology - the ability to machine parts at higher precision - and to new engine technology. Why did it take that long to implement this improvement? One of the major reasons is that the traditional machining lines for engines are non-upgradable, closed systems with a life time of 20 years. Drivers had to wait for the construction of new machining systems that utilize the new process technology and are able to produce the new engine technology. By contrast, RMS technology would allow rapid implementation of such a product improvement by the integration of the needed process technology into existing reconfigurable systems. Delivering improved products in shorter time is an important benefit to society.

Cost-effective, rapid accomplishment of the various reconfiguration modes listed in Table 1, requires the achievement of two economic objectives:

- **Rapid "Design and Build" of a New/Modified manufacturing System**
- **Rapid "Ramp-Up" of a New/Modified Installed manufacturing System**

Both objectives must be achieved at **low cost**.

Historical Perspective: Product Versus Process

Readers may ask why so much attention is being given to the process (i.e., the manufacturing system) — is it not the invention of a product that is most important for society? No, it is not enough to invent and design new products. History shows that innovative new products generate wealth for the economies that are able to *produce* them efficiently. For example, the videocassette recorder (VCR) and the compact disk were invented in the USA and Europe respectively, but are now produced primarily in Asia, where the rewards are being reaped.

History also shows that economic wealth at a national scale has frequently been created by the manufacturing system that produces a product rather than by the invention of the product itself. The most striking example is the automobile. At the turn of the 20th century England was the leading global economic power. The invention of the ***mass-production*** system and the moving assembly line by Henry Ford in 1913[2], rather than the invention of the automobile, was the reason for the transfer of global economic leadership from England to the USA. "Through its system of Mass Production, America won the economic battle with England."[3] The main objective of the mass-production system is the *reduced cost* of the product, which makes the product affordable to new customers, thereby benefiting society.

Another historical paradigm is the development of ***Lean Production*** in Japan beginning in the 1960's[4]. Lean production helped make Japan an economic superpower and added a major new objective to the objective of low cost: Enhanced product *quality*, which again benefits society.

Cost, quality, and responsiveness are the main economic objectives in manufacturing.

The mass-production paradigm made the USA an economic superpower by focusing on *product cost* reduction, while the lean manufacturing paradigm helped Japan become a global economic power by focusing on *product quality* improvement at low cost.

The new manufacturing paradigm, which we term **"reconfigurable manufacturing," focuses on the process** rather than the product. It aims at enhancing manufacturing responsiveness in the production of low-cost and high-quality products. Such manufacturing systems do not exist today, as explained in the next section.

The State-of-the-Art and Reconfiguration

Figure 3 summarizes the state-of-the-art in today's manufacturing systems. Most manufacturing industries currently use a portfolio of dedicated manufacturing lines (DML) and flexible manufacturing systems (FMS) to produce their products:

(i) Dedicated manufacturing lines, or transfer lines, are based on fixed automation and produce the core products of the company at high-volume. Each dedicated line typically produces a single part (e.g., a pump housing).

(ii) Flexible Manufacturing systems produce a variety of products on the same system. They consist of computer numerically controlled (CNC) machines, robots, and other programmable automation. The production capacity of FMSs is usually lower than that of dedicated lines and their initial cost is higher.

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[2] Ford proposed the term "Mass Production" in his 1926 article for the *Encyclopedia Britannica* , Vol. 2.

[3] J. Pine II: *Mass Customization.* Harvard Business School Press, 1993.

[4] J. Womack *et al.*, *The Machine that Changed the World,* Rawson Associates, 1990.

	Fixed Hardware
No Software	Manual Machines, Dedicated Manufacturing Lines
Fixed Software	CNC, Robot, FMS

Figure 3. State-of-the-art of classes of manufacturing systems

The common denominator for all these systems is that they use fixed hardware and fixed software. For example, only part programs can be changed on CNC machines, but not the core software nor the control algorithms.

Another type of manufacturing system that can be found in some plants is the *convertible transfer line*. This is actually a dedicated line that typically has a modular structure that enables its conversion from the production of one part to another, where both parts are from the same part family ("part family" means, for example, several types of engine blocks or several types of microprocessors). Typical conversion times range from two weeks to four months.

During the last few years, however, two enabling technologies for RMS have emerged: modular, open-architecture controls that allow reconfiguration of the controller[5], and modular machine tools that allow reconfiguration of the machine hardware[6] (see ERC/RMS Reports # 2 and 4). These emerging technologies show that the trend is toward the design of systems with **reconfigurable hardware** and **reconfigurable software** with *modularity* as a key characteristic, as depicted in Figure 4. The ultimate goal of RMS is to have machines and systems that are designed to be reconfigurable simultaneously in hardware and software.

	Fixed Hardware	**Reconfigurable Hardware**
No Software	Manual Machines, Dedicated Manufacturing Lines	**Convertible Transfer Line**
Fixed Software	CNC, Robot, FMS	**Modular CNC Machines**
Reconfigurable Software	**Modular Open-Architecture Controller**	**R M S**

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[5] Y. Koren, *Open-Architecture Controllers for Machine Tools*, ERC/RMS Technical Report #3, 1997.

[6] M. Mehrabi and A.G. Ulsoy, *State of the Art of Reconfigurable Machining Systems*, ERC/RMS Technical Report #2, 1997 and S. Kota, *Modular Machine Tools*, ERC/RMS Technical Report #4, 1997.

Figure 4. Classes of manufacturing systems

The core of the RMS paradigm is not only simultaneous design of modular open-architecture controllers with modular machines, but also an approach to reconfiguration based on system design. The RMS paradigm will create a new generation of machines and processes that allow effective reconfiguration. These reconfigurable manufacturing systems will be open-ended, so that they can be improved and upgraded rather than replaced. They will allow flexibility not only in producing a variety of products, but also in changing the system itself.

While reconfigurable manufacturing is a new paradigm, examples of reconfigurable products do exist. Today's desktop and laptop computers are all reconfigurable to some degree. For example, additional capacity or functionality can be created by adding, or upgrading, software, memory chips, disk drives, etc. One can replace a floppy disk drive with a new higher-capacity optical disk drive, or use a variety of PC cards (PCMCIA cards) to provide a modem or ethernet connection or extra memory or storage. In many cases, the concepts of standard interfaces and modularity, enable us to add modules (e.g. higher speed modems, new versions of software) that did not exist at the time that the computer was designed and built. The key point is that these computers have been designed at the outset to be upgradeable and reconfigurable such that they can provide exactly the functionality and capacity needed, exactly when needed.

The key is that reconfigurable systems must be designed at the outset to be reconfigurable, and must be created by using basic hardware and software modules that can be arranged quickly and reliably.

It is important to note that an FMS might be designed to be reconfigurable. A simple example is a tool changer on a CNC machine. If only six cutting tools are needed for the current application, but more might be needed in the future, the reconfigurable machine will be designed at the onset with a tool magazine of six tools that is expandable to 12, 24, and 48 tools. Consequently, both investment and maintenance costs are reduced. Even a dedicated transfer line might be reconfigurable if it has been designed at the outset to be reconfigured and has been constructed with modular machines and modular controls.

Agility and Reconfigurability

How are reconfigurable manufacturing systems related to agile manufacturing? Agility has been defined as "a comprehensive response to the business challenges of profiting from the rapidly changing, continually fragmenting, global markets for high-quality, high-performance, customer-configured goods and services."[7] Agility is therefore more of a business philosophy that teaches an organization how to respond to the challenges posed by a business environment dominated by change and uncertainty. By contrast, reconfigurability does not deal with the entire enterprise (which includes product design, organization, management, marketing, operations, etc.), but only with the responsiveness of the production system itself to new market opportunities in an environment of global competition. The RMS methodologies of rapid system design and ramp-up, as well as the capability to add incremental capacity and functionality in response to market demands, are one aspect of agility.

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[7] S. Goldman, R. Nagel, and K. Preiss, *Agile Competitors and Virtual Organizations*, 1995.

Perhaps the best way to distinguish between agility and reconfigurability is to ask the same question that the Agility Forum asks on their web page "What is Agility NOT?" They answer: "Agility is not a bag of tricks, a technique, a secret list of things to do. Agility is an approach to business..."[8]. By contrast, reconfigurability is a set of methodologies and techniques that aid in design, diagnostic, and ramp-up of reconfigurable manufacturing systems and machines that give corporations the ***engineering tools so that they can be agile*** and respond quickly to market opportunities and changes.

In summary, agile manufacturing focuses on the manufacturing enterprise, and the business practices needed to adapt to a changing global market characterized by uncertainty. It does not provide any operational techniques (such as those provided by lean manufacturing), or any engineering solutions (such as those provided by mass production). It shares with reconfigurable manufacturing a focus on the objective of manufacturing responsiveness. Consequently, agile manufacturing is an ideal complement to reconfigurable manufacturing.

The Economic Benefits of Reconfigurable Manufacturing Systems

If we take into account the entire life-cycle cost of a production system, reconfigurable systems will not be more expensive than flexible manufacturing systems, or even dedicated manufacturing lines. The main factor that makes the RMS less expensive is that unlike the other types of systems,

the RMS is installed with exactly the production capacity and functionality needed,

and may be upgraded (in terms of both capacity and functionality) in the future, ***exactly when needed***. Expanded functionality enables the production of more complex parts (or products) and the production of a variety of parts on the same system. It is usually associated with adding process capabilities, auxiliary devices, more axial motions, larger tool magazines, more capable controllers, etc.

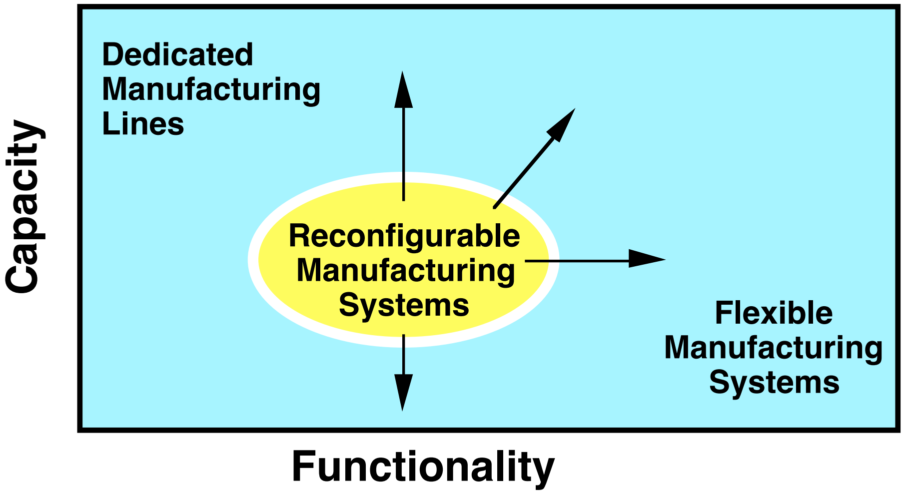

Figure 5. Mapping of several types of manufacturing systems in terms of capacity-functionality. The capacity of RMS can be quickly adapted to new market demands, and its functionality can be modified to accommodate new products. The illustration shows traditional DMLs and FMSs which are not reconfigurable. However, even DML and FMS may be designed to be reconfigurable.

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[8] S. Goldman, web site: www.agilityforum.org, 1997

As shown in Figure 5, traditional dedicated manufacturing lines have high capacity but limited functionality. They are cost effective as long as demand exceeds supply. But with saturated markets and increasing pressure from global competition, there might be situations where dedicated lines do not operate at full capacity. Flexible systems, on the other hand, are built with all the flexibility and functionality available, in most cases even with those that are not needed at installation time. The logic behind this is to "buy it just in case it may be needed one day." However, in these cases capital lies idle on the shop floor and a major portion of the capital investment is wasted. These two types of waste are eliminated with RMS technology. In the first case the RMS allows one to add the extra capacity exactly when required, and in the second case to add the additional functionality exactly when needed. Further, when product demand is decreased, the RMS capacity can be reduced and the extra modular components may be reused to augment other lines that have increased product demand.

As stated above, both DMLs and FMSs might be designed to be reconfigurable. This also raises the possibility of various types of RMSs, with *modules of different granularity*, that evolve from either DMLs or FMSs. For example, an RMS system can be designed with a CNC machine tool as the basic building block. This would require an evolution of current FMS systems through lower-cost, higher-velocity, CNC machine tools with modular material handling system, that also have in-process measurement systems to assure consistent product quality. On the other hand, an RMS system can be designed with single-axis drive modules as the basic building blocks.

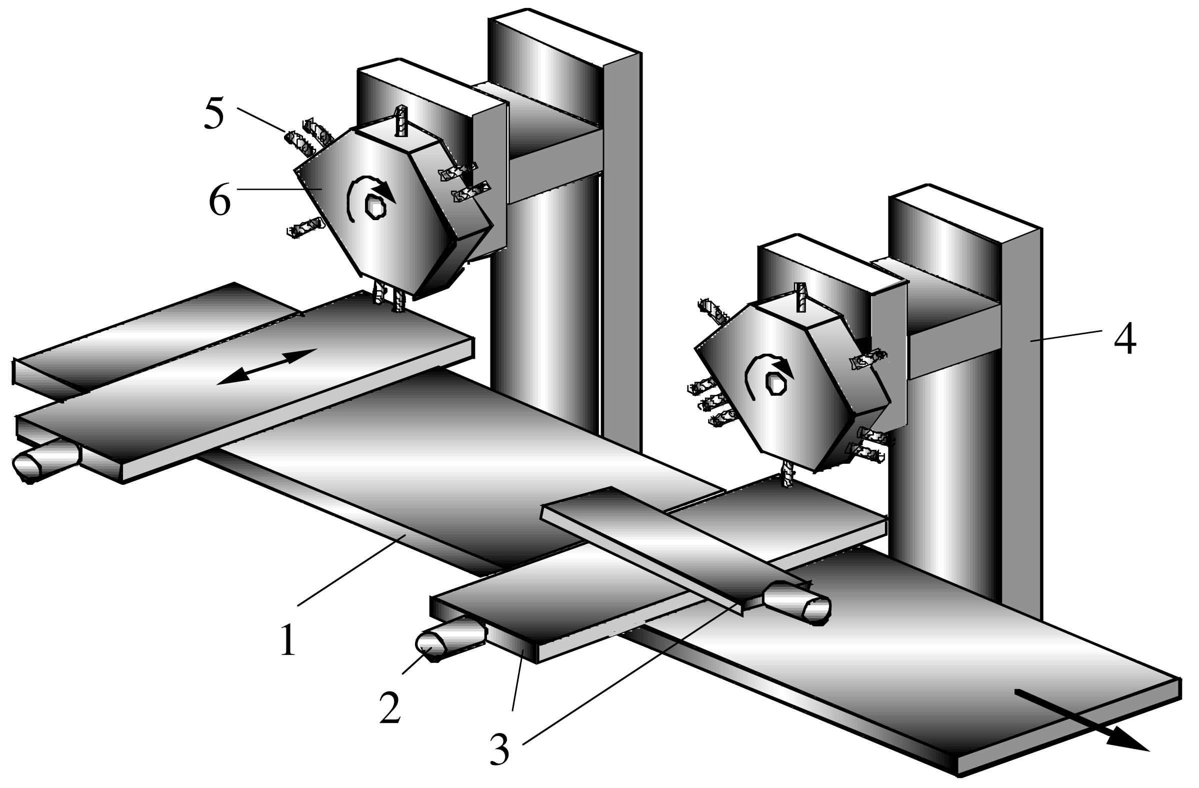

Figure 6. An RMS concept evolved from the modularization of a transfer line (concept by Y.K.; artist Ms. Z. Kalmar, 1992). Reconfiguration requires changing the customized turret modules (6) and the driven table modules (3). Note that several tools can operate simultaneously.

This would represent an evolution of RMS from DML, and require modular machine components and distributed controllers with high bandwidth communication.

With RMSs that evolve from modular DMLs , economies of scale will be achieved at the level of machine components. By creating modular components that can be reconfigured into a *variety* of systems, machine builders can gain global economies of scale and scope simultaneously, and yet provide customization of manufacturing systems. A conceptual example is shown in Fig. 6, where a dedicated transfer line is configured along a moving conveyer (1) using standard modules for machine columns (4), single-axis motor (2) driven table modules (3), tool (5), and customized turret modules (6) that fit the part to be machined. The reconfiguration of the line requires changing the turret modules and the table modules (e.g., adding a rotary table).

An economic benefit of a different type is the enhanced productivity achieved with RMS. If properly designed, RMS will provide the right balance between production speed and general flexibility[9]. 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* that cut the part simultaneously (each group of tools in one direction of motion), thereby achieving 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 are needed in the production of each part.

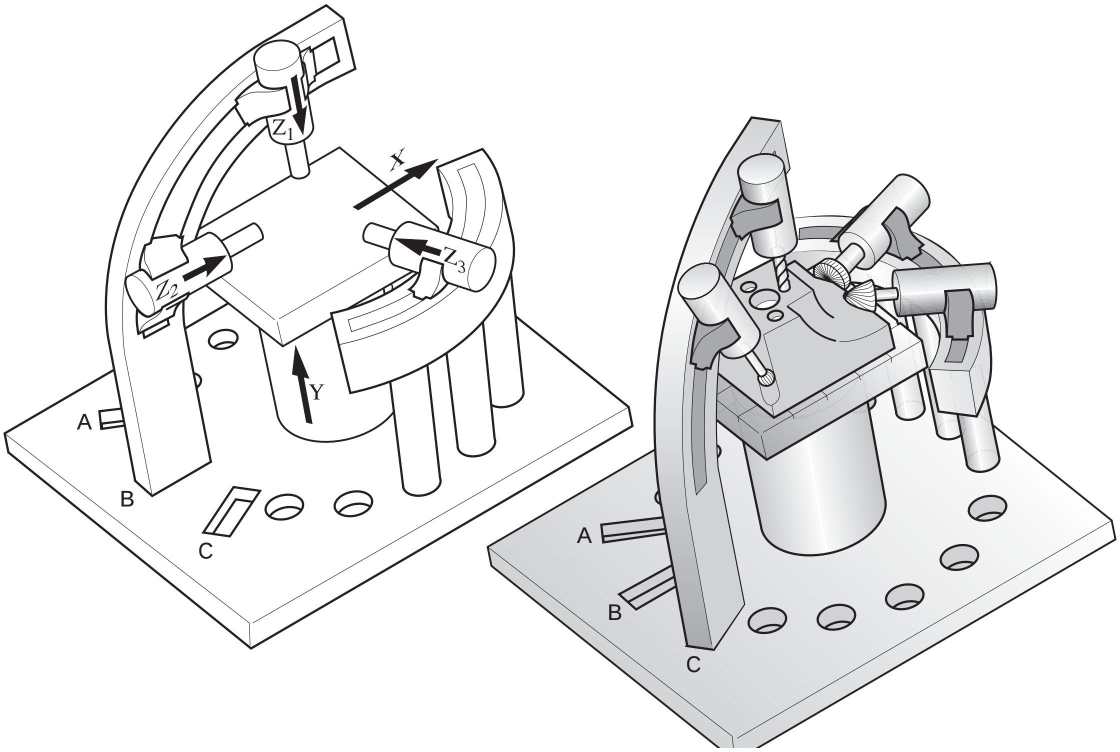

Figure 7. Two configurations of a reconfigurable machine tool (concept by Y.K.; artist: Rodney Hill,1996). Single-axis drive modules (Z_i) are basic building blocks. Clearly the

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[9] Similar ideas for computing systems are presented in J. Villasenor and W.H. Mangione-Smith, "Configurable Computing," *Scientific American,* June 1997.

mechanical design (e.g., stiffness of column and accuracy of locator holes) would need to be improved on the actual machine tool

A key characteristic of RMS machines is that, as a result of their modularity, they can be designed with only the minimum number of active axes-of-motion needed to provide the flexibility to produce a part family. We call this characteristic ***customized flexibility.***

This characteristic also allows the use of several tools that cut simultaneously, thereby increasing the productivity to the level achieved by DMLs. Note that this concept combines active degrees-of-freedom (driven by motors) with passive degrees-of-freedom (manually reconfigured) to achieve the customized flexibility.

For example, in the conceptual reconfigurable machine depicted in Fig. 7, several cutting tools attached to spindles (Z_1, Z_2, Z_3, Z_4) operate simultaneously on the part. Note that Fig. 7 shows a conceptual example. Clearly the mechanical design (e.g., stiffness of column and accuracy of locator holes) would need to be improved on the actual machine tool.

The scientific challenge is to extract the key geometric features of several parts from a part family and to design a reconfigurable machine that can produce these parts. The concept of design for a **part family** is the essence in designing a reconfigurable system. If a capability to machine any arbitrary part is required, then FMS rather than RMS is the desired solution.

The design of a reconfigurable machine for a part family should include the conversion of geometric features of all parts of the family to machining operations, specifying tool orientations and the tool path, and reconfiguring a machine (from a library of modules) to match the tool motions effectively. Each part can be produced with a certain machine configuration where several axes may cut simultaneously. The conversion from one part to another is done by adjusting passive degrees-of-freedom, as explained in the example below.

Figure 7 shows two configurations of the machine. The part is located on a table that can move in two directions X and Y. Spindles (Z_1 and Z_2), that can move simultaneously linearly along their axes, are located on a column. They can drill holes at various angles, thereby eliminating the need for a tilt-rotary table. Additional spindles (e.g., Z_3) can machine the part horizontally at various angles (replacing horizontal milling machine with a rotary table). Spindle units may be quickly added or removed, depending upon the application. Note that in the second configuration the column has been moved from slot B to C, and the horizontal unit (with the 3-leg support) has been moved to new locators. This machine (including all possible configurations) can access more points on a part than a 5-axis machining center, and has higher productivity than a single-tool CNC machine. However, it does not have the general flexibility that a 5-axis CNC machine has, but rather has only “customized flexibility” that changes with the configuration.

Scope of RMS

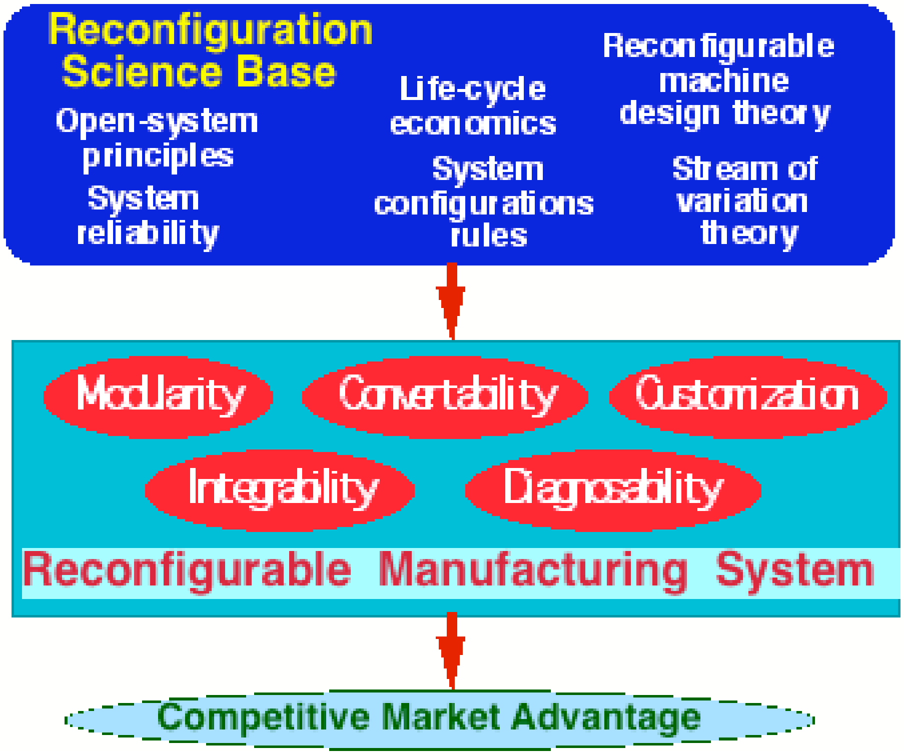
Rapid, controlled-cost response to market opportunities is the cornerstone of manufacturing competitiveness in the next decade. A wide range of manufacturing industries – from electronics to automotive and other consumer goods – share this goal. Even the **pharmaceutical industry** faces similar challenges. A recent article in the *Harvard Business Review*[10] deals with this issue in the context of drug production:

> "Manufacturing-process innovation is becoming an increasingly critical capability for product innovation. ... The time required to develop process technologies generally added a year to product-development lead times. ... Rapid ramp-up enables a company to penetrate the market quickly."

The issue of manufacturing responsiveness was also highlighted in a recent *U.S. News and World Report*[11] article about the **assembly of personal computers**:

> "With cutting edge innovation advancing rapidly, .. and competition intensifying so quickly, .. computer makers must re-engineer their factories to have the flexibility to constantly build new and improved models."

To achieve the goal of reconfigurable manufacturing, the manufacturing industry must gradually develop a common environment for integration through standards, or *de facto* standards. For such a common integration environment to evolve, first the fundamentals of reconfiguration must be understood, and the methodologies for design and integration of modules established. A set of methodologies, theories, and engineering rules that will contribute to a knowledge base for what could become known as "**reconfiguration science**" must be developed for system design, build, and ramp-up.



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[10] G.P. Pisano and S. Wheelwright, "The New Logic of High-Tech R&D," *Harvard Business Review*, October 1995.
[11] 8 July 1996

Figure 8. The design of RMS utilizes scientific knowledge to achieve certain key characteristics

To **rapidly design** a new RMS, or a new configuration, requires:

- A design methodology for new and reconfigured systems, that includes:
  - System Configuration and Integration Rules (e.g., see Fig. 12 below)
  - Life-Cycle Economic Modeling for Large Manufacturing Systems
  - System Reliability Laws
  - Control Configuration Rules

To **rapidly build and modify** an RMS requires:

- Open-System Principles (and development of modular, open-architecture controllers)
- Reconfigurable-Machine Design Theory (and development of new-generation of reconfigurable machines)

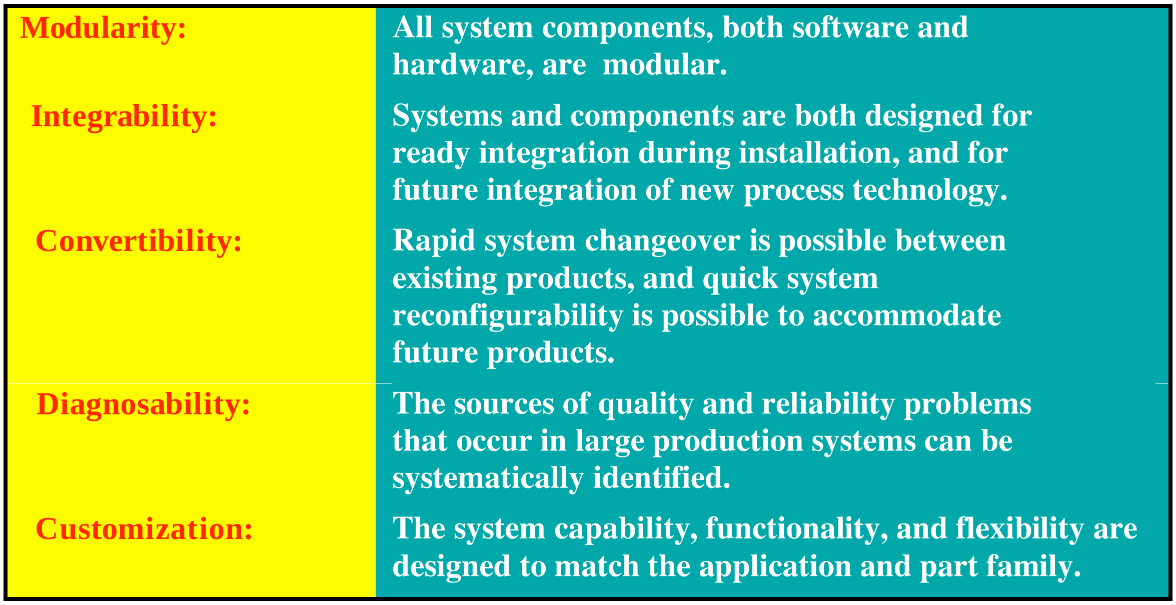
To **rapidly ramp-up** production requires a:

- Diagnostic methodology for reconfigurable machines
- Stream-of Variation theory[12] for root-cause analysis of quality problems for installed systems (e.g., see Figs. 15 and 16 below).

This science-base will allow one to design and build systems that possess special characteristics enabling the rapid, controlled-cost response needed by industry (see Fig. 8). It will be generic and applicable to many production domains (machining, assembly, semiconductor fabrication, and production of consumer products) and, when mature, quickly adopted by industry.

Key Characteristics of Reconfigurable Systems

To be effective, reconfigurable manufacturing systems must be designed at the outset to be reconfigurable. Otherwise, the reconfiguration process will be lengthy and impractical. Achieving this goal requires that an RMS possesses several key characteristics (see Fig. 9)**:**



Modularity:	**All system components, both software and hardware, are modular.**
Integrability:	**Systems and components are both designed for ready integration during installation, and for future integration of new process technology.**
Convertibility:	**Rapid system changeover is possible between existing products, and quick system reconfigurability is possible to accommodate future products.**
Diagnosability:	**The sources of quality and reliability problems that occur in large production systems can be systematically identified.**
Customization:	**The system capability, functionality, and flexibility are designed to match the application and part family.**

Figure 9. The key characteristics of reconfigurable manufacturing systems

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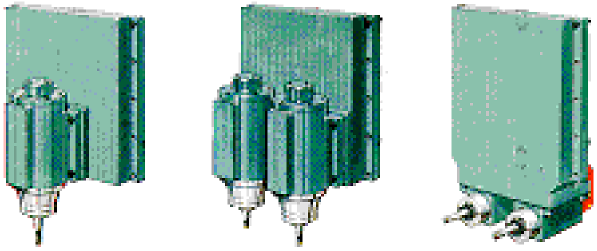
[12] S.J. Hu, "Stream of Variation Theory and Its Application to Body Assembly," *CIRP Annals*, 1997.

Modularity: In a reconfigurable manufacturing system, all major components are modular (e.g., structural elements, axes, controls, software, and tooling, see example in Fig. 10). When necessary, the components can be replaced or upgraded to better suit new applications. Modules are easier to maintain, thereby lowering life-cycle costs over current systems. New compensation and calibration algorithms can be readily integrated into the machine controller, resulting in greater accuracy. The modular approach is a natural one and has been used in many different contexts of the human endeavor. In all these instances, the fundamental questions are: (a) what are the appropriate building blocks, and (b) how should they be connected to synthesize a functioning whole? Selection of basic modules, and their synthesis methodologies, must allow creation of systems that can be easily integrated, converted, diagnosed, and customized.



Courtesy of Cargill Detroit

Figure 10. Machine tool spindle modules that can allow for single or multiple spindles in either a vertical or horizontal configuration.

Integrability: While there are hundreds of machine builders in the USA, only a half dozen of them are currently capable of supplying fully integrated flexible machining systems for high-volume production (above 200,000 units annually). The main reason is the lack of system integration rules and methodologies. To aid in designing reconfigurable systems, a set of system configuration and integration rules must be developed. In addition, the machine controls and the processing units must be designed for integration into a system.

Convertibility: System reconfiguration and setup need to be carried out quickly to be effective. To achieve this RMS contains advanced mechanisms that allow easy reconfiguration, as well as sensing and control methods that enable ease of calibration of the machines after reconfiguration.

Diagnosability: 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. Consequently, reconfigurable systems must be designed with product quality measurement systems as an integral part. These measurement systems are intended to help rapidly identify the sources of product quality problems in the production system and to correct them by utilizing modern information technologies, statistics, and signal processing techniques.

Customization: To reduce system cost, the machine and controller configuration must be customized to fit the dominant features of a part family and the application by utilizing the concepts of customized flexibility and customized control. ***Customized flexibility*** means that the dominant features of the part family being manufactured will determine the machine configuration. Eliminating unnecessary axes of motion, for example, will increase reliability and reduce cost without compromising flexibility. ***Control customization*** will be achieved by integrating control modules (e.g., user-developed process models, special compensation algorithms, diagnostics that match the system type, and customized process-management strategies) into generic controller platforms. The benefits of such customization are improved speed, accuracy, uptime, and machine life.

These characteristics determine the ease of reconfigurability of manufacturing systems:

A system that possesses these key characteristics has a high level of reconfigurability.

A system that lacks these key characteristics cannot be cost-effectively reconfigured.

Enablers for Reconfiguration

The reconfigurable system enables one to achieve the new economic objectives associated with manufacturing responsiveness:

- **Rapid design, and build, of a new/modified system**
- **Rapid ramp-up of a new/modified installed system**

To be effective, reconfiguration in RMS must be performed simultaneously at two levels:

- **The level of the entire system**
- **The level of the individual machines and their controls**

If a new product, or a change in the product demand, is the cause for reconfiguration, then the reconfiguration process will start at the system level and propagate to the machine and component level. If, however, the integration of a new process or sensor (that enhances productivity or quality) is the reconfiguration driver, then the reconfiguration process will start at the machine level, and subsequently affect the system.

To facilitate the development of the scientific approach to reconfiguration, the research issues are grouped into four areas: System Design, Machine-Level Design, System Ramp-Up, and Machine-Level Ramp-Up.

System Design. Design of reconfigurable systems requires a systematic approach, supported by software tools, that relates the product features to modules of processing units and yields a system layout and process plans. Experience plays a key role in carrying out these steps today. In the RMS paradigm CAD tools will be available for the design of all types of production systems, and not only for the products that they produce.

The steps required to achieve rapid “design and build” of a new or reconfigured manufacturing system are summarized in Figure 11. The steps in Fig. 11 are not decoupled, and the results must be refined through iteration. First, machine selection requires us to go from user requirements (e.g., product features and annual volumes), through selection of processing operations (e.g., drilling, milling, turning, grinding), to a set of reconfigurable machines and tools that perform these operations. The transformation from part geometry and tolerances to the selection of reconfigurable machines is a formidable challenge.

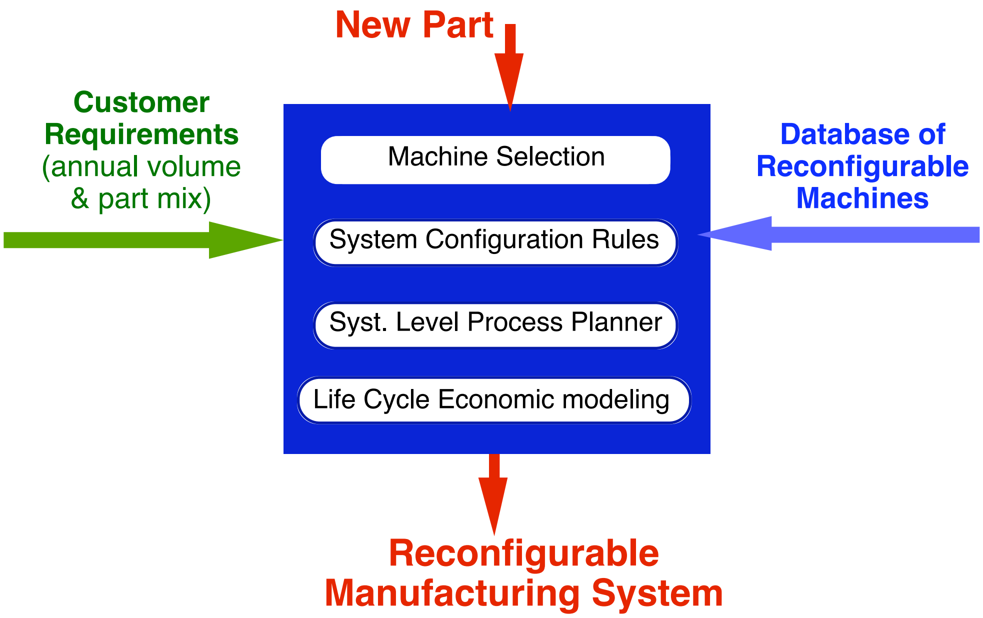


Figure 11. Computer-aided design tools required for system level design of reconfigurable manufacturing systems.

A critical decision in this process is the selection of the system configuration. The arrangement of the processing-units in series, in parallel, or in different hybrid configurations (see Fig. 12),

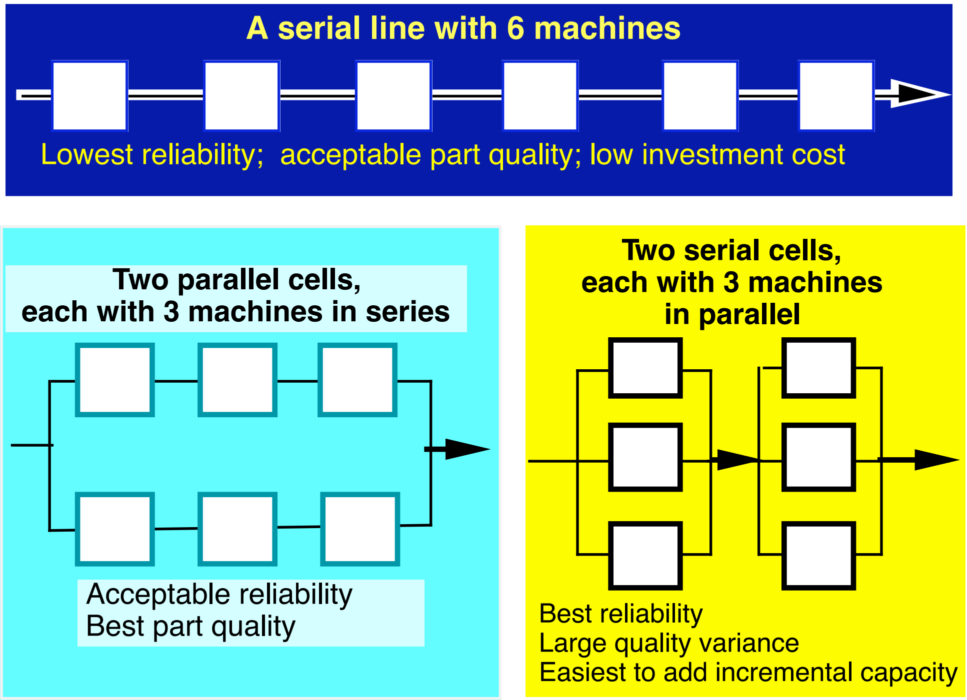


Figure 12. Three feasible system configurations with six machines. With 6 machines, there are over 30 possible configurations, and each has its own advantages and drawbacks. The optimal system selection depends on machine characteristics, quality requirements, and prediction of future market uncertainties

has a profound effect on factors such as product quality variations, overall system productivity, the ease of adding incremental production capacity, and cost. Selecting the optimal solution from the large number of possible alternatives (more than 2^{n-1} for n machines) requires the development of new configuration rules. Next, the required operations are distributed across the machines in a balanced manner by a system-level process planner. Finally, life-cycle economic modeling that estimates the system cost during its entire life-time, and accounts for future product changes and uncertainty in market conditions, must be used to select among the feasible manufacturing system alternatives.

Machine-Level Design. Reconfigurable manufacturing systems, as mentioned previously, require design at both the system and machine levels. The required design steps at the machine level are shown in Fig. 13. Modular machine component design, and an open-architecture controller are key enabling technologies. Machine components (e.g., structural modules, axis drive modules) and controller components (e.g., servo control algorithms, temperature control algorithms) must be cataloged and stored for reuse, and new modules added to the catalog as they are created. Furthermore, these modules must be configured into one or more feasible candidate configurations. Process planning software for reconfigurable machines is needed to plan the processing operations (e.g., sequence of cuts, their depths, feeds and speeds). Then an optimal design, based upon the system level specifications, must be selected from among the feasible candidate designs generated by the software.

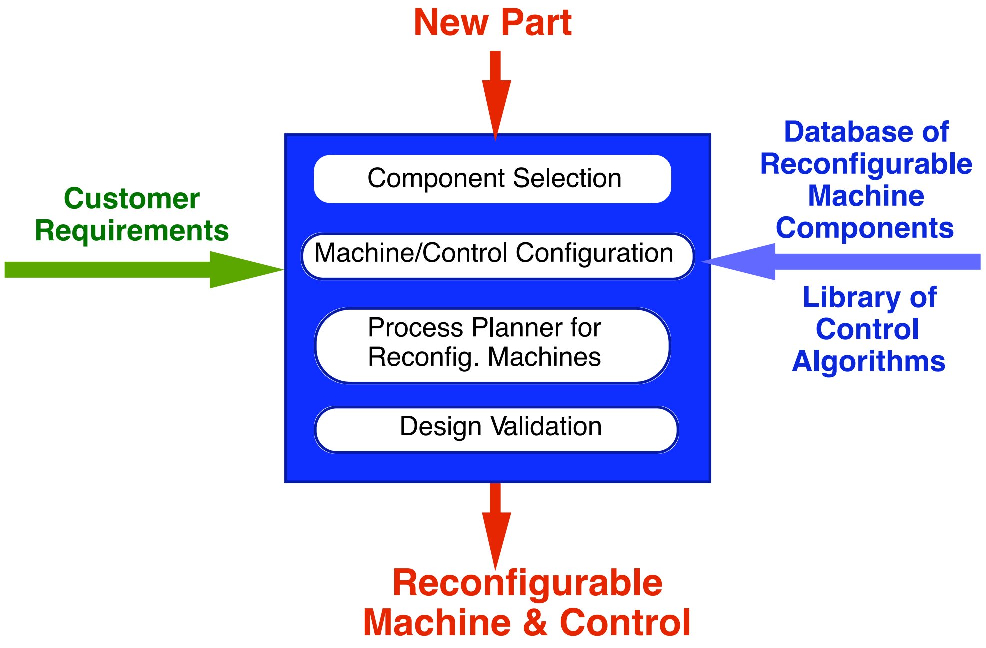


Figure 13. Computer-aided design tools for machine level design of reconfigurable machine tools.

System and Machine Ramp-Up. The objective of ramp-up time reduction requires diagnostics and ramp-up methodologies, again at both the system and machine levels. The basic engineering steps required are summarized in Fig. 14. The measurement step requires the selection of type and configuration of sensor modules (e.g., part dimensions, axis position, cutting force). The diagnostics step utilizes that sensor information to identify errors and faults (e.g., machine or fixture geometric errors, tool breakage). Diagnostics should be embedded at the component level, and propagate the information through the machine level, to the cell and factory computers. The measurement system and the diagnostic methodology should allow for machine/system **diagnosability** — identifying a sole source for a fault or a part quality problem. The compensation step, either automatically or through operator intervention, enables corrective action to be taken (e.g., calibration, adjustment of operating parameters, maintenance).

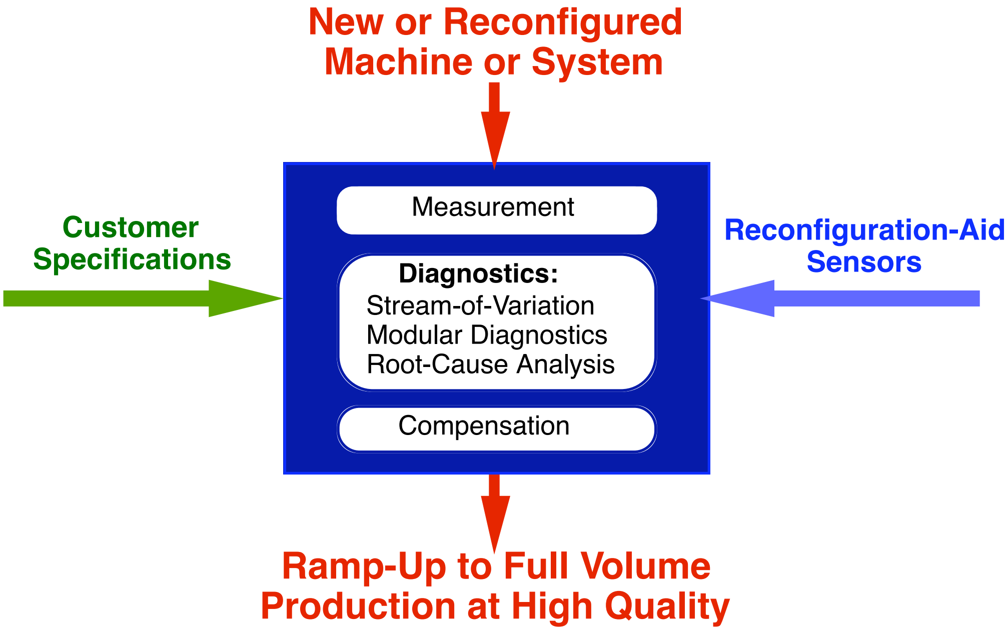


Figure 14. Computer-aided design tools for ramp-up of reconfigurable manufacturing systems

Example of System Ramp-Up. Figure 15 shows optical sensors on an automotive body assembly line. These sensors, when properly designed and located, can help diagnose problems on the assembly line (e.g., broken locator, incorrectly programmed robot) that can lead to consumer problems such as wind noise, water leakage, etc. Figure 16 shows, with results from actual production, the benefits that can be achieved in terms of rapid reduction of the variation (6σ) in critical body dimensions by applying the methodology depicted in Fig. 14 with the Stream-of-Variations (SoV) theory[13]. Note that both the reduction in variation is rapid, and the final level of variation is low.

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[13] *Ibid.*

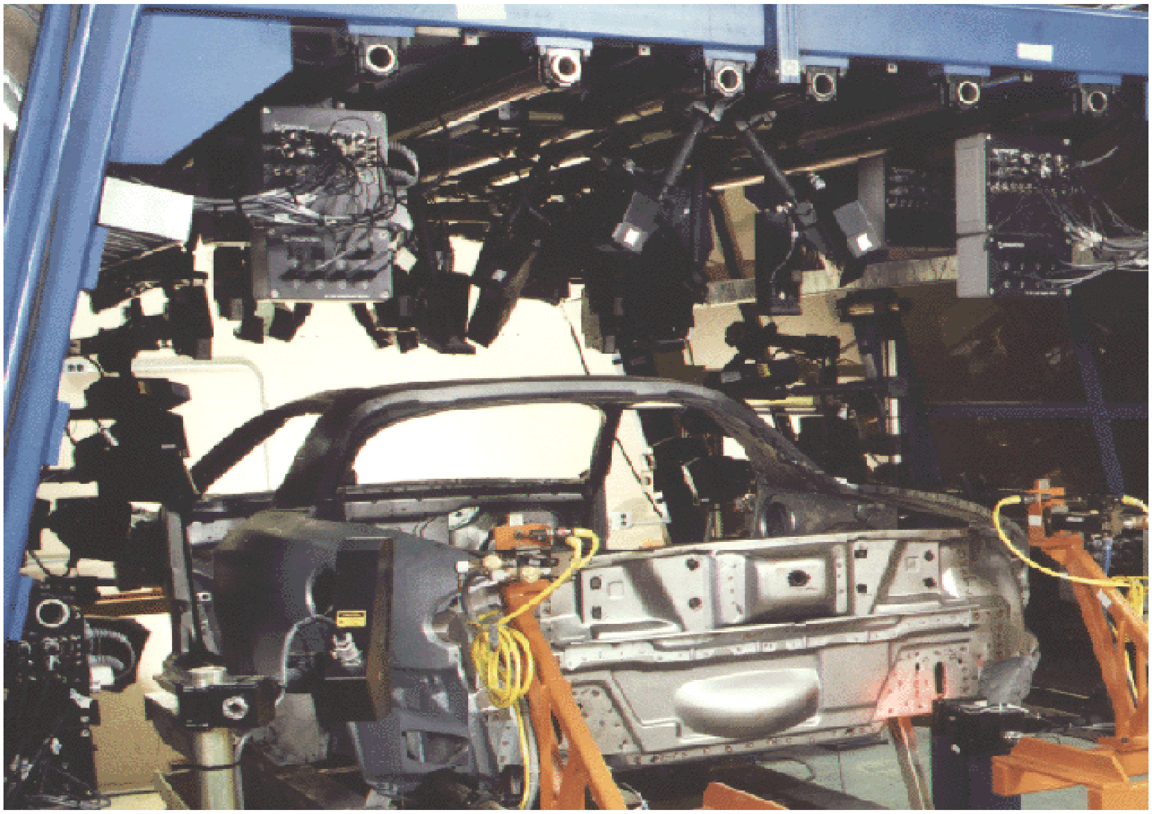

Figure 15. Optical measurement of automotive body dimensions using laser triangulation sensors, strategically located on the assembly line (based upon process knowledge) to achieve detection and isolation of faults.

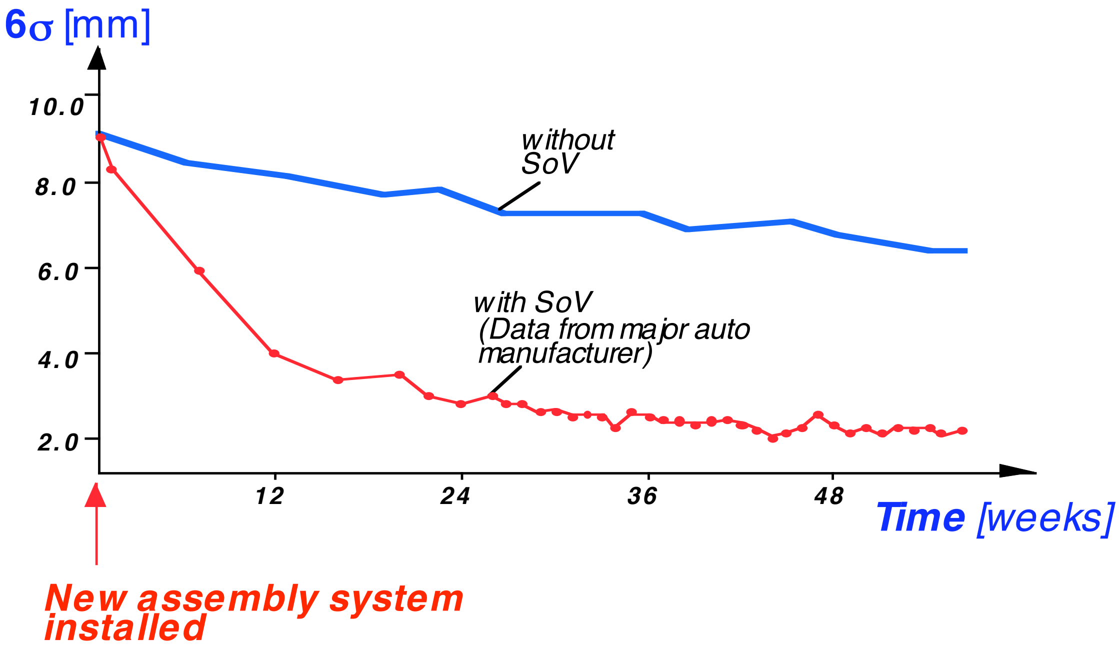

Figure 16. Results showing ramp-up time reduction in automotive assembly

Conclusions

Low product-cost and high product-quality have historically been the main economic objectives in manufacturing. However, 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), of which the key aspects are:

- To capture market share, a quick design and build or reconfigure of a manufacturing system for a new product as well as rapid ramp-up to full volume production, are needed. In other words, achieving *a short lead time* between initial product concept and ramp-up to full-volume production at high quality, is critical to all manufacturing industries.
- As the market grows and the product changes, the ability to add incremental manufacturing capacity becomes strategically important. Consequently, the ability to *rapidly reconfigure* and augment the manufacturing system in response to market pressures is critical.
- Manufacturing technologies are developing rapidly, and new technologies need to be incorporated into the manufacturing system to cost-efficiently maintain quality and productivity. Consequently, the ability *to integrate new manufacturing technologies* into the manufacturing system as they become available is significant in competing for market share.

To respond to these key manufacturing issues a new type of manufacturing system, a *Reconfigurable Manufacturing System* (RMS) is needed. RMSs are quite different than the current manufacturing technologies (i.e., dedicated manufacturing lines and flexible manufacturing systems) in that they provide exactly the capacity and functionality that is needed, exactly when needed.

RMS will change the relationship between suppliers of production equipment and the end-users. A continuos flow of profitable upgrades (rather than one-time sales) will develop enduring strategic relationships between machine builders and their customers.

As summarized in Fig. 17, the main enabler behind the previous mass-production paradigm that produced dedicated manufacturing lines is the concept of interchangeable parts. The lean manufacturing paradigm eliminates waste in manufacturing, by focusing on providing quality to the customer while cutting costs. It utilizes certain key production techniques, such as continuous improvement (*kaizen*), total quality management (TQM), robust design (Taguchi methods), statistical process control (SPC), just-in time (JIT) delivery, and others. Flexible manufacturing systems produce a variety of parts on the same machine or line by utilizing developments in computer technology to achieve programmable automation.

The new reconfigurable manufacturing paradigm requires development of systematic methods, and software tools, for the rapid design and build of manufacturing systems at both the system and machine level. For RMS to be successful, methods and tools for rapid ramp-up of new and reconfigured systems are required. Its enabler is the reconfiguration science- base, that allows the design of production systems that are modular, integratable, convertible, diagnosable, and customizable. When the new paradigm of reconfigurable manufacturing systems is realized, manufacturing will truly have entered the 21st century.

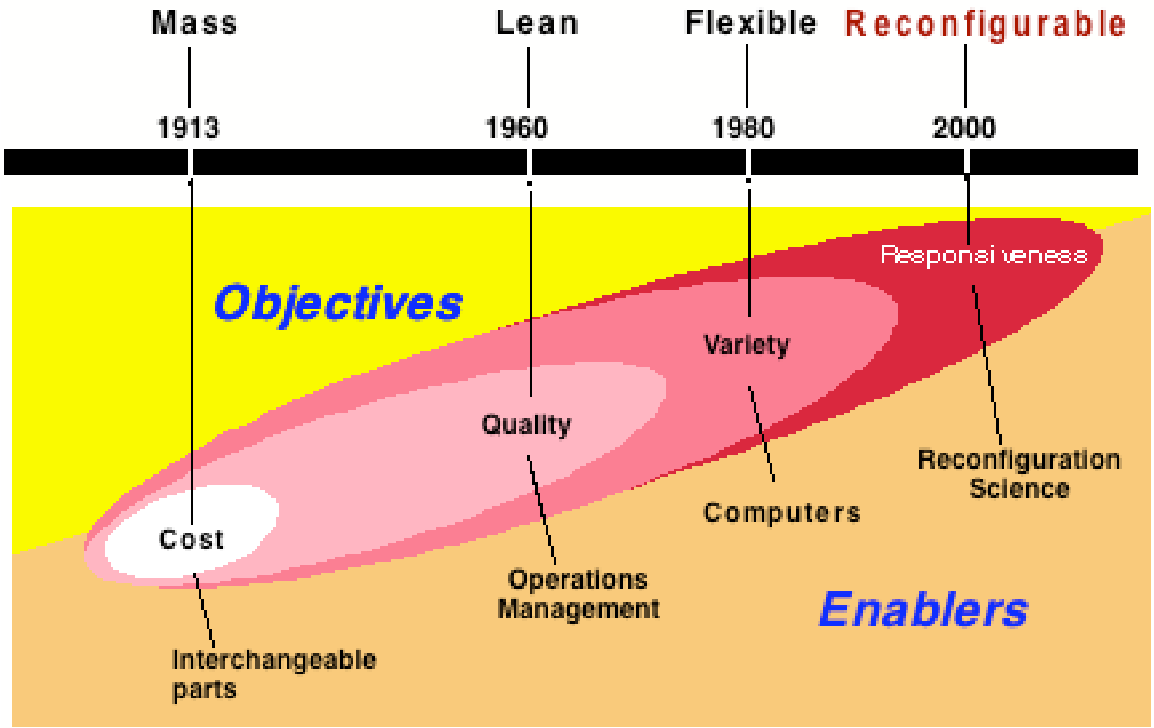

Figure 17. Historical perspective showing the major manufacturing paradigms of mass-production (objective is reduce cost; enabler is interachangeable parts), lean manufacturing (new objective is improved quality; enabler is operation management), flexible manufacturing (new objective is increase part variety; enabler is computers), and reconfigurable manufacturing (new objective is manufacturing responsiveness; enabler is reconfiguration science).

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