Reconfigurable Manufacturing Systems

Y. Koren (University of Michigan), U. Heisel (Universität Stuttgart), F. Jovane (Politecnico di Milano),
T. Moriwaki (Kobe University), G. Pritschow (Universität Stuttgart), G. Ulsoy (University of Michigan),
H. Van Brussel (Katholieke Universiteit Leuven)

Abstract

Manufacturing companies in the 21st Century will face unpredictable, high-frequency market changes driven by global competition. To stay competitive, these companies must possess new types of manufacturing systems that are cost-effective and very responsive to all these market changes. Reconfigurability, an engineering technology that deals with cost-effective, quick reaction to market changes, is needed. Reconfigurable manufacturing systems (RMS), whose components are reconfigurable machines and reconfigurable controllers, as well as methodologies for their systematic design and rapid ramp-up, are the cornerstones of this new manufacturing paradigm.

Keywords: Reconfiguration, Manufacturing system, Machine tools

1 THE CHALLENGE

The need and rationale for reconfigurable manufacturing systems arises from unpredictable market changes that are occurring with increasing pace during the recent years. These changes include:

- increasing frequency introduction of new products,
- changes in parts for existing products,
- large fluctuations in product demand and mix,
- changes in government regulations (safety and environment), and
- changes in process technology.

These changes are driven by aggressive economic competition on a global scale, more educated and demanding customers, and a rapid pace of change in process technology [1]. These drivers reflect a new balance among economy, technology and society. To survive in this new manufacturing environment, companies must be able to react to changes **rapidly** and **cost-effectively**.

To cope with the short windows of opportunity for introduction of new products, computer-aided design (CAD) has dramatically reduced product development times during the last decade (Figure 1, top). However, such design methodologies do not exist for the manufacturing system itself, and therefore its design time remains lengthy. Manufacturing system lead-time (i.e., the time to design and build or reconfigure the manufacturing system, and to ramp-up to full-volume, high-quality production) has now become the bottleneck.

Brief windows of opportunity can be captured, along with major economic savings, if the lead-time of manufacturing systems can be reduced. Reduced lead-time can be achieved through the rapid design of systems that are created from modular components, or by the reconfiguration of an existing manufacturing system to produce new products, as depicted in Figure 1, bottom [2]. In order to produce new products and accommodate required changes in existing products, new functions must be added to the manufacturing system through reconfiguration. This type of reconfiguration (i.e., adding manufacturing *functions*) is also needed for accommodating government regulations and integrating new process technology (such as new sensors, more reliable machine elements, etc.). Many reconfiguration periods will occur during the lifetime of the system. Short ramp-up (RU) becomes critical to successful reconfiguration.

A different type of reconfiguration is needed to cope with the large fluctuations in product demand and mix caused by the new market conditions. This type of reconfiguration requires rapid changes in the system production *capacity*, namely system scalability. In summary, a responsive system whose production capacity is adjustable to fluctuations in product demand, and whose functionality is adaptable to new products, is needed. Current manufacturing systems are not able to meet these requirements dictated by the new, competitive environment

2 TYPES OF MANUFACTURING SYSTEMS

Most manufacturing industries now use a portfolio of dedicated and flexible manufacturing systems to produce their products,

Dedicated manufacturing lines (DML), or transfer lines, are based on inexpensive fixed automation and produce a company's core products or parts at high volume (see Figure 2). Each dedicated line is typically designed to produce a single part (i.e., the line is rigid) at high production rate achieved by the operation of several tools simultaneously in machining stations (called "gang drilling"). When the product demand is high, the cost per part is relatively low. DMLs are cost effective as long as demand exceeds supply and they can operate at their full capacity. But with increasing pressure from global competition and over-capacity built worldwide, there may be situations in which dedicated lines do not operate at full capacity.

Flexible manufacturing systems (FMS) can produce a variety of products, with changeable volume and mix, on the same system. FMSs consist of expensive, general-purpose computer numerically controlled (CNC) machines and other programmable automation. Because of the single-tool operation of the CNC machines, the FMS throughput is lower than that of DML. The combination of high equipment cost and low throughput makes the cost per part relatively high. Therefore, the FMS production capacity is usually lower than

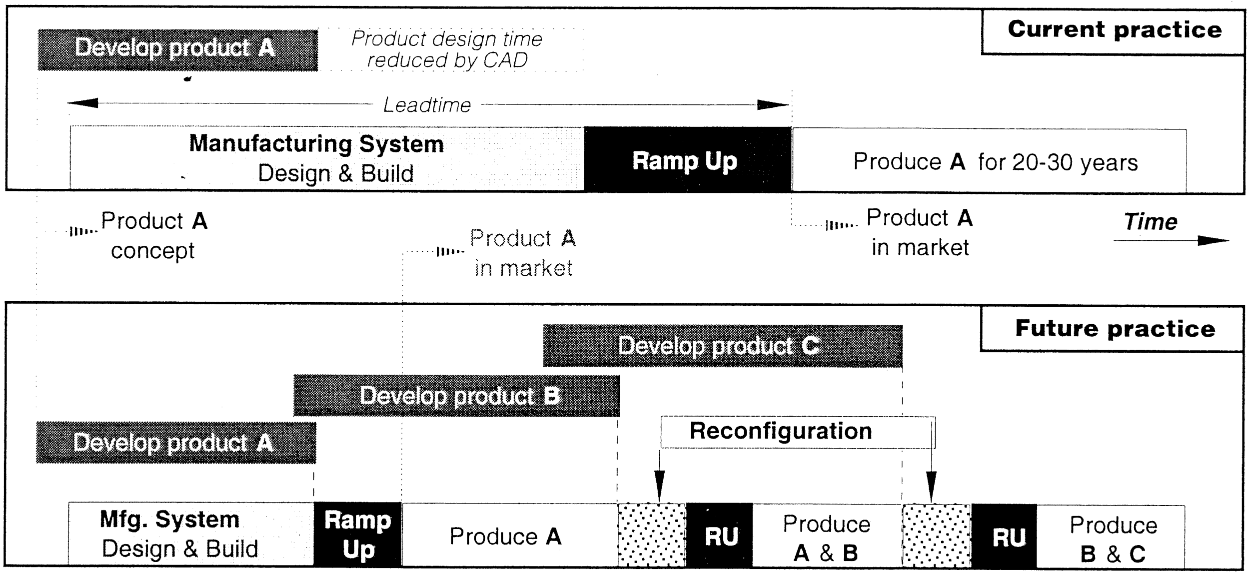


Figure 1: While product development time was reduced dramatically by CAD, nothing equivalent was done with the manufacturing system (top). Increase in frequency of new products introduction requires shortening the manufacturing system design time, and enabling its adaptation to production of new products through rapid reconfiguration.

that of dedicated lines and their initial cost is higher as depicted in Figure 2.

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

The challenge of coping with large fluctuations in product demand cannot be solved with dedicated lines that are not scalable. DMLs are not scalable because they are not designed for variable cycle times. Therefore, quite often, the available production capacity remains largely underutilized. A recent study carried out on a manufacturer of components for the car industry has shown that the average utilization of the transfer lines available was only 53% [3]. The reason for this low average utilization is that some products being in the early stages, or at the end of their life cycle are required in low volumes. Even products in the maturity phase do not always reach the production volumes forecast at the moment of the design of the Dedicated Manufacturing Line.

Conversely, this challenge is theoretically met by flexible manufacturing systems that are scalable when designed with multi-axis CNC machines that operate in parallel. Despite this advantage, however, a recent survey shows that flexible systems have not been widely adopted, and many of the manufacturers that bought FMSs are not pleased with their performance [4].

The high cost of FMS is one of the major reasons for the low level of acceptance or satisfaction with FMS. Why is FMS expensive? Unlike DML stations, CNC machines are not designed around the part. Rather, general-purpose CNCs are built before the manufacturer selects machines and before process planning is undertaken to adapt the machines and the process to the part. Since the specific application is not known to the machine builder, the flexible systems and machines are constructed with all possible functionality built in. This creates capital waste. It is also a common assumption that FMS should be able to produce (1) any part (within the machine envelope), (2) at any mix of parts, and (3) in any sequence. This approach increases cost since it *requires a parallel system structure for FMS* that utilizes high-power, general-purpose multi-axis CNCs with a very large tool magazine and multiple sets of tools — a very expensive solution.

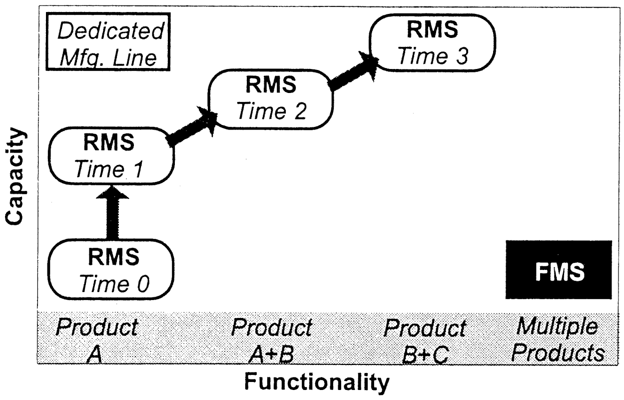


Figure 2: Both DML and FMS are static systems, while an RMS is a dynamic, evolving system.

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

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

As summarized in Table 2, a system with these features constitutes a new class of systems — a Reconfigurable Manufacturing System (RMS). The RMS is designed to cope with situations where both productivity and the ability of the system to react to change are of vital importance. Three

DML	FMS
Limitations: Not flexible *for a single part* Fixed capacity *not scalable*	Limitations: Expensive *machine focus* Low throughput *single-tool machines*
Advantages: Low cost Multi-tool operation	Advantages: Flexible Scalable

Table 1: Comparison between DML and FMS.

coordinates – **capacity, functionality, and cost** – define the difference between RMS and the traditional DML and FMS approaches. While DML and FMS are fixed in capacity-functionality, RMS capacity and functionality change over time as the system reacts to changing market circumstances (Figure 2).

	Dedicated	RMS/RMT	FMS/CNC
Machine Structure	Fixed	Adjustable	Fixed
System focus	Part	Part family	Machine
Scalability	No	Yes	Yes
Flexibility	No	Customized	General
Simult. Oper. Tool	Yes	Yes	No

Table 2: RMS combines features of dedicated and flexible systems.

Responsive systems are created by providing an adjustable structure, scalability, and flexibility (that although "customized," provides all the flexibility needed for the part family). Cost-effective systems are created by part-family focus and customized flexibility (rather than general flexibility) that enables the operation of simultaneous tools.

In the System-Cost vs. Capacity plane the DML is a constant at its maximum planned capacity, and then, for greater capacity, an additional, expensive line must be built. The FMS is scalable at a constant rate (adding machines in parallel), as depicted in Figure 3. The RMS is scalable, but at a non-constant rate that depends on the initial design of the RMS and market circumstances.

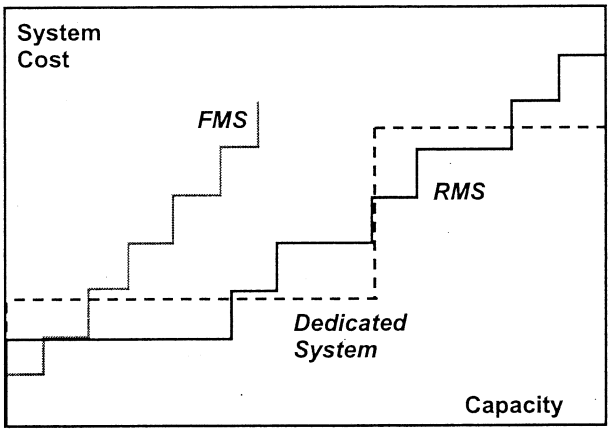


Figure 3: Manufacturing system cost versus capacity (or production rate).

The main components of RMS are CNC machines and Reconfigurable Machine Tools (RMTs) — a new type of modular machine with a changeable structure that allows adjustment of its resources (e.g., adding a second spindle unit). In addition to RMTs, also reconfigurable controls that can be rapidly changed and integrated in open-architecture environment are critical to the success of RMS.

The definition of a reconfigurable manufacturing system is, therefore, as follows

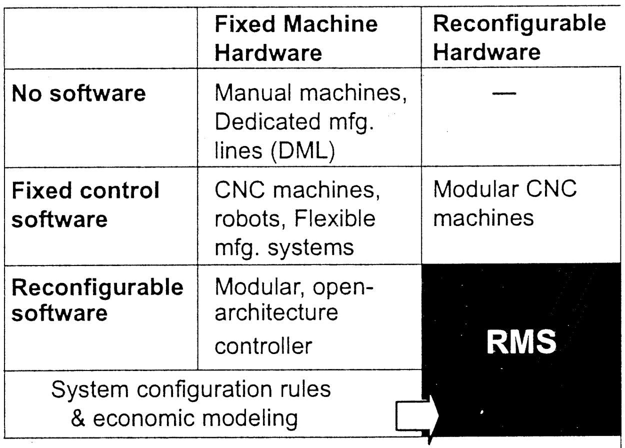
> **A Reconfigurable Manufacturing System (RMS) is designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements.**

If the system and its machines are not designed at the outset for reconfigurability, the reconfiguration process will prove lengthy and impractical. Systems designed for reconfigurability do not exist today, nor do their design and reconfiguration methodologies. However, many of the enabling technologies that are the cornerstones for reconfiguration do exist across the world.

3 TECHNOLOGIES ENABLING RECONFIGURATION

The common denominator for existing dedicated and flexible systems is their use of fixed hardware and fixed software. For example, only part programs can be changed on CNC machines, but not the software architecture or the control algorithms. Therefore, these systems, including CNC and FMS, are static systems and are not reconfigurable. Manufacturing systems designed at the outset for reconfigurability do not exist today. During the last few years, however, two technologies that are necessary enablers for reconfiguration have emerged: in software, modular, open-architecture controls that aim at allowing reconfiguration of the controller [5]; and in machine hardware, modular machine tools that aim at offering the customer more machine options [6]. These emerging technologies show a trend toward the design of systems with **reconfigurable hardware** and **reconfigurable software**, as depicted in Figure 4.

Reconfigurable hardware and software are necessary but not sufficient conditions for a true RMS. The core of the RMS paradigm is an approach to reconfiguration based **on system design combined with the simultaneous design of open-architecture reconfigurable controllers with reconfigurable modular machines** that can be designed by synthesis of motion modules. The ultimate goal of RMS is to utilize a systems approach in the design of the manufacturing process that allows simultaneous reconfiguration of (1) the entire system, (2) the machine hardware, and (3) the control software. The RMS paradigm will also create a new generation of reconfigurable machines that allow reconfigurations to achieve cost-effective scalability.



	Fixed Machine Hardware	**Reconfigurable Hardware**
No software	Manual machines, Dedicated mfg. lines (DML)	—
Fixed control software	CNC machines, robots, Flexible mfg. systems	Modular CNC machines
Reconfigurable software	Modular, open-architecture controller	**RMS**
System configuration rules & economic modeling		

Figure 4: Classes of manufacturing systems. RMS design not only combines reconfigurable hardware with reconfigurable software, but also includes systems perspective and economic modeling.

Unlike existing manufacturing systems that utilize fixed hardware and fixed software (e.g., CNC and FMS), the RMS will be designed through the use of reconfigurable hardware and software. With such design, the system **capacity and functionality** are not fixed but **change over time** in response to market demand, as shown in Figure 2. This new type of reconfigurable manufacturing system will allow flexibility not only in producing a variety of parts, but also in changing the system itself. Both the reconfigurable systems and the reconfigurable machines must be designed at the outset to be reconfigurable, and must be created by using basic hardware and software modules that can be integrated quickly through the use of designated interfaces.

To fulfil the requirements of an open, modular machine structure, the modules and their interfaces must be specified in a well-defined manner. When examining a self-contained machine module, three main interfaces can be identified: mechanical, power, and information or control interface (Figure 5). Only with the use of well-defined interfaces will

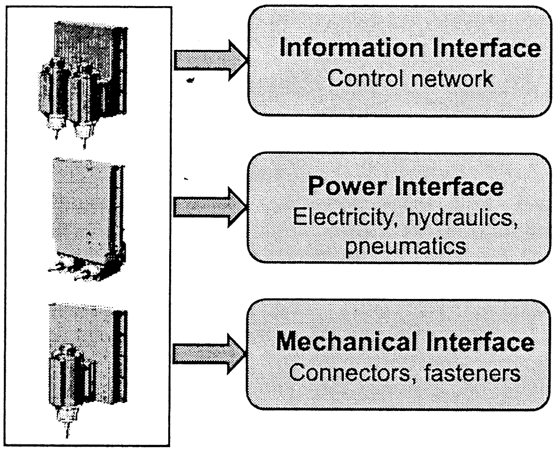


Figure 5: Interfaces for machine modules.

reconfigurable manufacturing systems become open-ended so they may be improved and upgraded rather than simply replaced.

Key Characteristics. Reconfigurable systems must be designed at the outset to be reconfigurable, and must be created by using hardware and software modules that can be integrated quickly and reliably; otherwise, the reconfiguration process will be both lengthy and impractical. Achieving this design goal requires a RMS that possesses the several key characteristics listed below.

Modularity. In a reconfigurable manufacturing system, all major components are modular (e.g., structural elements, axes, controls, software, and tooling).

Integrability. Machine and control modules are designed with interfaces for component integration. The integrated system performance is predicted based on a given performance of its components and the interfaces of both software and machine hardware modules.

Customization. This characteristic has two aspects: customized flexibility and customized control. Customized flexibility means that machines are built around parts of the family that are being manufactured and provide only the flexibility needed for those specific parts, thereby reducing cost. Customized control is achieved by integrating control modules with the aid of open-architecture technology, providing the exact control functions needed.

Convertibility. In a reconfigurable system the optimal operating mode is configured in batches that should be completed during one day, with short conversion times between batches. Conversion requires changing tools, part-programs, and fixtures, and also may require manual adjustment of passive degrees-of-freedom

Diagnosability. Detecting unacceptable part quality is critical in reducing ramp-up time in RMS. As production systems are made more reconfigurable and are modified more frequently, it becomes essential to rapidly tune the newly reconfigured system so that it produces quality parts.

Modularity, integrability, and diagnosability reduce the reconfiguration time and effort; customization and convertibility reduce cost. Therefore, these key RMS characteristics determine the ease and cost of reconfigurability of manufacturing systems. **A system that possesses these key characteristics has a high level of reconfigurability.**

We will discuss below the state of the art and later elaborate on methodologies aimed at achieving the objectives of

- system–level design for RMS,
- reconfigurable machine design,
- reconfigurable control design in open-architecture environment, and
- ramp-up time reduction for new and reconfigured systems.

4 STATE OF THE ART

Reconfigurable manufacturing is the latest development in the general field of computer-integrated manufacturing systems. One of the first firms to develop an integrated manufacturing system was Molins Company Ltd. In 1967 this company presented the "Molins System 24", a flexible and integrated system, developed by Mr. Williamson, showing a novel way to increase productivity. In this system the machining stations were linked by an automated handling system for workpieces fixed on pallets. Four years later, in 1971, Sundstrand developed the "Shuttle Car System", a rail-type pallet transfer system on which workpiece flow to and from the machining stations, located along the rail track. This system, however, was suitable only for long and variable machining times. At the Leipzig Spring Fair in 1972, Auerbach, a machine tool factory, presented the manufacturing system "M250/02 CNC". Equipped with two three-axis machining centers, three two-arm changers and one four-arm robot, this system enabled a five-face machining of prismatic parts. A central computer was used to control the machining centers, but the workpiece handling was handled manually from a central operator's station. In 1977 the development of Flexible Manufacturing system Complexes (FMC), a test-factory consisting of modular machining units and assembly robots for the production of a whole range of parts within a given envelope started in Tsukuba, Japan (see below). In the late 1970´s the development of Flexible Manufacturing Systems started, providing the possibility to produce small batches of many different parts using a single manufacturing system. Group-structured production cells linked with automated material handling systems emerged in the 80´s (e.g., by Max Müller and Fritz Werner). In the early 1990´s the idea of agile production systems has been pursued, enabling short changeover times between manufacturing different products. Since the mid-nineties the trend has been going towards Reconfigurable Manufacturing Systems, systems that are capable of being quickly adapted to changing market requirements by providing exactly the needed functionality and capacity at any time.

Advances in reconfigurable manufacturing will not occur without machine tools that have modular structures to provide the necessary characteristic for quick reconfiguration. However, the lack of machine tool design methodology and the lack of interfaces are the major barriers that impede modularity [1,7,8,9, 10, 11]. Reconfiguration seems increasingly difficult the closer one gets to the ironware side because hardware interfaces are much more difficult to realize than software or control interfaces. While the latter is more a standardization issue, the hardware interface issue is difficult because of its inherent technical complexity.

As to the hardware modularity issue, there are very few documented research projects described in the literature that tackle the problem in a generic way. Perhaps the first sizeable attempt to solve the problem, and still a landmark achievement, was the FMC (Flexible Manufacturing system Complex provided with laser) project [12] launched in 1977 by MITI in Japan, and culminating in 1983 in a test factory built in Tsukuba, Japan. Although the project was carried out a long time ago, the fundamental concept is still valid. Figure 6 shows the conceptual design of this complex machining mechanism composed of modular machine units and assembly robots. An example of modularized machining cell is also shown in the figure. The machine modules were stored in a warehouse and assembled to fit the product to be produced. Upon completion of production, the machines were to be disassembled into their modules and stored. Modular assembly of the plant was completely task-driven. The FMC system was meant to produce a whole range of prismatic parts within a given envelope.

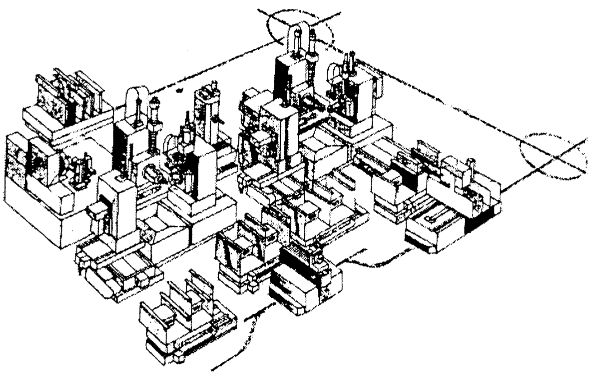


Figure 6: The FMC project in Japan.

Another large-scale initiative was launched by the European Union (EU) in the early nineties. Based on a European Commission-sponsored report [13] on the state and future of the European machine tool industry, it formulated a survival strategy for the European machine tool sector. The report asserts that, if machine tools were designed and built modularly, then machine tool builders could specialize in particular modules instead of in complete systems. System integrators would then build complete systems from the modules according to the specific needs of the users. This strategy requires splitting a machine tool into a set of autonomous functional units that can be plug-and-play interfaced to form complete systems for particular needs. Several European projects have been completed or are under development to achieve this goal. A few of them are discussed below.

The European MOSYN (Modular Synthesis of Advanced Machine Tools) project, lead by the Hannover University, looks at customer-specific configurations of modular machine tools. Another known project is KERNEL, which seeks to develop two different modular machine tools using equal-axis modules. The "Special Research Program 467" at Stuttgart University, supported by the German research foundation, focuses on transformable business structures for multi-variant serial production. A sub-project within SRP 467 was entitled Reconfigurable Machining Systems, and assigned the goal of developing the basis for the realization of capacity and functional reconfigurability of machining systems. This project attempted to enable short-term adaptability of machine tools' capacity and functionality to the quickly changing production situation caused by turbulent environments [14]. The use of equal modules for different machines (see example in Figure 7), and the design of interfaces, are important research issues in this project, as well as in another project entitled MOTION (Modular Technologies for Intelligent Motion Unit with Linear Motor and Axis Control) [15, 16].

In 1996 the Engineering Research Center of Reconfigurable Machining Systems (ERC/RmS) was founded at the University of Michigan by the National Science Foundation and 25 companies with the mission to develop the complete spectrum of RMS. The ERC/RmS has over 100 researchers that are developing RMS technology in three main areas. (1) Reduction of design lead-time of reconfigurable systems, (2) Design of reconfigurable machines and their reconfigurable controllers, and (3) Reduction of ramp-up time. The Center was awarded a patent for a reconfigurable machine tool [17]. The ERC/RmS takes a system perspective, not only in combining modular machines and controllers, but also in including the underlying methodologies for RMS design and operation. These include, for example, methods for system configuration analysis and design, economic modeling, synthesis of reconfigurable machine tools, and calibration and ramp-up of RMS. An experimental RMS testbed serves as the verification tool for the developed technology. The aim of the center is to develop a scientific base for reconfiguration of machining systems. The science base will be applicable to other manufacturing domains.

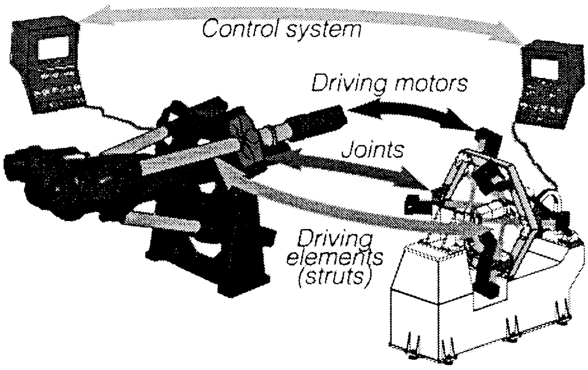


Figure 7: Exchangeability of Modules.

Reconfigurable Modular Manipulator System, a related research initiative developed at Carnegie Mellon University [18] consists of plug-and-play compatible modules that can be assembled in a large number of different configurations to tailor the kinematic and dynamic properties of the manipulator to the task at hand. A similar concept is the cellular robot developed in Japan [19] that consists of modules from which a complete robot can be assembled. Finally, some projects carried out in the framework of the international Intelligent Manufacturing Systems (IMS) initiative also deal with problems of modularity and reconfigurability [20].

The recent Delphi study, Visionary Manufacturing Challenges for 2020, conducted by the USA's National Research Council has identified reconfigurable manufacturing as first priority among "six grand challenges" for the future of manufacturing [21]. Various aspects of RMS are now under investigation by researchers across the USA (e.g., [22]).

Regarding issues of control, research efforts have been focused on open control architectures. On a global scale, the three most important initiatives in open architecture control systems are the EU project, OSACA, and its German successor, HÜMNOS; the Japanese initiative OSEC; and the North American OMAC-TEAM project [5]. With the goal of specifying reference architecture for control systems, the OSACA project (collaboration among Stuttgart University, Aachen University, and industry) started in 1992. The main outcome from the OSACA project is the object-oriented design and specification of a vendor-neutral open architecture for machine control systems. OMAC is an initiative driven by the desire to establish a set of application programming interfaces (APIs) to be used by vendors to sell controller products and services to the aerospace and automotive industries.

In addition to exhibiting openness, controllers of future reconfigurable machines will be distributed and heterogeneous. The above-mentioned projects have not explicitly taken these issues into consideration, although they allow control of heterogeneous, distributed processes to some extent. Worth mentioning in this respect is the EU-sponsored project HEDRA (Heterogeneous and Distributed Real-time Architecture) [23], which uses the real-time kernel VIRTUOSO. Also the MOTION project, mentioned above, tackles synchronization and interpolation issues when combining several intelligent single-degree-of-freedom linear motion control modules.

Several machine tool builders develop their current products as modularized systems to facilitate design and to offer customers a customized product at an affordable cost. Such modularized systems include horizontal and vertical turning centers, as well as transfer lines. However, designing a system with a combination of modules from different manufacturers requires standardization of the mechanical interfaces. Compared with the standardization of interfaces for information technology, such mechanical interfaces have not taken on an important effort to date [24]. A standardization of products across the range of manufacturers is advantageous for the use of the same modules for different machine tools, whereby machine quality can be improved, cost reduced, and reconfigurability of the machines enhanced.

To help assess the near-future (5–10 years) developments in manufacturing systems, a survey has been conducted by the UM ERC/RMS. In this study, experts in the field of manufacturing were asked to make predictions based on their knowledge of the manufacturing field, and to present the rationale behind their forecasts. This survey project has accomplished two main goals: (1) to examine the results to-date associated with the use of existing manufacturing systems, such as flexible machining systems; and (2) 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 identified key enabling technologies needed to realize these benefits. The results of this study have been documented in an ERC/RMS report [4]. The main conclusion of the report is that, to achieve the required responsiveness, manufacturing should be viewed, designed, and optimized as a system (as a whole). Existing major barriers to this achievement are the lack of available tools and methodologies to analyze the trade-off among processes, equipment, life-cycle costs, and initial investment.

5 SYSTEM-LEVEL DESIGN ISSUES IN RMS

Unpredictable, frequent market changes already characterize the environment of many manufacturing companies. Changing orders cause altering requirements concerning the output capacity and the processing functions of the manufacturing systems. Reconfigurable manufacturing systems meet these requirements by offering a rapid adaptability of both their capacity and functionality to the new situation. This adaptability feature of reconfigurable manufacturing systems also offers a short-term resetting of the manufacturing systems to produce different variants of the current products. Furthermore it provides system adaptability to new products and thereby guarantees a high long-term benefit-to-cost-ratio [2, 25].

Similar to flexible systems [26, 27, 28, 29] reconfigurable manufacturing systems are equipped with automated workpiece and tool supply. The structure of the supply systems influences significantly the productivity, part quality, and reliability of the reconfigurable manufacturing systems [30, 31].

Life-Cycle Economics. If we take into account the entire life-cycle cost of a production system in an uncertain market, reconfigurable systems can be less expensive than flexible manufacturing systems or even dedicated manufacturing lines. The main factor that makes the RMS less expensive is that **RMS is installed with precisely the production capacity and functionality needed** and may be upgraded, in capacity and functionality, in the future, **exactly when needed**. Expanded functionality enables the production of new parts of the same part family on the same system, which in turn expands the lifetime of the system. RMS allows one to add the extra capacity exactly when required, which solves the under-utilized capacity problem of dedicated lines. RMS also allows the additional functionality to be added exactly when needed which saves the investment for unneeded functionality associated with FMS. Thereby the two types of waste that occur in dedicated and flexible systems are eliminated with RMS technology.

Definition. A system configuration is defined as a set of machines (including controls) and the connections among them. Machines may be either given or composed of modules. The definition of the **system-level configuration task** is as follows:

> **Given: (a) a part or a part family, (b) volume and mix, (c) libraries containing (i) a fixed set of machine modules (each described by shape, interfaces, kinematics, and stiffness), (ii) constraints regarding the assembly of these modules and (iii) a fixed set of machines (each described by a set of kinematics, processes, etc.), and (d) constraints that describe the permitted sequences of processes on the part;**
>
> **Build configurations that specify all these requirements, or detect incompleteness in the given sets of machines or machine modules.**

The number of possible configurations is very large. An increased number of machines cause a combinatorial explosion of system configurations. For example, for six machines there are 54 possible configurations: a serial, a parallel and 52 hybrids (parallel-serial combinations). Each configuration has to be evaluated for throughput (function of reliability, machine speed, mix and desired volumes), part quality, and cost. This situation makes the consideration of alternative configurations extremely difficult. Simulation software and throughput analysis tools are widely used by industry to design manufacturing lines. However, these tools do not account for part quality issues. Hence, up front trade-offs between quality and throughput could not be done concurrently. Novel evaluation algorithms that enable a quick integrated throughput-quality analysis of configurations were introduced in [30]. These algorithms, however, solve each demand scenario as an independent case, and do not optimize the system during its entire lifetime for different configuration scenarios. Work is underway to calculate the optimal scalable system configuration.

Furthermore, conducting only economical evaluation is insufficient in many cases and the dynamics of the system must be also considered. Ranking alternative configurations may be also done by other criteria such as the ability to react to change, environmental impact, of compliance with production systems already installed in the company. The Analytical Hierarchical Process (AHP) methodology and the ELECTRE methodology have various means of weighting the various objectives [3]. In [32], multi-criteria genetic algorithms are used to optimise machine tool configurations at the conceptual stage. The optimisation criteria are static stiffness, dynamic stiffness, and workspace.

Modular Structure. Reconfigurable manufacturing systems need a modular structure to meet the requirements for changeability [33], which is provided by a modular system structure [34]. The primary goal in developing reconfigurable manufacturing systems is to develop machine modules, which can be quickly exchanged between different manufacturing systems. This exchangeability can be accomplished by equal structure of the machines and the control systems and the standardization of the interfaces combining the modules, which enables a short-term adaptability to market changes by reconfiguration of the manufacturing system.

To guarantee easy reconfigurability not only the physical system must be updated, but also the management and control software must take into account the new characteristics of the plant. This is needed to ensure the proper flow of materials, tools, and information. It is worth mentioning that one of the main reasons for the failure of the early FMSs was the rather problematic supervision of the system. In RMS the supervisory program must be adaptable to different system configuration. A project called OpenFront that is conducted at the ERC/RMS is developing control software to manage new plant reconfigurations [35].

One of the simple countermeasures to cope with changes in the production volume is to add or remove machine tools in the machining system. Figure 8 shows an example of construction of reconfigurable transfer line proposed and implemented by Toyoda Machine Works. The line includes five base kinds of modularized base machines with different capabilities in cutting performance. Each machine is equipped with an automatic tool changer. Toyoda claims that

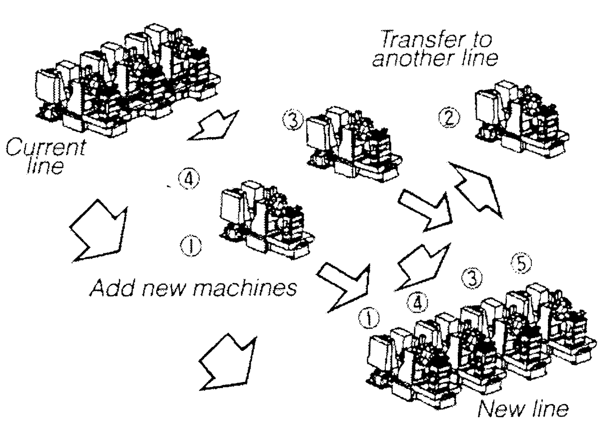


Figure 8: Exchangeability of modules.

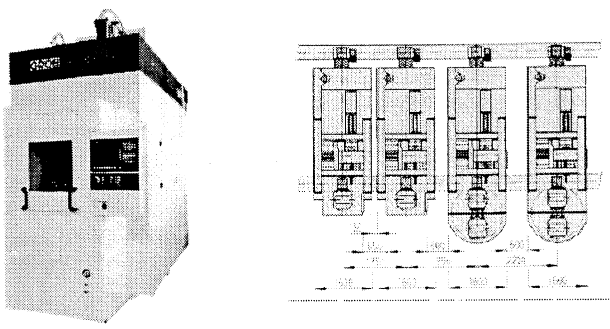


Figure 9: Machining centers as modules of a large machining system.

flexible and modularized work clamping jigs and work transport units are the keys to success of this type of reconfigurable machining line.

The influence of the modular structure on the reconfigurability of manufacturing systems depends on the choice of the module granularity. Thus, for example, machine tools can be used as modules in constructing a RMS similar to flexible manufacturing systems (Figure 9). There are also other examples for manufacturing systems, which are divided into different system levels to enable the exchangeability of modules between workpiece dependent subassemblies (spindle units, workpiece transport), standard subassemblies (machine column) and the basic machine.

The functions of a machining system can be classified as main and auxiliary functions. Main functions are located within the power flux of a machining process and can be divided into active and passive functions. Active main functions characterize the machining power and represent dynamic functions, e.g. positioning motions and cutting motions. Passive main functions characterize the behavior of the machine and represent functions such as tool or workpiece tracking and force bearing. Auxiliary functions, such as supply functions, chip removal etc., are located outside the power flux.

The rapid adaptability of reconfigurable manufacturing systems is possible by the use of mechanical modules, control modules, hydraulic and electric modules. Modules that can be exchanged and integrated represent a modular set. The realization of modular sets requires a standardization of the interfaces connecting the modules.

Interfaces. To realize reconfigurable manufacturing systems and their modularity, standardization of the module connecting interfaces is required. The choice of the module granularity specifies the type of interface. Interfaces can be divided into international, national and company-specific standardized interfaces. National and international tool and tool holding fixtures like hollow shanks are examples for existing standardized interfaces. Guiding profiles, indexing modules and clamping elements of pallet systems are also standardized, while drive elements and carrying devices are not, which handicaps the exchangeability of pallets between different systems.

The interfaces of a machining system can be subdivided into three types:

- The system-interface determines the connections between machining systems, needed to combine several machines to a manufacturing system. Appropriate interfaces prescribe the logistic connection and the connection to further machining systems. This type of interface is standardized in order to combine different systems.
- The module interfaces represent interfaces between singular modules. They are standardized in order to integrate modules of different manufacturers into a machining system.
- Submodule-interfaces determine the connections inside the modules and make it possible to assemble modules from sub-modules. This enables e.g. to combine different driving motors (sub-modules) with a spindle system (sub-modules) to generate different spindle-unit-modules (modules). The national or even international standardization of these interfaces is not useful as it might handicap the manufacturer's progress and innovation in developing modules.

To configure machining systems mainly the interfaces between the modules have to be considered. The configuration of single modules requires the consideration of the submodule interfaces, and the configuration of manufacturing systems necessitates the contemplation of system interfaces.

Interfaces can be divided into mechanical interfaces and interfaces for data, energy and auxiliary material transmission. Mechanical interfaces transmit forces and moments, align elements and fix them together. The other interfaces care for the component supply with required media. Mechanical interfaces can be specified to dynamic and fixed interfaces. Dynamic connections can be opened and closed with quick grippers used for tool fixtures like hollow shanks while fixed interfaces are used for connections only to be unlocked in case of system configuration.

6 RECONFIGURABLE MACHINE TOOLS

The two core engineering methods needed for machine-level design are (i) a method for systematic design of modular, reconfigurable machines, and (ii) design principles for open-architecture controller. The machine design method should utilize a library of machine modules each can provide a fundamental motion. This mathematical approach may generate new types of machines – reconfigurable machine tools (RMT).

In the case of machining systems, the reconfigurable machines should perform such processes as turning, milling, drilling and tapping, or combination of these processes. In the broader manufacturing case, combined processes, such as machining, heat treatment, assembly and metrology are to be considered. The discussions here, however, are basically limited to machining processes. The challenge in this case is to design an optimum reconfigurable machining system in terms of cost, productivity, part quality, and reconfiguration time.

The modular design of machine tools is a key enabling technology to reconfigurability, as the machining system can easily be reconfigured by simply removing, adding or changing the constituent units or modules of the system or the machine. The concept of modular design of machine tools is already well known. However, recent development of new machine hardware is opening new possibility to modular

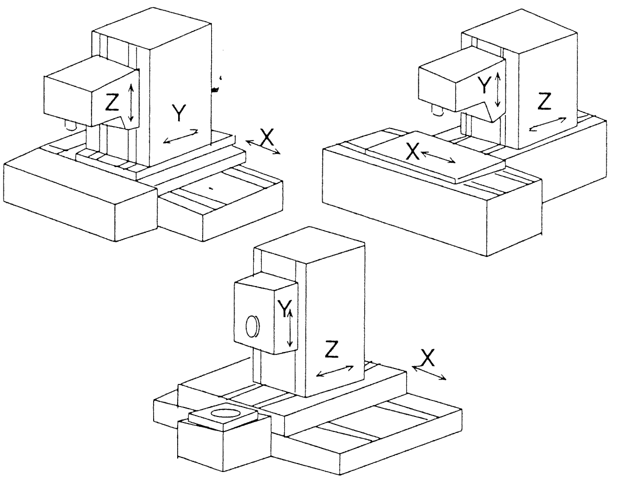


Figure 10: Modular machining centers.

design of machine tools. Figure 10 shows schematic illustration of typical 3-axis modular machining centers. The discussion here is basically focused on how to increase reconfigurability of this type of machine tools.

Variation of products. The primary aim of a reconfigurable machine tool (RMT) is to cope with various changes in the products or parts to be manufactured. The following possible changes must be taken into consideration:

(a) Workpiece size
(b) Part geometry and complexity
(c) Production volume and production rate
(d) Required processes
(e) Accuracy requirements in terms of geometrical accuracy, surface quality, etc.
(f) Material property, such as kind of material, hardness, etc.

Reconfigurability for workpiece size In order to cope with simple changes in the size of the workpiece, it will be enough to prepare machine units (modules), such as a column, table, spindle unit, etc. with different sizes. Reconfigurability is achieved by changing modules.

Reconfigurability for part geometry. In order to increase the machine functionality for geometrical complexity of the parts, the number of axes-of-motion is increased by adding new motion units or by replacing one of the units with one having several degrees of freedom. Figure 11 shows a schematic illustration of a possible reconfiguration of a 5-axis machining center. Some of the commercially available 5-axis machines are reconfigured by replacing a rotary worktable with a three-axis table, and the others by replacing the spindle head with a versatile spindle head unit.

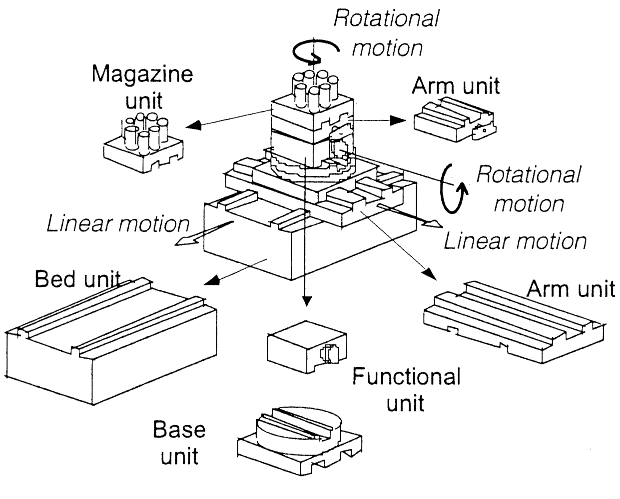


Figure 11: Assembly of modules for a rotary axis.

Reconfigurability for production volume and rate In order to increase production rate, the capacity of the machine spindle unit can be changed from single-spindle unit to dual or even multi-spindle unit. The multi-spindle unit is a very powerful tool to increase the productivity. Modularized spindle units with different speed range and horsepower are good examples of utilizing reconfigurable machine tools. An example of a reconfigurable machine tool is depicted in Figure 12, which shows a part mounted on a rotary table machined simultaneously with four spindles. The number of spindles may vary to accommodate the desired production rate. Each spindles is a module with Z axis. Two additional manual axes allow to adjust the location of the spindle and its cutting angle.

Reconfigurability for changes in machining process In order to cope with changes in the machining process, not only the cutting tool must be changed, but sometimes even the configuration of the machine tool must be changed as well. In some applications not only turning, but also milling and drilling operations can be performed on a turning center utilizing a milling spindle, which replaces the fixed tool post. The challenge is, however, adding for example a grinding unit to the turning center when needed. The machine in Figure 12 (a top view shown) may be converted to a vertical turning center, in which the part is machined with multiple tools that may perform drilling, milling, and turning operations.

Reconfigurability for machining accuracy RMTs consist of modules, each has its own interface. In such cases, the mechanical interfaces that are specified by geometrical features, have associated tolerances. The undesirable addition and/or superposition of tolerance fields can have a negative effect on the machine accuracy after reconfiguration. It is not easy to increase the machining accuracy by simply changing the machine modules with other modules of higher accuracy, as the machining accuracy is determined by the combined motions of the tool and the work and also by accuracy of the relative arrangement of the modules and their interfaces. The machining accuracy is also influenced by the static and dynamic rigidities of the machine, and the thermal deformation of the machine as well [36].

Parallel-Kinematics in Reconfigurable Manufacturing Systems. Parallel-kinematic machines may form a special class of reconfigurable machine tools. They can be categorized into different classes depending on the type of their strut- i.e. those with constant length and those with variable length – and on their drive design such as linear drives, ball screw drives and rack-pinion drives [37]. An exhaustive analysis of the fundamental technical principles of existing parallel-kinematic machines and/or prototypes has been presented in [38,39,40].

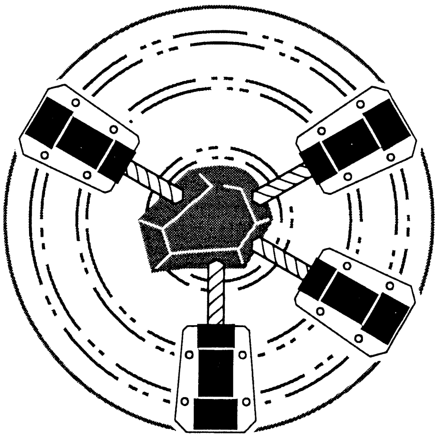


Figure 12: Top view of a vertical turning-milling center with multiple spindles.

Most parallel-kinematics machines are realized as tripod or hexapod systems, which differ, by the number, the specification and configuration of its struts. The characteristics of these kinematics result from their low moved masses and the high strut stiffness [24]. As these machines consist of simple and identical modules [41]. It is possible to configure different machines from these modules.

The use of many equal modules implies the standardization of drive elements, joints and module interfaces. As a result struts, joints and drives become exchangeable between systems of different configuration, which enables the design of singular reconfigurable manufacturing modules. These parallel-kinematic machines can be used as particular modules in transfer lines for the machining of cylinder blocks with automated workpiece flow and as stand-alone C-styled or portal styled laser centers for the machining of sheet metal (Figure 13). It is also possible to realize flexible manufacturing systems for additive machining with this type of kinematics.

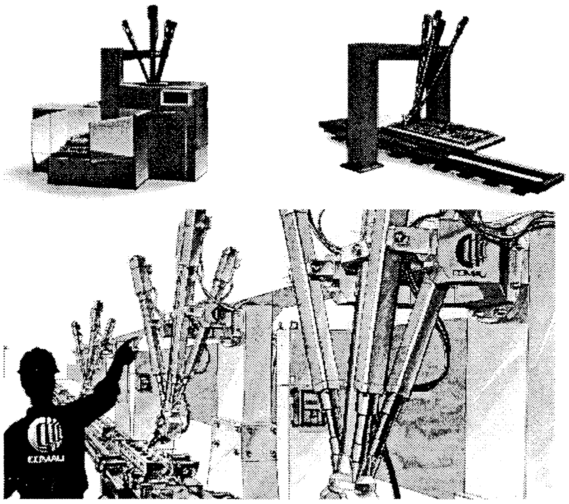


Figure 13: Tripod-kinematic machines integrated into a machining line

Challenges The concept of modular design of a machine tool is not new, but it has not been widely adopted in practical use so far. The main problems with modular and reconfigurable design are as follows:

(1) Design Methodology for RMT: The development of a mathematical framework for synthesis of reconfigurable machine tools (RMTs) and their validation is a major challenge. The Engineering Research Center at the University of Michigan is developing a mathematical theory for synthesis of RMTs, which includes [42]:

- Development of a formal and a unified representation scheme for mechanical (kinematic, and structural) functions of modules.
- Compilation of a library of machine modules (see Figure 14).
- A methodology for systematic synthesis of reconfigurable machine tools using screw theory for kinematics (see Figure 14) and graph theory structural synthesis.

(2) Interfaces: It is not so easy to assemble the machine modular accurately enough to meet the accuracy requirements of the machine tool. The interfaces between the modules to be assembled must be standardized and accurately manufactured. Methodologies must also be developed to rapidly measure and adjust the alignment of the modules. Reduction of the static and dynamic rigidities at the interface is also a problem to be solved.

(3) Module Autonomy: Most of the movable and drive units are supplied with electricity and are connected with the controller by wires. Some of them also require hydraulics and compressed air (see Figure 5 above). The wiring and piping with the external energy sources are a nuisance. The location of hydraulic pumps, compressors and accumulators can be an obstacle for reconfiguration of the machine units. It is desirable that each module should be autonomous and independently workable.

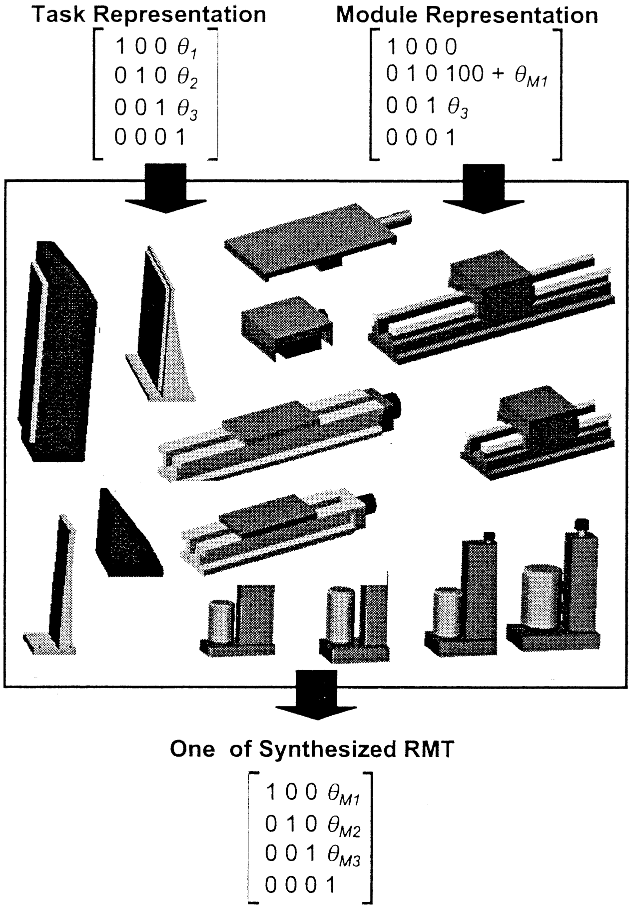


Figure 14: The process of a formal design method for RMTs.

In conclusion, to cope with the changes in product variation and volume the machining systems and the machine tools have been replaced or new machine tools have been introduced in the past. It is no more cost effective to do so, as the changing cycle is becoming shorter and the variations larger. The modularized machines and machine modules are expected to solve this problem by reconfiguring the machining system and machine tools. Effective utilization or re-use of modularized machine tools and machine units also contribute to sustainable society.

7 CONTROL FOR RECONFIGURABLE MACHINES IN OPEN ARCHITECTURE

Similarly to building a library of machine modules, controller software components (e.g., servo control algorithms, temperature control algorithms, interpolators, etc.) are also catalogued and stored for re-use. The modules needed for the application are selected, and then configured by a method termed a "Control Configurator" that aids in integrating the controller for the selected machine (both continuous and discrete control), and automatically checks its real-time constraints. Finally the reconfigurable controller has to be implemented as an open-architecture control.

The modular design of the machine components directly influences the requirements for the corresponding control equipment. In order to support the modular construction of reconfigurable machines, the control system itself must be designed according to the principles of an open architecture. IEEE defines this as "an open system provides capabilities that enable properly implemented applications to run

Capability	Meaning	Hardware options	Software options
Modular	decentralized structures are supported	Standardized and distributed comm. systems	distributed appl. modules
Interoperable	components can cooperate		standardized data exchange
Portable	integr. of components in diff. environments		standardized API
Scalable	increased performance, topology can be modified	processor upgrade	parallel software tasks
Extendable	functionality can be enhanced	additional plug-in cards	addtl. application modules

Figure 15: Capabilities of a control system for reconfigurable machines.

on a wide variety of platforms from multiple vendors, interoperate with other system applications, and present a consistent style of interaction with the user" [43]. The controller openness is the enabling technology needed to integrate, extend, replace and reuse hardware and software components in a control system even after its installation at the shop floor (Figure 15).

Due to the nature of hardware there is only limited flexibility in reconfiguring the mechanical or electrical parts of a machine. Manual manipulation is required to modify an existing structure to a new configuration. This is different for the software-oriented components of the control. The immaterial nature of software allows the modification of functionality in a very dynamic way.

To obtain the maximum integration flexibility, reuse and distribution of software modules must be achieved. A neutral **system platform** which is independent from specific applications and which can be easily adapted to a specific hardware is indispensable to fulfil these requirements [44]. The system platform encapsulates all specific parts of a control system in order to provide a neutral interface to the application software. The system platform is based on electronic equipment such as computer boards, plug-in cards or intelligent I/O nodes connected via control networks. On top of the platform is located the system software which provides the functionality needed to support openness for the application software.

From the required capabilities for application modules the basic functionality of the system software can be derived (Figure 16). The desired portability of AM's leads to the need for the definition of a uniform application program interface (API) to access the system platform. This enables modules to be placed on any system platform that offers the API. This makes it also possible to change a certain configuration by repositioning a module in the system and by this modifying a given topology. It implicitly demands that the system software has to shield the application software completely from the system hardware.

The system software for an open control system defined as above has to contain at least three components:

(i) an operating system, or run-time system, to execute modules,
(ii) a configuration system to combine modules into a running system at boot-up of the control, and
(iii) a communication system to enable information interchange between modules on the basis of a standardized protocol.

Issues related to real-time limitations caused by the communications network bandwidth are discussed in [45].

Although combined control components on the physical level depends on the control system platforms (Figure 16 right), the platform looks transparent to the user, since a set of uniform APIs is provided for the **application software**. The API hides all the hardware aspects and offers one homogeneous system platform even in distributed control systems. Examples of such system platforms are CORBA of the Object Management Group (OMG) and DCOM of Microsoft. As these commercial platforms have no dedicated real-time capabilities they cannot directly be used as platforms for machine- and process-related control software. For this reason, a specific system platform was designed and implemented by the European OSACA initiative [46]. This software can be very easily ported to different operating systems and also supports real-time features. The software was already ported to various operating systems including the MS-Windows family, several real-time operating systems (such as OS-9 and VxWorks) and different UNIX derivatives. For the physical coupling of distributed platforms a wide range of communication standards (such as Sercos, Profibus, Ethernet) are available.

Using the above described principles of a control system platform with a system-independent API, application software can be designed and implemented in a very modular and flexible way. In order to support a concurrent design of the machine and the related control software it is helpful that the software modules correspond to the components of the machine. In terms of object-oriented principles it means that a machine object corresponds to a controller object offering the control functionality of the machine object (see Figure 17).

Control software elements are deposited in a module library. They are capsulated into independent units that contain both

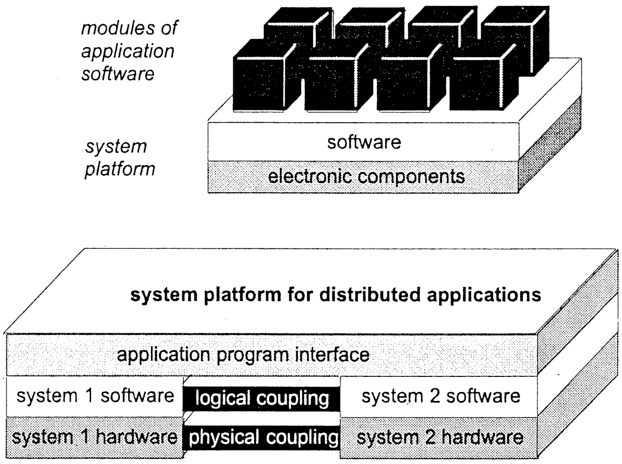


Figure 16: Structure of the system platform (top) of an open controller architecture (bottom).

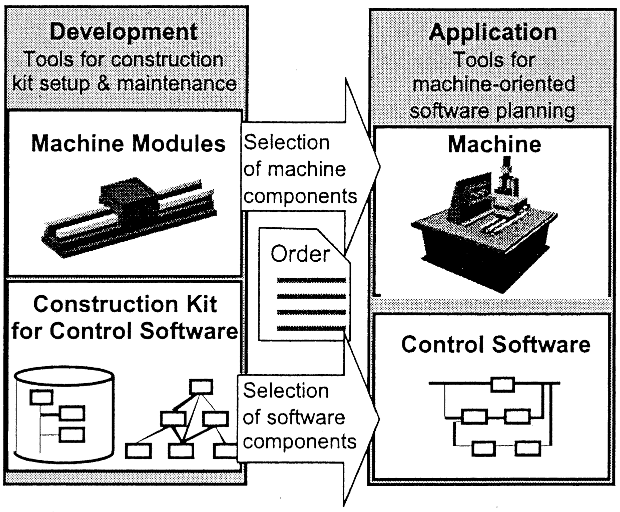


Figure 17: Concurrent Engineering of Structure of Machine and Control Software

structural and functional information. This causes a high reusability of the modules.

Based on this library, new configurations are generated by selecting the modules into a project and by associating the provided communication interfaces with each other. Automatic testing mechanisms prevent the generation of faulty configurations.

After the termination of the configuration process, the target code for the control is generated. This can be carried out according to vendor-neutral or vendor-specific formats and can cover PLC and NC code.

Using a graphical configuration tool reduces the time for creating a control configuration by using libraries and building plans. Software can thus be produced at lower cost. At the same time the quality of the software increases because of its integrated testing mechanisms and for being based on models. First prototypes of such configuration tools have been designed and developed within the German projects MOWIMA and HÜMNOS [47].

8 SYSTEM RAMP-UP

Ramp-up time reduction is a critical objective for responding to short windows of opportunity for new products as well as for scaling systems to cope with changing demand. Ramp-up period is defined as

> **The period of time it takes a newly introduced or reconfigured manufacturing system to reach sustainable, long-term levels of production in terms of throughput and part quality, considering the impact of equipment and labor on productivity.**

Since the RMS paradigm calls for high frequency of system changes to accommodate production of new products, rapid ramp-up of a manufacturing system after installation and especially after reconfiguration is essential to the success of RMS. Systematic methodologies for root-cause analysis of part quality problems combined with rapid methods for on-line part inspection are the key for a rapid ramp-up.

Achieving the objective of ramp-up time reduction requires diagnostics and ramp-up methodologies, at both the system and machine levels. As production systems are made more reconfigurable, and their functionality and layouts are modified more frequently (see Figure 1), it becomes essential to rapidly tune the newly reconfigured system so that it produces quality parts. If ramp-up is not done quickly, the reconfiguration advantage is lost.

The reason for the possibility of getting deteriorated quality parts after reconfiguration is that reconfigurable machines are mostly designed on the basis of modularized systems whereby each of the individual modules has its own interfaces [24]. Therefore, it is imperative to perform diagnostics of the reconfigured system after assembly, and perform the subsequent error calibration and compensation of the system. Consequently, reconfigurable systems must be designed with product quality measurement systems as an integral part.

The basic engineering steps required are summarized in Figure 18. 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 the sources for a fault or a part quality problem. Ideally, the sole cause or source for errors should be identified. The compensation step, either automatically or through operator intervention, enables corrective action to be taken (e.g., calibration, adjustment of operating parameters, maintenance).

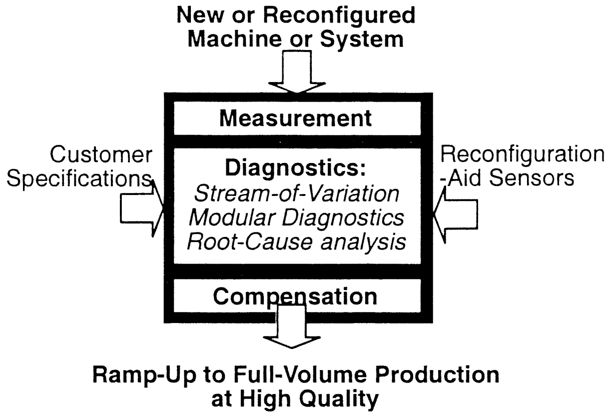


Figure 18: Ramp-up process of RMS.

In order to guarantee short system ramp up after each reconfiguration, it is necessary to measure product features or process variables that must be selected step by step on the basis of the specific problem and situation on hand. To reach this goal it is necessary to have both reconfigurable sensors and inspection devices and appropriate quality control and reliability tools that help in defining where inspection points must be introduced and which sampling strategy should be applied.

The measurement systems of RMS 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. Because of the complex structures of reconfigurable systems, many conventional techniques, such as for example laser interferometry for the determination of tolerances, are no longer suitable. Consequently, research is currently being undertaken in relation to the suitability of 3-D measurement systems that can measure part and product dimensions in-process [47]. These systems can be subdivided into mechanical (e.g., triangulation or articulated arm with a probe), optical (e.g., interferometry), and ultrasonic systems.

The comparative tests using the different 3-D measurement systems relative to the results from the coordinate measuring machine yielded results having significant deviation. Thus the practical application of commercial systems has to date been technically unsatisfactory and on account of the high investment costs renders the systems non-economical. Within the framework of new research and development work, improved methods for the calibration and error compensation are being sought. In Germany, close cooperation between industry and the universities is taking place within the contact of the ACCOMAT Project, as depicted in Figure 19 [48]. The principle of operation of the measurement system is based on a technique well known in navigational engineering and utilizes an intelligent tooling system in which

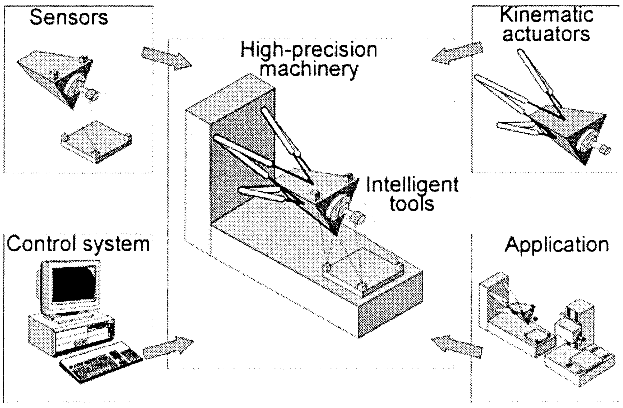


Figure 19: ACCOMAT system for 3-D measurement

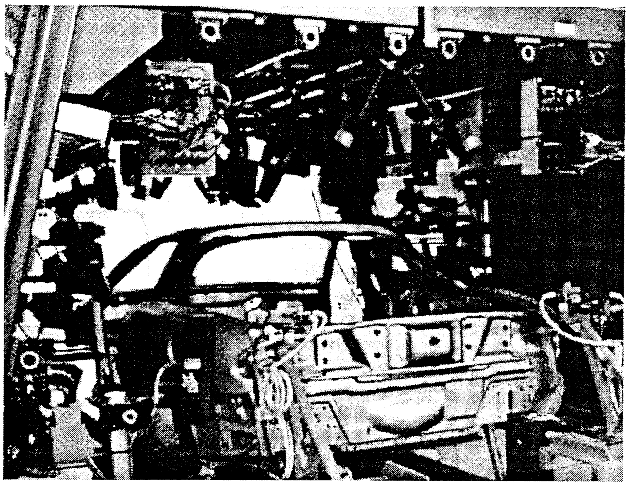


Figure 20: Optical measurement of automotive body dimensions using laser triangulation sensors to achieve detection and isolation of faults.

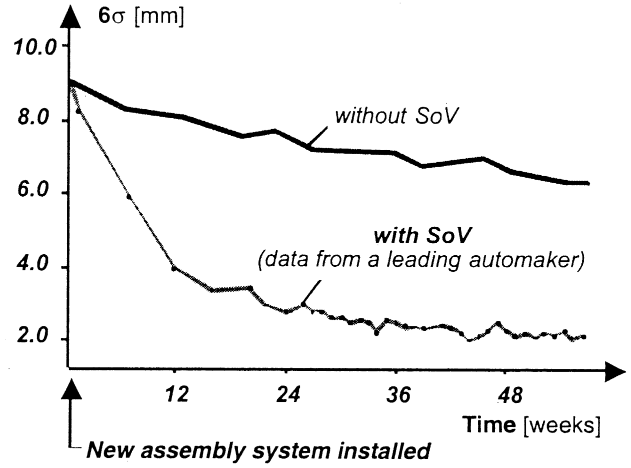


Figure 21: Results showing ramp-up time reduction in automotive assembly.

the sensor and pictuation elements are integrated for its calibration.

Example of System Ramp-Up. Figure 20 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 21 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 Figure 18 with the Stream-of-Variations theory [49]. Note that both the reduction in variation is rapid, and the final level of variation is low.

The Stream-of-Variation (SoV) methodology combines engineering process models with statistical analysis to account for how product dimensional variations accumulate as the product moves through a manufacturing system. It can be used, with appropriately selected and placed sensors, to diagnose the root causes of the dimensional errors in the production system. This is schematically illustrated in Figure 22 for an automotive body assembly process [49]:

- Obtain measurement data for a set of bodies and calculate the standard deviations of all measurement points.
- Group all the measurement points according to the six sigma threshold, Tv (e.g., 2.0 mm).
- Calculate the correlation matrix for the group of measurement points with six sigma larger than Tv.
- Use clustering analysis to divide the measurement points into subgroups. Each group forms a case study (i.e., potential problem). The location of the process fault is in the assembly station that is one level higher in the hierarchy and has the above grouped component as input.

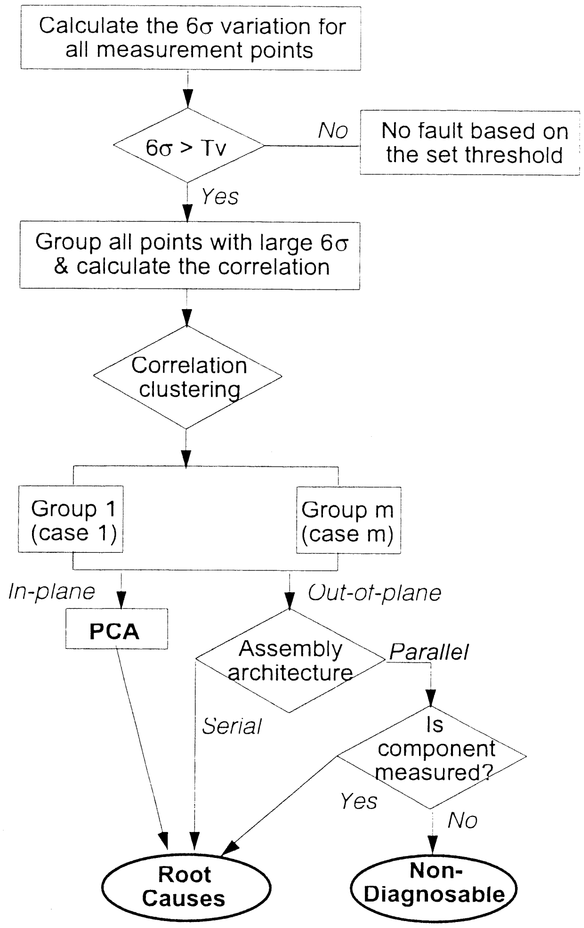


Figure 22: A flow-chart of the stream-of-variations methodology.

- Perform principal component analysis for grouped measurements that have variation in the in-plane direction. Display eigenvectors to animate variation patterns for purposes of visualization. If the grouped measurements have variation in the out-of-plane direction, identify assembly architecture (i.e., serial vs. parallel). Serial assembly is fully diagnosable, while parallel assembly requires additional measurement to be diagnosable.

Using this methodology, fault stations and root causes of variation can be systematically identified. This strategy has been applied to reduce variation, and to shorten launch time, in many automotive assembly plants. A typical result, from actual automotive body production, has already been illustrated in Figure 21.

9 CONCLUSIONS

Global economic competition and rapid social and technological changes have forced manufacturers to face a new economic objective: **manufacturing responsiveness** (i.e., adaptation of the manufacturing system to market conditions). To respond to these challenges a new type of manufacturing system, a Reconfigurable Manufacturing System, is needed. RMSs are quite different than the current manufacturing technologies (i.e., dedicated manufacturing lines and flexible manufacturing systems) in that they are designed at the outset with adjustable resources in order to provide exactly the capacity and functionality that are needed, exactly when needed.

Design for Reconfigurability is recently emerging as an important new trend in designing manufacturing systems. Therefore, reconfigurable manufacturing is a broad area that continues to attract multi-disciplinary talents for its development. Some of its research topics include:

- Life-cycle economic modeling of manufacturing systems, to determine the product-demand range in which RMS is the optimal choice.
- Automatic generation of system configurations and their impact on throughput, part quality and cost that leads to the establishment of configuration theory.
- Optimal scalability of configurations for demand scenarios
- Ramp-up methodology for changing configurations at both the machine level and the system level.
- Reconfiguration of monitoring and information systems in RMS environment.
- Reconfigurable controls for large systems in open-architecture environment
- Methodology to generate reconfigurable machines for given manufacturing tasks..
- Relationships between machine builders and users of reconfigurable systems.
- Benefits of reconfigurable systems to society and their impact on job creation.

The industrialized world is faced with the challenge of maintaining its high quality of life and welfare despite global economic competition. A competitive manufacturing industry is required to keep jobs and generate new ones directly, and, through induced services indirectly. To contribute to sustainability, the manufacturing industry must move towards a closed and optimized life cycle of products and related processes [50]. This, in turn, should evolve following the change in economical, social and technological context, thus achieving sustainability [51]. RMS, hence, may be seen as a methodology for achieving process sustainability at two different levels: (1) tactical level, to respond to turbulence of the demand, internal and external change, and (2) strategic level, to account for market evolution.

Competition was indeed mainly based on the ability to optimize the technological solution for a given context. In recent years, however, the context has become more and more turbulent: society has new needs in rapid evolution, economy is deeply affected by the evolution toward globalization, and technology exhibits an exponential growth. Given such turbulence, competition is more and more based on the ability to quickly adapt to change.

Therefore the emphasis is no longer placed on the optimization of the technological solution in a static way, but on the dynamical problem of continuously adapting the technological solution at low cost. Reconfigurable manufacturing systems can represent one of the cornerstones of this strategy.

10 ACKNOWLEDGMENTS

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