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Reconfigurable manufacturing systems: Key to future manufacturing

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Presented in this article is a review of manufacturing techniques and introduction of reconfigurable manufacturing systems; a new paradigm in manufacturing which is designed for rapid adjustment of production capacity and functionality, in response to new market conditions.

A definition of reconfigurable manufacturing systems is outlined and an overview of available manufacturing techniques, their key drivers and enablers, and their impacts, achievements and limitations is presented. A historical review of manufacturing from the point-of-view of the major developments in the market, technology and sciences issues affecting manufacturing is provided. The new requirements for manufacturing are discussed and characteristics of reconfigurable manufacturing systems and their key role in future manufacturing are explained. The paper is concluded with a brief review of specific technologies and research issues related to RMSs.

Keywords: Reconfigurable manufacturing systems, manufacturing systems, system characteristics, system design, machine design, ramp-up time reduction

1. Introduction

Changing manufacturing environment characterized by aggressive competition on a global scale and rapid changes in process technology requires to create production systems that are themselves easily upgradable and into which new technologies and new functions can be readily integrated. These conditions require a responsive new manufacturing approach that enables (Next Generation Manufacturing Project, 1997):

- the launch of new product models to be undertaken very quickly, and rapid adjustment of the manufacturing system capacity to market demands;
- rapid integration of new functions and process technologies into existing systems, and
- easy adaptation to variable quantities of products for niche marketing.

The manufacturing systems used for this new approach must be *rapidly designed*, able to *convert quickly* to the production of new models, able to *adjust capacity* quickly, and able to integrate technology and to produce an increased *variety of products* in unpredictable quantities.

Table 1 summarizes the major manufacturing paradigms and their definitions and Fig. 1 shows their economic objectives. *Mass production* systems were focused on the reduction of product cost. *Lean manufacturing* places emphasis on continuous improvement in product quality while decreasing product costs (see Fig. 1). *Flexible manufacturing systems* make possible the manufacture of a variety of products (flexibility) on the same system. While this is an important objective, these systems have met with limited success. For instance, flexible manufacturing systems (FMSs) developed in the last two decades: (i) are *expensive*, since in many cases they include more functions than needed, (ii) utilize *inadequate system software*, since developing user-specified software is extremely expensive, (iii) are *not highly reliable*, and

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Table 1. Summary of definitions and objectives

Systems (machining/manufacturing)	*Definitions and Objectives*
Machining system	One or more metal removal machine tools and tooling, and auxiliary equipment (e.g., material handling, control, communications), that operate in a coordinated manner to produce parts at the required volumes and quality.
Dedicated machining systems	A machining system designed for production of a specific part, and which uses transfer line technology with fixed tooling and automation. The economic objective of a DMS is to cost-effectively produce one specific part type at the high volumes and the required quality.
Flexible manufacturing systems	A machining system configuration with fixed hardware and fixed, but programmable, software to handle changes in work orders, production schedules, part-programs, and tooling for several types of parts. The economic objective of a FMS is to make possible the cost-effective manufacture of several types of parts, that can change overtime, with shortened changeover time, on the same system at the required volume and quality. *Note*: A part family is defined as one or more part types with similar dimensions, geometric features, and tolerances, such that they can be produced on the same, or similar, production equipment.
Reconfigurable manufacturing systems	A machining system which can be created by incorporating basic process modules—both hardware and software—that can be rearranged or replaced quickly and reliably. Reconfiguration will allow adding, removing, or modifying specific process capabilities, controls, software, or machine structure to adjust production capacity in response to changing market demands or technologies. This type of system will provide customized flexibility for a particular part family, and will be open-ended, so that it can be improved, upgraded, and reconfigured, rather than replaced. The objective of an RMS is to provide the functionality and capacity that is needed, when it is needed. Thus, a given RMS configuration can be dedicated or flexible, or in between, and can change as needed. An RMS goes beyond the economic objectives of FMS by permitting: (1) reduction of lead time for launching new systems and reconfiguring existing systems, and (2) the rapid manufacturing modification and quick integration of new technology and/or new functions into existing systems.

(iv) are subject to *obsolescence* due to advances in technology and their fixed system software/hardware. The high risk of an expensive flexible production system becoming obsolete is one of manufacturers' most troubling problems. Because advances in computers, information, processing, controls, optics, high-speed motors, linear drives, and materials sometimes occur in cycles as short as six months, today's

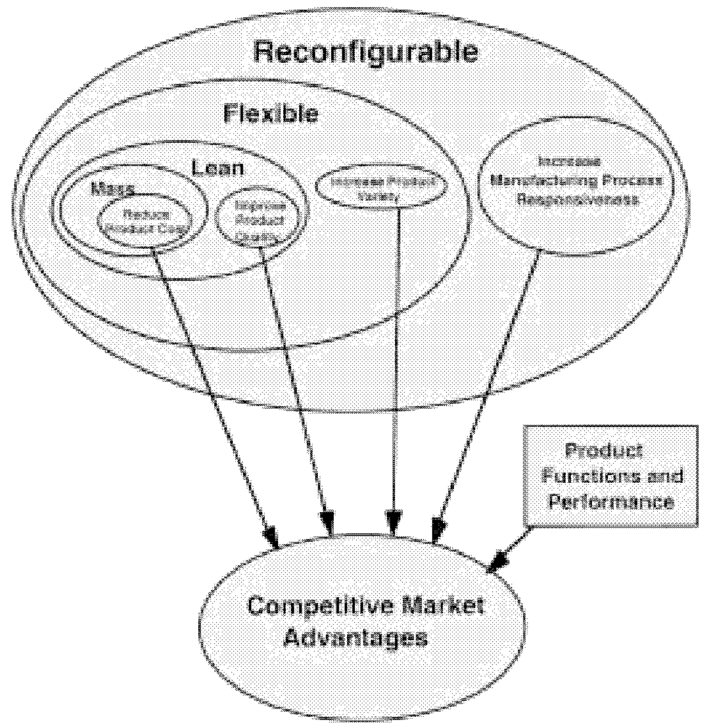

Fig. 1. Economic goals for various manufacturing paradigms.

most efficient production system can become inefficient after a short time. Furthermore, the current customer-driven market and increased awareness of environmental issues lead to the ever-quicker introduction of new products. But adaptation of existing production systems to new products is slow and the launching of new systems can take a long time (up to two years for a machining system).

2. Overcoming the limitations

To address these limitations, future manufacturing systems technology must meet the following objectives, which go beyond the objectives of mass, lean, and flexible manufacturing:

- Reduction of lead time (including ramp-up time) for launching new manufacturing systems and reconfiguring existing systems.
- The rapid upgrading and quick integration of new process technology and new functionality into existing systems.

2.1. *Definition of a reconfigurable manufacturing system*

This new type of manufacturing system, which we call *the reconfigurable manufacturing system*, will allow flexibility not only in producing a variety of parts, but also in changing the system itself. Such a system will be created using basic process modules—hardware and software—that will be rearranged quickly and reliably. These systems will not run the risk of becoming obsolete, because they will enable the rapid changing of system components and the rapid addition of application-specific software modules. This system will be open-ended, so that it can: (i) be continuously improved by integrating new technology, and (ii) be rapidly reconfigured to accommodate future products and changes in product demand rather than scrapped and replaced.

Our definition of a reconfigurable manufacturing system is as follows (Koren and Ulsoy, 1997; Koren *et al.*, 1997):

A reconfigurable manufacturing system is designed for rapid adjustment of production capacity and functionality, in response to new circumstances, by rearrangement or change of its components.

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.

2.2. *Comparison of manufacturing systems*

Reconfigurable manufacturing systems will not be more expensive than flexible manufacturing systems or even dedicated transfer lines. Unlike the other types of systems, the RMS aims to be installed with the exact production capacity and functionality needed, and may be upgraded (in terms of both capacity and functionality) in the future, when needed. Expanded functionality enables the production of more complex part types and the production of a variety of part types on the same system; it will be associated with adding process capabilities, auxiliary devices, more axis motions, larger tool magazines, and expensive controllers.

As shown in Fig. 2, dedicated transfer lines typically have high capacity but limited functionality (Koren and Ulsoy, 1997). They are cost effective as long as they produce a single few part types and demand exceeds supply. But with saturated markets and increasing pressure of global competition, there are situations where the dedicated lines do not operate at their full capacity, which creates a loss. Flexible systems, on the other hand, are built with all the flexibility and functionality available, even, as in

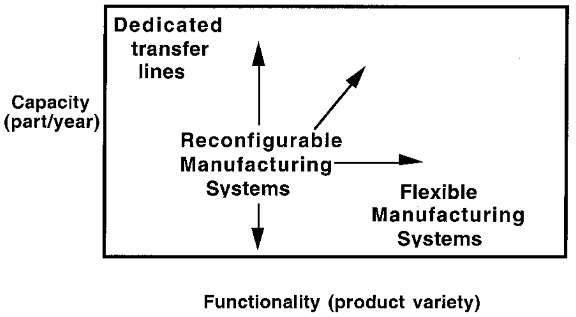

Fig. 2. Mapping several types of manufacturing systems in capacity-functionality coordinates.

some cases, with those that may not be needed at installation time. The logic behind this is "to buy it just in case it may one day be needed". 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 will be eliminated with RMS technology. In the first case the RMS aims to allow the addition of the extra capacity when required, and in the second case to add the additional functionality when needed. Referring again to the capacity versus functionality trade-off in Fig. 2, we see that RMSs may, in many cases, occupy a middle ground between DMSs and FMSs. This also raises the possibility of various types of RMSs, with different granularity of the RMS modules, that evolve from either DMSs or FMSs, respectively. For example, an RMS can be designed with a CNC machine tool as the basic building block. This would require an evolution of current FMSs through lower-cost, higher-velocity, CNC machine tools with modular tooling, that also have in-process measurement systems to assure consistent product quality. On the other hand, an RMSs can be designed with drive system modules, rather than CNC machines, as the basic building blocks. This would represent an evolution of RMSs from DMSs, and require, for example, modular machine tool components and distributed controllers with high band width communication.

While an RMS may lie between a DMS and an FMS in terms of capacity and functionality (see Fig. 2), this is not its distinguishing feature. The key feature of RMS is that, unlike a DMS and an FMS, its capacity and functionality are not fixed. The RMS will be designed through the use of reconfigurable hardware and software, such that its capacity and/or functionality can be changed over time and unlike the other manufacturing systems, it does not have a fixed hardware/software. It is clear that current trends in open-architecture control (reconfigurable software) and in modular machines (reconfigurable hardware) are key enabling technologies for RMS. In fact, an RMS must have certain key characteristics which are summarized in Table 2. While modularity is most apparent, the characteristics of integrability, convertibility, diagnosability, and customization are also important.

How are reconfigurable manufacturing systems related to agile manufacturing? Agility is defined as "a comprehensive response to the business challenges

Table 2. Key characteristics of a reconfigurable manufacturing system

1. Modularity:	Design all system components, both software and hardware, to be *modular*.
2. Integrability:	Design systems and components for both *ready integration* and future introduction of new technology.
3. Convertibility:	Allow *quick changeover* between existing products and quick system adaptability for future products.
4. Diagnosability:	*Identify quickly the sources of quality and reliability problems* that occur in large systems.
5. Customization:	Design the system capability and flexibility (hardware and controls) to *match the application* (product family).

of profiting from the rapidly changing, continually fragmenting, global markets for high-quality, high-performance, customer-configured goods and services'' (Goldman, Nagel, and Preiss, 1995). Agility is therefore more of a business philosophy that teaches how to respond to the challenges posed by a business environment dominated by change and uncertainty. In this regard, virtual enterprise, virtual manufacturing, and virtual companies are introduced in support of creating business partnerships; they are necessary tools in search for agility (Noaker, 1994; Sheridan, 1993; Iacocca Inst. Report, 1991). 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 to new market opportunities in an environment of global competition with niche market production. 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, is one aspect of agility.

Perhaps the best way to distinguish between agility and reconfigurability is to ask the same question that the Agility Forum at Lehigh University 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...'' (Goldman, web site www.agilityforum.org, 1997). 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 that they need to be flexible* 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 complimenting to reconfigurable manufacturing.

3. Historical perspective

In the previous sections, the new requirements for manufacturing were discussed and the novel concept of reconfigurable manufacturing systems was explained. Here we put these ideas in a historical perspective. In the following subsections, a summary of the changes in management systems, manufacturing techniques, and the contribution of the human being in these transitions is covered.

3.1. *Management systems and human resources*

In response to the changes in global economy and to stay competitive, there has been massive restructuring such as move from highly centralized structure to team-based management, diminished role for middle management, and new skill requirements, i.e., multiple skilled workforce (Jaikumar, 1993; Attaran, 1995; Aronson, 1997; Horte and Lindberg, 1991; Elmuti, 1996; McDermott and Brown, 1996; Buzacott, 1995; Bjorkman, 1995; Clegg, 1988). The above changes are required, in part, in order to utilize the latest advances in communication and information technology (Chen, Chung, and Gupta, 1994; Buzacott, 1995). Furthermore, new technological developments have a major impact on the role of the human in manufacturing. Note that manufacturing is a combined effort of the human and machine interacting in ways required to achieve a final goal, which is the product. In this regard, there are two contrasting views which reflect the two extremes of manufacturing automation (Seppala, Tuominen, and Koskinen, 1992; Adler, 1995): the first views the human as the source of errors and therefore, extensive automation of manufacturing is desired; but, the rival view considers the human as the sources of error recovery. It maintains the idea that there are always roles for the human to play and emphasize on the multiple skill workforce.

3.2. *Manufacturing*

Our literature survey suggests that there are different views on classifying the periods of development in manufacturing (Garro and Martin, 1993; Jaikumar, 1993; Buzacott, 1995). For example (Jaikumar, 1993) described six epochs of manufacturing by reviewing the events in terms of approaches to process control such as accuracy, precision, etc. However, in terms of manufacturing techniques, the evolution of manufacturing systems can conveniently be divided in three major epochs: (1) pre-CNC, (2) CNC, and (3) knowledge epochs. They are briefly explained in the following subsections.

3.2.1. *Pre-CNC Epoch (pre-1960s)*

Some of the historical events (for details, see Mehrabi and Ulsoy, 1997a) related to manufacturing (in particular machining) are depicted in Table 3. In the pre-CNC period, most of the machines and their control were mechanical. In production, transfer lines were utilized to reduce cost through the use of interchangeable parts. There was local competition, there were no demands for product variations (long and sustained period of a single product) and there were lack of integration in production systems (Schonberger, 1983).

3.2.2. *CNC Epoch (1960–1990)*

The invention of numerically controlled (NC) machines and their subsequent evolution (i.e., CNC, DNC) dramatically affected manufacturing (see Table 3). They had major impact on production rates, improved quality and accuracy, more accurate control of the machine (software/hardware), and easier integration. Consequently, a number of manufacturing techniques such as flexible manufacturing systems and Japanese production techniques such as Kaizen (continuous-improvement), Just-In-Time (JIT) (elimination/minimization of inventory as ideal goal to reduce costs), lean manufacturing (efficiently eliminate waste, reduce cost, and improve quality) (Schonberger, 1983) and total quality management (TQM) (increased and faster communications with customers to meet their requirements) techniques attracted considerable attention (Sakakibara, Flynn, and Schreder, 1965; Mondon, 1981a,b; Schonberger, 1983).

On close examination of the manufacturing techniques introduced in this period (e.g., FMSs, lean, JIT), one observes that in development of their underlying concepts, the machine-tool is considered as a single entity. However, as Garro and Martin (1993) pointed out, novel machine-tools should have modular structures to provide the manufacturing systems with necessary tools for quick integration and restructuring as required for rapid response to the fluctuating market. The infrastructures of the aforementioned manufacturing techniques such as software, hardware, control, elements of the control, material handling, communication, and the machines do not allow these changes to happen. One may argue that these manufacturing techniques may be modified to accommodate for necessary changes (typical examples of the recent attempts to combine JIT/FMSs or lean/FMSs to complement each other can be found in the literature (Chen, Chung, and Gupta, 1994; Gupta and Lonial, 1992; Buzacott, 1995). But these attempts fall short simply because there is a need for fundamental change at the lowest level (i.e., machine element).

3.2.3. *Knowledge epoch (post-1990)*

This period is characterized by intensified global competition and progress in computer and information technology. Rapid progress was made in areas such as management information systems, development of application programs for various purposes, advances in communication systems (hardware and software), and penetration of computer technology in various fields (Gyorki, 1989; Sheridan, 1989; Beckert, 1990; Teresko, 1990). Therefore, global competition and information technology are the driving forces behind recent changes in manufacturing. Every effort is made by manufacturers to respond faster to the market by producing higher quality products at lower

Table 3. Historical summary of key events related to RMSs

Pre CNC Epoch (1900–1960)			
Period	*Scientific understanding*	*Engineering & Technology*	*Marketplace changes*
1900–1960	1900: Scientific approach to the cutting metals presented at Paris Exhibition. 1906: Development of high-speed tools from alloys by F.W. Taylor and M. White. 1906-late 1930s: Development of new machine-tools, tools and tooling materials and new power systems. 1930s–40s: Progress made in theory of control and new methods of analysis of control systems. 1946–1947: Invention of transistor (J. Burdean, W.H. Brattain and W. Schockley at AT&T Lab). Early 1950s: Integrated circuits (IC) and the first electronic digital computer were invented. 1952: Numerical control (NC) was developed by MIT and Parsons Machine Tool Company; the beginning of modern machine tools. 1958: The invention of the machining center (Kearney and Trecker).	1819–1918: Development of internal combustion engines. 1909: Ford introduced the production line (beginning of primary automation lines). 1923: Automatic transfer machines were developed. Late 1930–1940: Practical application of automatic control systems for military purposes during World War II. 1946: First electronic computer (ENIAC) developed (using vacuum tube) at the Univ. of Pennsylvania by J. W. Mauchly and J. P. Eckert. Late 1949: Beginning of application of automatic control to various systems, machines, and processes. Improvement and expansion of large-scale assembly lines and mass production. Mid 1950s-late 1950s: Beginning of development of NC languages (like APT). 1960: First implementation of robot in industry (manufactured by ''Unimate'' and implemented at Ford). Mid 1950s-early 1960s: Beginning of development of NC languages (like APT).	1903: Ford Motor Company was founded. 1918–1945 (end of World War II): US a world industrial power. Rapid growth of research and development (R&D) and science-based industry. 1921: To obtain more effectiveness in operations, General Motors started to implement technical analysis of the quantity of materials needed for car production. 1947: The term ''automation'' was coined by D. S. Header (Ford Motor Co.) and the first automation department was founded. Late 1950s: Manufacturing evolution after World War II and rapid growth of a technology-based economy, rapid growth of electronics, and automation (late 1950s).

Table 3. (Continued)

Period	*Scientific understanding*	*Engineering & Technology*	*Marketplace changes*
1960–1990	1960–1972: Computer numerical control (CNC) was introduced (commercial) due to advent of minicomputers.	1960: First implementation of robot in industry(manufactured by ''Unimate'' and implemented at Ford).	1960–1980: Emphasis, especially in Japan, on lean manufacturing, which achieves high-quality manufacturing at low cost.
	Early 1970s: Increased research in implementing digital servo control, and higher levels of process control, in machining using newly available computing power.	1965–1966: First production line computer control (at IBM and GM) and the first production line computer control (at IBM and GM).	1973: The oil crisis.
	1973: The initial concepts of computer-integrated manufacturing (CIM) published.	1968: The first programmable logic controller (PLC) was designed and used at GM.	Mid 1970–mid1980: Major depression in machine tool industry and simultaneous recession in automotive industry.
	Mid to late 1970s: Development of the first CAD program (PADL) by H. Volckez.	1970s: Emphasis on utilization of operations management techniques, such as continuous improvement, just-in-time, statistical process control, etc.	Mid 1970: Entry of Japan into the US machine-tools market and expansion of market share for Japanese autos in the US.
	1970s and 1980s: Advanced control and systems theories (e.g., system identification, stochastic control, robust control theory, adaptive control, neural networks, expert systems, and fuzzy logic) are developed.	1971:The first microprocessor (Intel 4004) was invented by M. E. Hoff Jr.	Mid-1970–mid1980: Increased number of nameplates and reduction in single-model volumes, resulting in the need for lower-volume production systems.
	Development of geometric modeling and computer-aided design (CAD) techniques.	1974: The first minicomputer-controlled robot was commercialized by Cincinnati Milacron.	Dramatic changes in engine technology (e.g., smaller size,use of aluminum, lower emissions) and significant changes to transmission design (front wheel drive).
	Flexible manufacturing system (FMS) paradigm, where multiple products can be produced on the same line, is postulated.	Mid-1970s: Just-in-time (JIT) was first developed and promoted by Toyota Motor Corporation.	
		1977: The first personal computers came on the scene through Radio Shack, Commodore, and Apple.	
		Mid to late 1970s: Beginning of computer-aided manufacturing (CAM) applications.	

Table 3. (Continued)

		Knowledge Epoch (1990-Now)	
1990–1994	1990s: Evolution in underlying concepts of manufacturing systems, industrial machines, and machine-tools (in particular) showing migration from centralized and isolated systems toward decentralized, modular forms (e.g., modular machines and tooling, open architecture control); research and development in higher performing, more intelligent, accurate, and higher speed machine tools. Micromachining was a new approach to constructing sensors.	1990s: Widespread design and implementation of computers in control of processes; computer-integrated manufacturing (CAM) systems; manufacturing cells and information management systems; design and implementation of advanced control techniques for industrial processes and systems; application of linear motors to machinery; development of varieties of software/ hardware and operating systems; availability of higher computing power and faster communication systems.	1990s: Production of a greater variety of goods at higher production rates. Rapid market changes (due to changes in demand). Demand for higher quality and more variety. 1993: SCADA (Supervisory Control and Data Acquisition) (GM).
1995–	1995: The Reconfigurable Manufacturing System (RMS) paradigm emerges to address the need for responsiveness to changes in the market and technology	1995: PC-based machine tool controllers, for both PLC and CNC functions, become widely available	1996: The NSF Engineering Research Center (ERC) for Reconfigurable Machining Systems (RMS) is established

costs and in smaller quantities. The concept of agile manufacturing was introduced in 1991 and it focused on faster response and customization of products (Sheridan, 1993; Kusiak and He, 1997). However, it is mainly focused on a business philosophy for the manufacturing enterprise rather than the production system level (i.e., it does not emphasize on specific engineering developments or operational techniques). This is reflected in recent attempts to introduce the enabling technologies for agile manufacturing or CIM (Wright, 1995). Examples show that agility is implemented by changing the tools and workholding equipment (mostly auxiliary equipment). In essence, there are minimum changes to the machine structure and software (Mason, 1995).

The overall trends in various sectors of manufacturing can be summarized as follows:

- There has been massive restructuring at all levels of organizations in response to globalization of the economy and new market conditions.

- Management systems have moved from hierarchical structures to leveled systems and the roles of the middle management are reduced (i.e., removing the obstacles and providing direct routes between high and low levels for faster reorganization/data transfer and required modifications).
- The restructuring of organizations emphasizes moving from highly centralized to decentralized team-work (i.e., essentially creating modules and dividing the tasks among them to enhance flexibility, integration, and faster execution of new tasks).
- The human should acquire multiple-skills (on a continuous basis) to enable her to participate in the group discussions and properly respond to the needs of the system (i.e., the knowledge, decision making and intelligence are moved from the top and they are distributed among the basic elements).

It is seen that in general, all these trends are toward modularity, autonomy, and self-sufficiency at the lowest possible levels (i.e., elements of an organization). These are essential characteristics of a modern dynamic organization. They offer the system the advantages of fast and easy integration, continuous evolution, adaptable structure, and upgrading. In a similar way, there are needs of new approaches to manufacturing such that they can properly respond to the new market conditions characterized by large fluctuations in product demand and smaller production volumes. It should be emphasized that in a modern manufacturing environment, computers and information systems can be partly viewed as an interface between the two other elements, i.e., the human mind (virtual; very limited physical action) and the machines (i.e., physical elements who do the actual physical job). The computer technology has evolved enormously in the last decade or so. It has certain characteristics which are dictated by the systems. With some time-lag, organizations realize the need for change and are utilizing computer/information technology. The above restructuring (in terms of human resources, i.e., the other element of manufacturing) are required for a suitable and efficient means of communication between human and computer/information technology. In spite of all these dramatic changes, manufacturing techniques and machine-tools have remained unchanged.

On close examination of the manufacturing techniques introduced so far, one observes that:

- They do not posses a modular structure in terms of software/hardware. Therefore, they are not always flexible enough and cannot accommodate rapid changes.
- The level of modularity are at fairly higher levels in contrast to the requirements of modularity at the lowest element (for instance, FMSs are not very modular at cell level; even the existing machine-tools are not modular at component level). This makes upgrading and integration of the new components quite complicated.
- There are risks involved in integration of the information systems and control software (Attaran, 1995). This is due to the fact that the control structures of the current manufacturing systems are highly centralized (hardware/software). Therefore, integration of new modules, their diagnosis, and maintenance are very difficult.

4. Future trends

It is difficult to forecast long term trends for manufacturing systems, since the changes are happening at a fast pace. However, it is possible to extrapolate future trends from the current situation by analyzing and specifying the key drivers behind the changes. Certainly, availability and distribution of information plays an important role in this transition and it is considered as one of the key drivers. In this regard, there are needs for improvements and standardization of various components (such as data interfaces, protocols, communication systems, etc.) so that data can be transferred to the desired location at a faster rate. This has a considerable effect on high/low level elements of the future manufacturing systems (Next Generation Manufacturing Project, 1997; Rogers and Bottaci, 1997). At high levels, it has a major impact on manufacturing firms by facilitating their integration and collaboration to form larger enterprises. Therefore, manufacturer may be viewed as a local sector of a larger/global enterprise (i.e., teaming at a high level) (Iacocca Inst. Report, 1991). To stay a competitive member of the enterprise, the infrastructure (low level) of production plants should have certain characteristics such as modularity at various levels (i.e., extensive team-based approach in terms of human resources), flat management, multiple skill personnel for quick restructuring in response to the market. Faster communication also provides a basis for rapid technology access which in turn makes education globally available (high level); as a result the current worldwide gaps of technical skills will be reduced (Next Generation Manufacturing Project, 1997). This clearly identifies the important role for continuous education, upgrading and requirements of development of multidisciplinary programs to prepare the required/qualified work force for this competitive market (low level). It should be mentioned that all of these changes are required for faster response to market globalization, global competition, and higher customer expectations (i.e., product variety, quality, and lower costs).

There have been reports relevant to future manufacturing technologies, processes, and machine-tools (The Association for Manufacturing Technology Report, 1996; Next Generation Manufacturing Project, 1997; Aronson, 1997; Ashley, 1997). They have all agreed that manufacturing should be viewed, designed, and optimized as a system (as a whole) to achieve the required responsiveness (i.e., shorter lead-time and ramp-up time). In this regard, there is a need for a fundamental understanding of manufacturing processes, equipment, and technologies and their relations to the rapidly changing market. Although there are many projects underway, however, we are still at the beginning of a new era of modern manufacturing systems and there are many barriers to their advances (see the Next Generation Manufacturing Project, 1997). As reported, there is a lack of available tools and methodologies to analyze the trade-off among

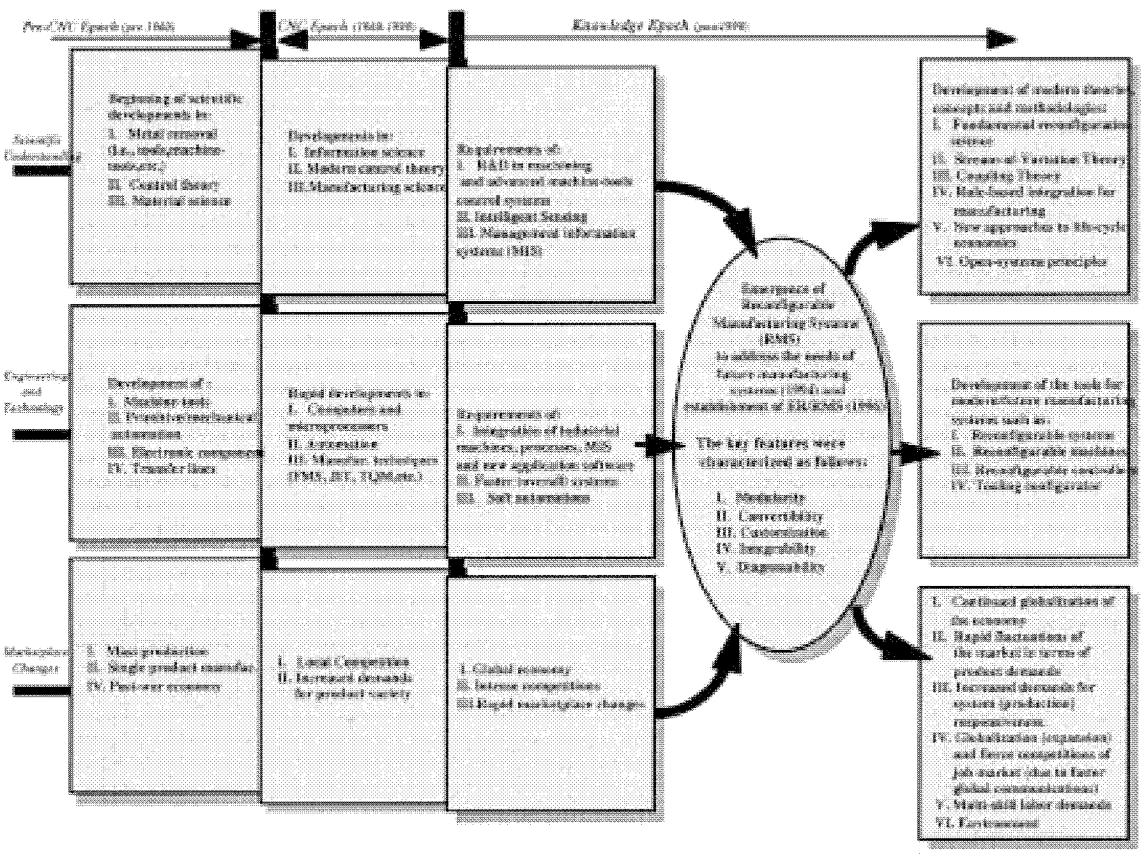

Fig. 3. The key role of reconfigurable manufacturing systems (RMSs) in future manufacturing.

processes, equipment, life-cycle costs, and initial investment. Also, there is a lack of effective communication among product designers, process designers, and machine-tool designers as it is necessary for design of a better manufacturing system.

Advances in manufacturing will not occur without the proper machine-tools and equipment. Machine tools are going under some fundamental changes in terms of their structure (modular structure), components (controllers, hardware/software, spindles, tooling), and sensors. Therefore, new theories, design concepts, and methodologies should be developed for these purposes (see Fig. 3) (Garro and Martin, 1993; The Association for Manufacturing Technology Report, 1996; Next Generation Manufacturing Project, 1997; Aronson, 1997; Ashley, 1997; Rogers and Bottaci, 1997). These changes are fundamental to the success of future reconfigurable manufacturing systems.

To help assess the near-future (5–10 years) developments and relevant issues in manufacturing systems, a survey is currently underway at the University of Michigan. In this study, national/international experts in the field of manufacturing are provided an opportunity, via a series of survey instruments, to make predictions based on their deep knowledge of the manufacturing field to present the rationale behind their forecasts, to discuss their own and other experts' predictions, and to revise their own in light of such discussions. This survey project hopes to accomplish two main goals. The first is to examine the results to date associated with the use of existing manufacturing systems such as flexible machining systems: its accomplishments, strengths, and shortcomings in the manufacturing environment. The second is to examine the potential roles, justifications, and enabling technologies for reconfigurable machining systems in future manufacturing facilities. As part of this second goal, the panel will identify key enabling technologies needed to realize these benefits. The results of this study will be reported in the near future (Heytler, 1997).

5. Technologies for reconfigurable machining systems

As shown in Fig. 4, there are many aspects of reconfiguration. These include various configurations of the production system (e.g., serial, parallel, and hybrid), reconfiguration of the factory communication software, configuration of new machine controllers, building blocks and configuration of modular machines, modular processes, and modular tooling. There are a number of key interrelated enabling technologies that should be developed and implemented to achieve the goals of reconfigurable manufacturing systems. Detailed discussion of the relevant issues are provided in (Koren and Ulsoy, 1997; Mehrabi and Ulsoy, 1997a,b) and are the subject of another report that will be published later. Their brief discussions are provided in the following paragraphs.

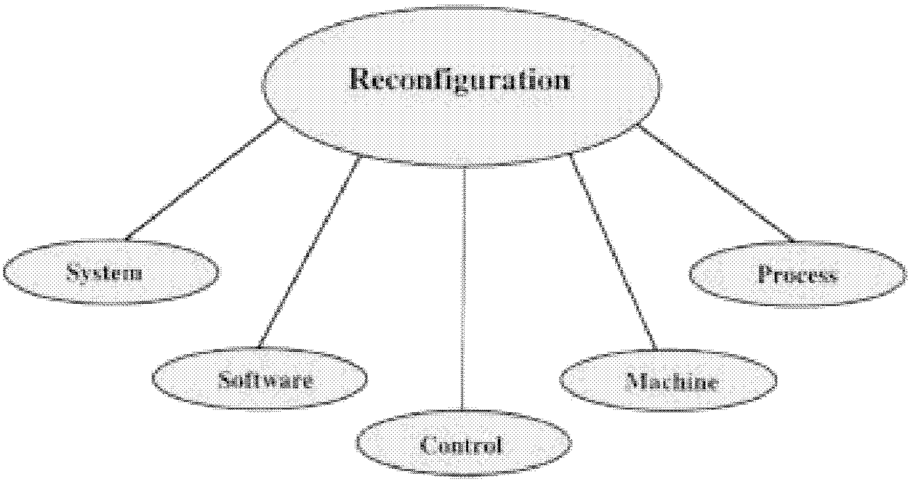

Fig. 4. Aspects of reconfiguration (reconfigurable system, software, controller, machine, and process) for an RMS.

At the system level, there could be several system configurations for production of the same part family. Development of the necessary tools and methodologies to design the system, and evaluate various configurations (based on life-cycle economics, quality, system reliability, preferences of decision maker(s)) is needed. As far as system software/hardware architecture is concerned, it should have certain features to support the five key characteristics of RMSs. It should have a modular structure and be "open" such that upgrading and customization of the system is practical while integration of new software is possible. Control, monitoring and sensing of RMSs are other important subjects to be studied. By noting that the system configuration changes (based on market demand), the parameters of the production machines such as mass, inertia, and some other physical parameters will change accordingly. Therefore, the controller and process monitoring systems should have the ability to reconfigure and adapt themselves to these new conditions. Development of a unified approach for design and construction of reconfigurable machine-tool systems is another important challenge in the design of an RMS. Like any other design problem, a compromise should be made among certain variables of the system. The RMS design problem is, however, quite complex since the number of variables is large.

6. Key research issues in reconfigurable manufacturing systems

In the process of designing and operating reconfigurable manufacturing systems one has to distinguish from among system-level issues, component-level (i.e., machine and controls) issues, and ramp-up time reduction issues. For a system to be reconfigurable, these subsystems and their components must be designed to be reconfigurable at the outset. In order for a system to be reconfigurable, it must consist of subsystems and components that have been designed at the outset, using scientific knowledge, in order to posses certain key characteristics of reconfigurable manufacturing systems (see Fig. 5). To achieve each of these new goals one must start with the definition of a part family (see Fig. 6), and then to research the system-level design issues, link them with machine-level research issues (i.e., reconfigurable machines, controls, and machining processes) and complement them with the methods and tools for ramp-up time reduction. Some of the research issues that should be

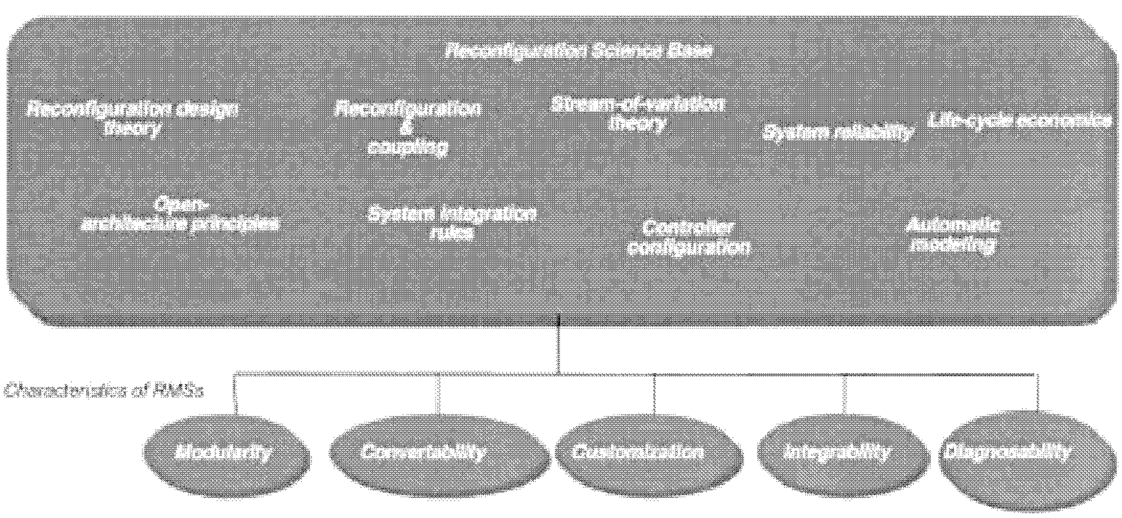

Fig. 5. Science base for RMSs.

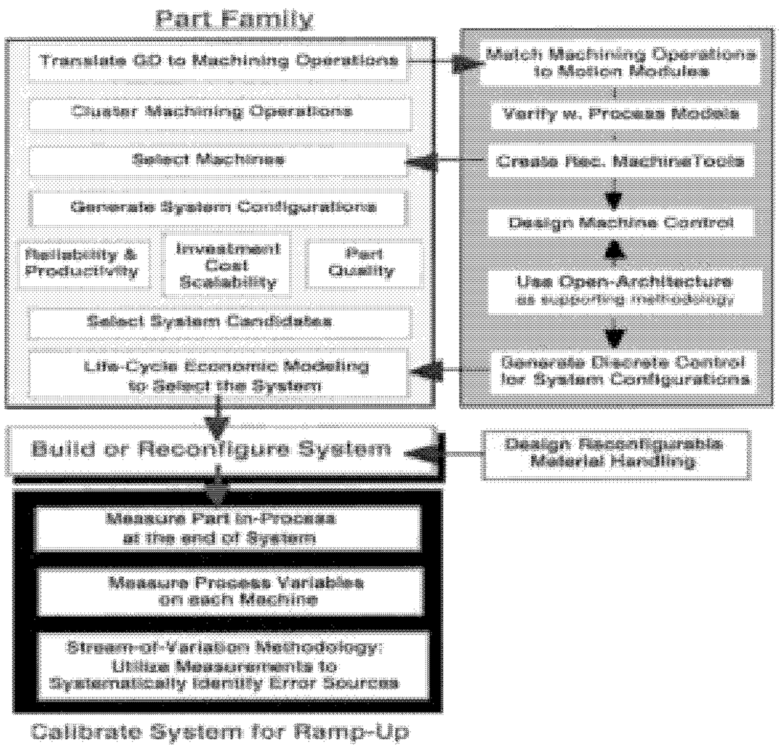

Fig. 6. Steps involved in system design of RMSs.

developed to support system-level goals, machine-level goals, and ramp-up reduction goals are described in the following subsections.

6.1. *Research issues in system-level design*

Design of reconfigurable systems is accomplished through a systematic approach, supported by software tools that relate the product features to modules of processing units and yield a system layout and process plan. System level design starts with the common geometric features and tolerance of the part family (the input). The outcome is an optimized system configuration and economic machining system that fits the customer requirements (part mix and volume) and the customer manufacturing practices.

Some of the key research issues in system level design are:

- Development of a systematic approach for design of RMS at the system level.
- Analysis of the impact of system configuration on reliability, quality, and cost.
- Economic analysis of various system configurations and their selection.
- Analysis and design of the full process from recognizing customer needs (or anticipated needs) through operation selection and system specification.

6.2. *Research issues in machine-level design*

Reconfigurable manufacturing systems require design at both the system and machine levels. As described previously, the design must be modular, integrable, customized, convertible, and diagnosable to support reconfiguration and ramp-up. Modular machine component design, and an open-architecture controller are key enabling technologies. However, they are not sufficient, and methods for the rapid and efficient reuse of such modules is also essential for reconfigurability. Machine components (e.g., structural modules, axis drive modules) and controller components (e.g., servo control, thermal compensation 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 used 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, is selected from among the feasible candidate designs generated by the RMS machine-level design software.

Some of the key research issues in machine level design are:

- Development of fundamental principles and techniques for the design and analysis of reconfigurable machines along with their controllers, and
- Design and development of a set of simple reconfigurable machines and controllers to quickly produce two different parts for the proof of concept.

6.3. *Research issues for ramp-up time reduction*

After the RMS is reconfigured, the production system must typically be "fine-tuned" before it can consistently produce at the required quality and production volume. This is referred to as ramp-up, and can take months or even years with traditional production systems. For RMS to be practical, it is necessary to significantly reduce ramp-up times for both new and reconfigured systems. We have identified lack of systematic approaches to diagnosing component failure as being the most critical obstacle in ramp-up. Literature reviews revealed that no systematic approach exist to identify root-causes of components failure, and quality and process variations. Also, lack of robust components that can operate reliably and safely under different condition is a major issue in ramp-up reduction. Therefore, some of the basic research goals should be aimed at development of methodologies and fundamental theories for ramp-up time reduction for reconfigurable machining systems.

Some of the key research issues related to ramp-up time reduction are:

- Development of systematic approaches and fundamental principles to identify root-causes of components failure, and quality and process variations.
- Design of robust components that can operate reliably and safely under different operating conditions.

A recent study (National Research Council, 1998) has identified reconfigurable manufacturing as the highest priority for future research in manufacturing, and one of the six key manufacturing challenges for the year 2020. The Engineering Research Center for Reconfigurable Machining Systems (ERC/RMS) at the University of Michigan has already established several key research projects in most of these areas. However, we are just at the beginning of a new era in manufacturing and there are many more research topics to be explored.

It should be mentioned that while there are needs for development of new underlying theories to resolve some of these issues, it is possible to use or extend the existing theories or concepts in the context of RMSs. For example, some of the concepts already developed in the area of expert systems and artificial intelligence (AI) can be adopted and used to address similar issues in the context of reconfigurable manufacturing systems. AI can have potential applications in the areas such as operation and process planning, production scheduling, production optimization, process control, fault diagnosis, and module selection process of RMSs. Examples of general applications of AI in these subjects can be found in (Kusiak, 1987; Kumara, Kashyap, and Soysters, 1988; Badiru, 1991).

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