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Manufacturing

A. Galip Hulsoy

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Manufacturing Systems and Their Design Principles

M. G. Mehrabi
University of Michigan

A. Galip Ulsoy
University of Michigan

Yoram Koren
University of Michigan

1.1 Introduction

Manufacturing has always been the key to success among nations in the world economy (Figure 1.1). A responsive manufacturing system working in harmony with the rest of an enterprise has a major impact on its competitiveness; it plays a vital role in the successful introduction of new products or continuous improvements of existing products in response to demands of the market (Cohen, 1987).

A wide variety of items are produced by manufacturing firms, depending upon the market demands they may be custom made or mass produced. Manufacturing systems used for their production are designed and tailored to specific requirements. Consequently, several manufacturing techniques are adopted to address new market demands.

This chapter is devoted to a high-level overview of manufacturing techniques, their objectives and design principles. In this regard, some of the available manufacturing techniques are explained and their achievements, advantages, and limitations are discussed. Due to the significant impact of computers on manufacturing, an effort is made to introduce the role of computers and information technology in modern manufacturing systems. In this regard, applications and functions of computers in various stages of product design, generation of the sequence of operations and process planning, control of the machines and monitoring of the processes (on/off line), automation, networking and communication systems, and quality control of the production systems are explained. Later in the chapter, the design principles of manufacturing systems and their components

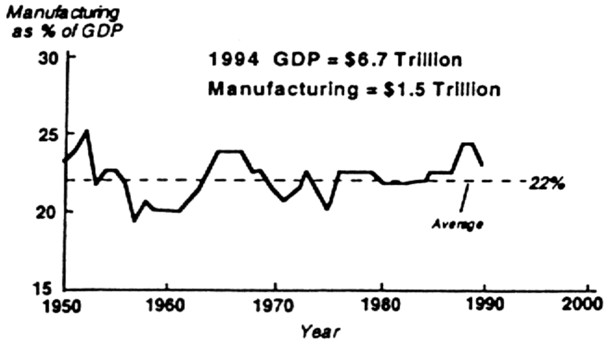


FIGURE 1.1 Despite assertions that the U.S. is becoming a service industry, manufacturing has consistently accounted for about 22% of GDP. (Source: U.S. Bureau of Labor Statistics.)

are presented as well as some of the issues related to their enabling technologies and barriers. The chapter concludes with a discussion of some of the future directions in manufacturing systems.

1.2 Major Manufacturing Paradigms and Their Objectives

New technological developments and market demands have major impacts on manufacturing. As a result, several shifts in the focus of manufacturing processes can be observed, which can be conveniently divided into three major epochs: (1) precomputer numerical control, (2) computer numerical control (CNC), and (3) knowledge epochs (Mehrabi and Ulsoy, 1997; Mehrabi, Ulsoy, and Koren, 1998). In the pre-CNC epochs (before the 1970s), the emphasis was on increased production rate; little demand existed for product variations and the market was characterized by local competition. Mass production uses dedicated lines designed for production of a specific part; it uses transfer line technology with fixed tooling and automation. The objective is to cost-effectively produce one specific part type at high volumes and with the required quality.

The emphasis on cost-effective production was supplemented with a focus on improved product quality in the CNC epoch (the 1970s and 1980s). Manufacturing was dramatically affected by the invention of CNC machines as they provide more accurate control and means for better quality. Japanese production techniques such as Kaizen (continuous improvement); just-in-time (JIT) (elimination/minimization of inventory as the ideal goal to reduce costs); lean manufacturing (efficiently eliminate waste, reduce cost, and improve quality control; and total quality management (TQM) (increased and faster communications with customers to meet their requirements) attracted considerable attention. Furthermore, CNC machines provided necessary tools for easier integration/automation which, in turn, contributed to manufacturing of a product family on the same system. Consequently, flexible manufacturing systems (FMSs) were introduced to address changes in work orders, production schedules, part programs, and tooling for the production of a family of parts. The economic objective of an FMS (see Figure 1.2) is to make possible the cost-effective manufacture of several types of parts that can change over time, with shortened changeover time, on the same system at the required volume and quality. It has a fixed hardware and fixed (but programmable) software (see Figure 1.3). In terms of design, the system possesses an integral architecture (hardware/software), i.e., the boundaries between the components and their functionalities are often difficult to identify and are tightly linked together. This type of architecture does not allow for reconfiguration changes to be made. Therefore, an FMS has limited capabilities for upgrading, add-ons, customization, and changes in production capacity.

In the knowledge epoch (i.e., starting in the 1990s), focus shifted to the responsiveness of a manufacturing system characterized by intensified global competition, the fast pace of technological innovations, and enormous progress in computer and information technology (Jaikumar, 1993; Mehrabi

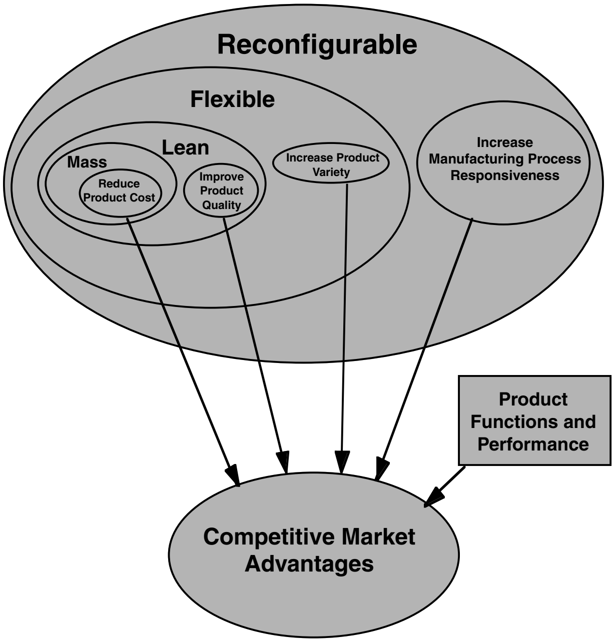


FIGURE 1.2 Economic goals for various manufacturing paradigms.

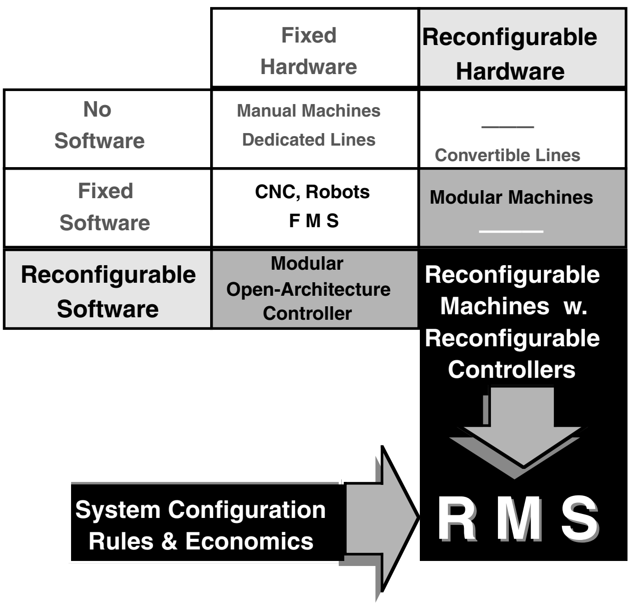


FIGURE 1.3 Key hardware and software features of manufacturing systems.

and Ulsoy, 1997; Mehrabi, Ulsoy, and Koren, 1998). Rapid progress was made in areas such as management information systems, development of software/application programs for various specific purposes, advances in communication systems (hardware and software), and penetration of computer technology in various fields (Gyorki, 1989). Therefore, global competition and information technology are the driving forces behind recent changes in manufacturing. These conditions

TABLE 1.1 Summary of Definitions

Systems (Machining/Manufacturing)	Definitions
Machining System	One or more 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 System (DMS)	A machining system designed for production of a specific part, and uses transfer line technology with fixed tooling and automation.
Flexible Manufacturing System (FMS)	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.
Reconfigurable Manufacturing System (RMS)	A machining system that 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.

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.

require a responsive manufacturing system that can be rapidly designed, able to convert quickly to the production of new product models, able to adjust capacity quickly, able to integrate process technology, and able to produce an increased variety of products in unpredictable quantities. Agile manufacturing (Goldman, Nagel, and Preiss, 1995) was introduced as a new approach to respond to rapid change due to competition. It brings together individual companies to form an enterprise of manufacturers and their suppliers linked via advanced networks of computers and communication systems. Agile manufacturing, however, does not deal with production system technology or operations.

More recently, reconfigurable manufacturing systems (RMSs) were introduced (Koren and Ulsoy, 1997; Mehrabi and Ulsoy, 1997) to respond to the new market-oriented manufacturing environment. In terms of design, an RMS has a modular structure (software and hardware) that allows ease of reconfiguration as a strategy to adapt to market demands (see Table 1.1). Open-architecture control systems are one of the key enabling technologies of an RMS, and have the ability to integrate/remove new software/hardware modules without affecting the rest of the system. Another key enabling technology is modular machines (Moon and Kota, 1998; Garro and Martin, 1993). System design tools are also needed to properly configure a system from these software and hardware building blocks (see Figure 1.3). This means an RMS has the ability to be converted quickly to the production of new models, to be adjusted rapidly to exact capacity requirements as the market grows and product changes, and to integrate new technology. 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, and can change as needed. An RMS goes beyond the economic objectives of an 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.

1.3 Significance of Functionality/Capacity Adjustments in Modern Manufacturing Systems

Due to the globalization of economies, responsiveness is becoming the cornerstone of manufacturing competitiveness. Therefore, rapid, controlled-cost response to market demands is the key to the success of manufacturing companies. This section is devoted to discussion of the abilities of

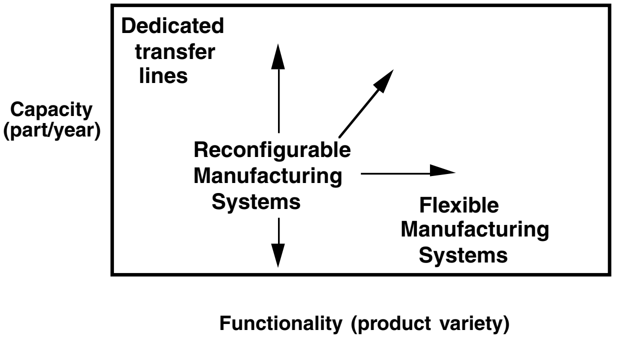


FIGURE 1.4 Mapping several types of manufacturing systems in capacityfunctionality coordinates.

available manufacturing systems in terms of the rapid adjustment of capacity and functionality in response to the market demands. Figure 1.4 provides mapping of the available manufacturing systems in capacity-functionality coordinates. As is shown, dedicated transfer lines typically have high capacity but limited functionality (Koren and Ulsoy, 1997). They are cost effective as long as they produce a limited number of part types and demand exceeds supply. But with saturated markets and the increasing pressure of global competition, situations exist 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, including some cases that may not be needed at installation time. 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 allows the addition of the extra capacity when required, and in the second case, adds functionality when needed. Referring again to the capacity vs. functionality trade-off in Figure 1.4, the 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 RMS 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 bandwidth communication.

1.4 Critical Role of Computers in Modern Manufacturing

A number of steps are involved in manufacturing a part from its conceptualization to production. They include product design, process planning, production system design, and process control. Computers are used extensively in all these stages to make the entire process easier and faster. Potential benefits of using computers in manufacturing include reduced costs and lead times in all engineering design stages, improved quality and accuracy, minimization of errors and their duplication, more efficient analysis tool, and accurate control and monitoring of the machines/processes, etc. Some of the applications of computers in manufacturing are shown in Figure 1.5. In computer-aided design (CAD), computers are used in the design and analysis of the products and processes. They play a critical role in reducing lead time and cost at the design stages of the products/process. Also, computers may be utilized to plan, manage, and control the operations of a manufacturing system: computer-aided manufacturing (CAM) (Bedworth, Handerson, and Wolfe, 1991). In CAM, computers are either used directly to control and monitor the machines/processes (in real-time) or used off-line to support manufacturing operations such as computer-aided process planning (CAPP)

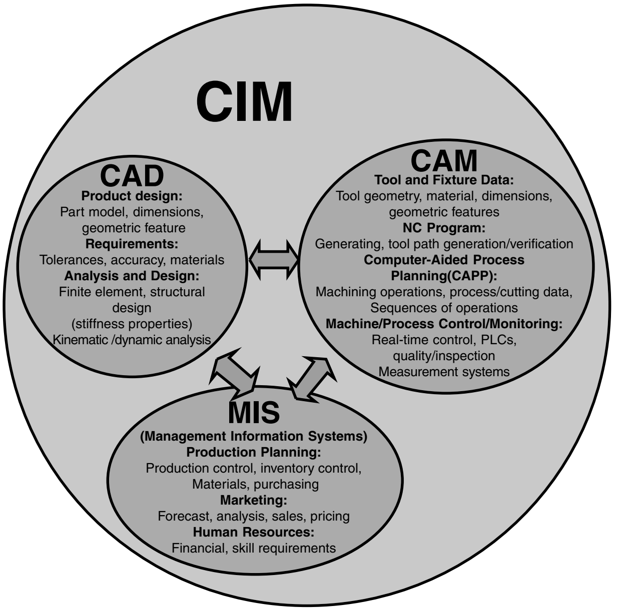


FIGURE 1.5 Applications of computer technology in manufacturing.

or planning of required materials. At higher levels, computers are utilized in support of management. They play a critical role in all stages of decision making and control of financial operations by processing and analyzing data and reporting the results (management information systems, MIS) (Hollingam, 1987). Computers facilitate integration of CAD, CAM, and MIS (computer-integrated manufacturing, CIM) (Vajpayee, 1995) (see Figure 1.5). They provide an effective communication interface among engineers, design, management, production workers, and project groups to improve efficiency and productivity of the entire system.

1.5 Design Principles of Modern Manufacturing Systems

Manufacturing is a complex process that begins with evaluating the market and investigating the demands for a product, and ends with delivery of the actual product. Successful marketing should take into account the factors that affect current and future demands for a product. It provides management with appropriate inputs for decision making and directing resources of a company toward production of a part that is needed in the market. This sets the stage for product design and manufacturing as described in the following sections.

1.5.1 Product Design and Design for Manufacturability

At the product design stage, designers and product engineers generate new ideas and study various aspects of design. Also, production engineers investigate the availability of the resources and capabilities of the production system. CAD systems are extensively used at this stage for rapid design and revisions of a product (Groover and Zimmers, 1984). Designs for manufacturability (DFM) and assembly are used to emphasize the significance of the links between design of a product and its manufacturing (Beckert, 1990). Design for manufacturing focuses on appropriate product design, process planning, and manufacturing to ensure optimum results (Vajpayee, 1995). It emphasizes the importance of quality and its relation with the machines/processes accuracy of machined (produced) parts tolerances, and correction of a product defect at the design stage (as opposed to after production) and its significant impact on cost of a product.

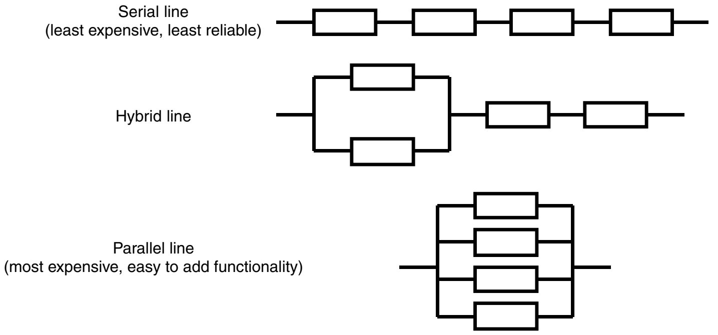


FIGURE 1.6 Several possible configurations with four machines.

1.5.2 Process Planning and System Design of Manufacturing Systems

Once a product design is completed, it is produced by using machines and other equipment (e.g., material handling) and resources. Computers are used extensively to identify optimal machining configurations by taking into account the cost, quality, and reliability of the entire system (see Figure 1.6), control the activities of planning and distributing the sequence of operations among the machines, and to specify machining parameters such as feed, speed, etc., computer-aided process planning (CAPP) (Bedworth, Handerson, and Wolfe, 1991; Vajpayee, 1995).

Two basic approaches to CAPP exist, variant and regenerative. The variant technique is used mostly for process planning of a family of products. With this technique, group technology (GT) is used to create and classify the plans (for a family of parts), and store them in a database. For the next design, the required plans are retrieved from the database already created for this family of parts (Groover and Zimmers, 1984). With the regenerative method, process plans are produced for every new product and as such, no database of plans exists (Gyorki, 1989; Vajpayee, 1995). It is more sophisticated than the variant method and has the advantage of facilitating integration of process planning stage with product design while the needs for human experts are minimized or totally eliminated.

1.5.3 Software/Hardware Architecture and Communications in Manufacturing Systems

An integral part of a manufacturing system is the software required to handle tasks at various levels such as control, monitoring, and communications among mechanical, electrical, and electronic components (low level) as well as higher level tasks such as process planning, user interface, process control, data collection/report from the process, etc. Therefore, the structure and functionality of the control software are very critical and directly affect the performance of the entire system. The controllers of the machines, networking and data communication between CNC controller/PLC (programmable logic controllers) or PLC/PLC, have been through proprietary networks (similar situation as with controllers); i.e., related control systems, communication systems, protocols, and software/hardware are not open to users or other vendors (Aronson, 1997; Altintas and Munasinghe, 1996). Therefore, further system enhancements, integration of sensors, and new technologies are severely restricted. Open-architecture principles and systems are introduced to accommodate these features (see Figure 1.7).

Another critical issue in the design of modern intelligent manufacturing systems is communication. Let us consider a set of sensors/devices communicating with a central computer/controller. Traditionally, they should be hard-wired to the central controller/PLC; therefore, the costs associated with wiring, connections, control cabinet, space, labor, maintenance, and trouble shooting are quite

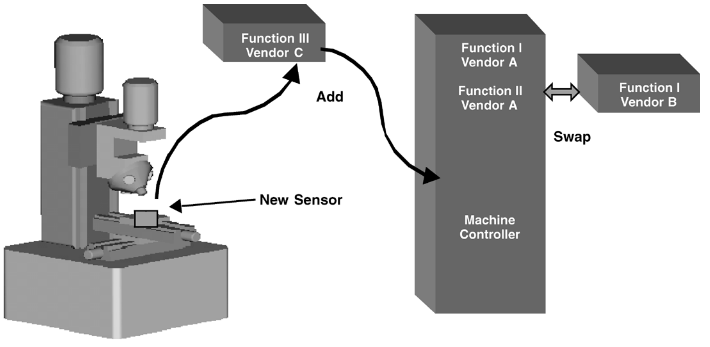


FIGURE 1.7 Open-architecture principle in machine tool control systems.

high. With a proper communication system, the same sensor/device is connected to a network (locally) which takes care of all data reporting and condition monitoring of the entire manufacturing system.

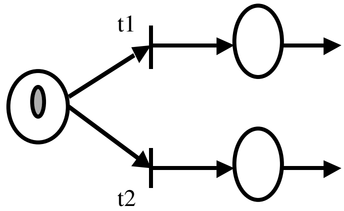
Recent developments in built-in intelligent control devices and communication networks, such as Devicenet, address some of these issues (Proctor and Albus, 1997; Proctor and Micholski, 1993). In the Devicenet network, local devices have built-in intelligence (with little cost) and their communication capabilities are enhanced. Therefore, control decisions/actions are made locally and the entire control system for manufacturing is decentralized. Also, progress is made in the development of standard terminology for message and instruction sets, such as manufacturing message specification (MMS), which is necessary for shop floor communication.

1.5.4 Monitoring and Control of Manufacturing Systems

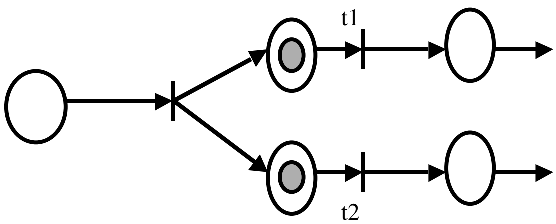
One of the key factors in evaluating product quality is precision in machining. To achieve that, the cutting operation is tightly controlled by using real-time data collected from sensors located at different locations of the workpiece, tool, and machine. Also, some measurements are made for process monitoring purposes with the objective of preventing irrepairable damages to the workpiece and the machine. In general, real-time measurements of the following variables are required: dimensional errors, quality of surface finish, thermal deformations during machining, and dynamic deformations of the workpiece; chatter vibration, cutting force, condition of the chip, and identification of the cutting for process monitoring; thermal deformation, dynamic deformation of the machine elements, and structural vibration of the machine tool and wear, failure, and thermal deformations of the tool (Rangwala and Dornfeld, 1990; Li and Elbestawi, 1996).

Currently, commercially available controllers of CNC machines have been equipped with proprietary control systems; i.e., the users do not have access to the controller and further modifications/enhancements of the system (by the users) are either impossible or very costly. This has significantly hindered the applications of efficient control algorithms, addition of new sensors for process improvement/monitoring purposes, and has suppressed the automation of the entire production system. PC-based control systems (Koren et al., 1998; Hollenback, 1996) are the answer to the limitations mentioned above; they are very suitable for operating in an open-architecture environment (see Figure 1.7).

The same view is valid for programmable logic controllers (PLCs). To date, PLCs have been used in industrial automation to control and monitor discrete event systems. The functionality of PLCs can be enhanced, however, by proper implementation of available I/O boards (and compatible software) on a much more compact and industrial PC platform such as PC/104. This offers the advantage of integrating the functional logic (discrete) of PLCs and machine-tools' motion control (continuous) by utilizing modeling capabilities of Petri nets (Park et al., 1998) (see Figure 1.8).



(a) Conflict: if t1 fires, t2 is not enabled and visa versa



(b) Concurrency: t1and t2 can be fired independently

FIGURE 1.8 Examples of modeling capabilities of Petri nets.

1.6 Future Trends and Research Directions

It is very difficult to forecast long-term trends for manufacturing systems, because the changes are happening at a very 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 play an important role in this transition and are considered key drivers. In this regard, the need for improvements and standardization of various components (such as data interfaces, protocols, communication systems, etc.) exists so that data can be transferred to the desired location at a faster rate (Agility Forum, 1997).

There are many research efforts underway; however, we are still at the beginning of a new era of modern manufacturing systems, and there are many barriers to their advancement. Advances in manufacturing will not occur without the proper machine tools and equipment. Machine tools are undergoing some fundamental changes in terms of their structure (modular structure) and components (controllers, hardware/software, spindles, tooling, sensors, etc.). Therefore, new theories, design concepts, and methodologies should be developed for these purposes (Garro and Martin, 1993; Lee, 1997; Moon and Kota, 1998). These changes are fundamental to the success of future manufacturing systems.

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