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Publisher's version / Version de l'éditeur:
https://doi.org/10.1080/00207540600905646
International Journal of Production Research, 46, 4, pp. 967-992, 2007-05-17

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IMTI-XP-530

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May 2007

A version of this document is published in / Une version de ce document se trouve dans:
International Journal of Production Research, 46, (4), pp. 967-992, May 17, 2007, DOI: 10.1080/00207540600905646

Reconfigurable Manufacturing Systems: The State of The Art

Keywords: Reconfigurable Manufacturing Systems (RMS),
system architecture, system configuration, Open Architecture Control (OAC),
reconfigurability, modularity

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Reconfigurable Manufacturing Systems: The State of The Art

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Abstract: In this paper, general requirements of next generation manufacturing systems are discussed, and the strategies to meet these requirements are considered. The production paradigms which apply these strategies are also classified. Particular emphasis is put on the paradigm of Reconfigurable Manufacturing System (RMS). Some key issues of the RMS design are discussed, and a critical review is presented concerning the developments of RMSs. Finally, suggestions of the RMS research are made and future research directions are identified.

Keywords: Reconfigurable Manufacturing Systems (RMS),
system architecture, system configuration, Open Architecture Control (OAC),
reconfigurability, modularity

1. Introduction

Due to excessive production capability and economic globalization, the manufacturing environment becomes turbulent and uncertain. Manufacturing enterprises are forced to reassess their production paradigms, so that a manufacturing system can be designed and operated efficiently in the ever-changing environment. Many production paradigms have been proposed, but for the near future, it is unlikely to be feasible for a manufacturing system to change its paradigm at will. The confusions and controversies are often raised among the readers to understand and adopt new production paradigms. For example, at the 3rd Conference on Reconfigurable Manufacturing held at the University of Michigan during May 10-12, 2005, the attendees have had a controversy about the definition of RMS. Some insist that an RMS is an intermediate paradigm between Mass Production and Flexible Manufacturing System (FMS), some argue that an RMS is an advanced paradigm whose flexibility must be higher than that of an FMS, and the others think it is not very meaningful to distinguish RMSs from FMSs.

In this paper, a critical review is conducted on the RMSs and relevant technologies. In section 2, the characteristics of the current manufacturing environment are overviewed, and the key requirements for new generation manufacturing systems are described. In section 3, general strategies to meet these requirements are proposed. Popular production paradigms are reviewed and classified. Taxonomy of these production paradigms is provided to illustrate their overlapping and differences. In section 4, the paradigm of the RMS is put the emphasis on. The definition of an RMS is discussed. Three critical issues, which are involved in design and control of the RMSs, are revealed. In sections 5 to 7, the solutions to these issues are investigated. In section 8, a summary is provided and the paper is concluded with some identified future research directions.

2. Requirements of Manufacturing Environment

A manufacturing system transforms raw materials into products. Its ultimate objective is to gain value such as profit, reputation, and market share. An enterprise can survive only if this objective is achieved appropriately. Manufacturing environment has a great impact on the performance of a manufacturing system. Current environment has some critical requirements for a manufacturing system (Ishii et al. 1995, NRC 1998, Stake 1999, and NRC 2000). These requirements are briefly summarized as follows

(i) Short lead-time. Product lead-time affects the performance of a manufacturing system in different ways (Smith and Reinertsen 1997): 1) if a product is introduced early, it is an advantage over the competitors since their lag in matching or surpassing is larger; 2) early product introduction increases peak sales. The earlier a product is made, the better its prospect is for obtaining and retaining a large share of the market; 3) a new product brings a higher profit margin.

(ii) More variants. Products become versatile and customerized. Versatility implies a product needs more components for additional functions and features. Customerization means a product has options for individual tastes (Tseng and Du 1998, Fralix 2001). A manufacturing system is forced to produce more product variants to meet fragmented, sophisticated and personalized needs.

(iii) Low and fluctuating volumes. The required volumes of many products are falling since: 1) the limited market niches are shared by global competitors; 2) the life cycle of a new product becomes shorter and the durability of the product becomes longer. Different-generation products exist on the market at the same time; and 3) product customization has fragmented the entire market demands into small portions.

(iv) Low price. The product price is a primary feature to most of the customers. On the one hand, the globalized market offers customers with more windows to purchase low-price products with the same quality and service. On the other hand, the price is heavily time-dependent, and the price margin can be reached its limit very soon after the product is introduced into the market.

Many other requirements, such as quality and durability, are not discussed here since the customers tend to regard them as essential features of a product. The aforementioned requirements have a significant impact on the best choice of production paradigms.

3. General Strategies to Meet Requirements

A good understanding of a manufacturing system can help to identify general strategies to meet the requirements. A manufacturing system can be modeled from different perspectives (AMICE 1988, Kosanke et al. 1999, Krause and Jansen 1996). As shown in Figure 1, a manufacturing system is modeled in terms of direct manufacturing activities. The meanings of shapes and abbreviations have been explained in the figure. A manufacturing system is functioned to meet customers' requirements (*R*) by producing required products (*P*). A final product will be an assembly of a set of basic parts. Manufacturing activities include '*design*', '*manufacturing*', and '*assembly*' (Boothroyd et al. 1994). 'Design' is to define system components and their assemblies based on customers' requirements, 'manufacturing' is to fabricate basic parts, and 'assembly' is to put all basic parts together to create final products for customers. Both of the hardware and control resources are required in accomplishing these activities. Hardware resources refer to the resources involved in "process" flow and the control resources refer to the resources involved in "information" flow (Williams 1998). A computer model of the manufacturing system is needed for design and simulation of a hardware system. Efforts can be made at all of the domains of a manufacturing system to meet the manufacturing requirements.

*<Insert **Figure 1** here>*

3.1. Strategies to reduce lead-time

Product lead-time has been defined in different ways. Here, lead-time refers to the amount of time required to meet a customer's order. Product lead-time is the time spending in direct production activities. As shown in Figure 2, three strategies can be applied to reduce lead-time. (1) To reduce or eliminate indirect activities such as transferring and buffering. In particular, the customer's order needs to be processed as early as possible. (2) To reduce time for direct activities by increasing system capacity and reducing system ramp-up time. (3) To operate the system concurrently. Manufacturing activities are overlapped with each other, so that they can be finished with a minimized delay.

<*Insert **Figure 2** here*>

3.2. Strategies to increase variants

A product is normally assembled from a set of basic parts. A product can be varied by using different types of parts and/or different assemblies. As shown in Figure 3, efforts can be made in manufacturing and assembling basic parts. (1) To optimize a product platform. Manufacturing and assembling activities can be well balanced, and the resources involved in manufacturing and assembly processes are utilized efficiently. (2) To increase variants or versatility of manufacturing resources. More variants of the parts can be manufactured. (3) To increase variants or versatility of assembly resources. More variants of assemblies can be implemented.

<*Insert **Figure 3** here*>

3.3. Strategies to deal with low and fluctuated volume

Product platform is a set of subsystems and interfaces that form a common structure from which a stream of related products can be efficiently developed and produced (McGrath 1995). A good product platform may reduce system sensitivity to change on product volume; but the change of the product volume has a great impact on the required manufacturing capability. As shown in Figure 4, the following strategies could be applied in dealing with low and fluctuating volumes. (1) To modularize the product platform. Basic parts are interchangeable in the same product family, so that the demands of the products of the same family can be maintained even if the volumes of some specific products are reduced. (2) To change manufacturing or assembly resources dynamically. These resources could be reconfigured to adapt new products.

<*Insert **Figure 4** here*>

3.4. Strategies to reduce the cost

The ways in which activities are organized and resources have an impact on the cost. As shown in Figure 5, the strategies to reduce the cost include: (1) to reduce or eliminate the cost caused by indirect activities; (2) to reduce the cost caused by direct activities; (3) to reduce the cost by system integration. Moreover, the increase of the market return can alleviate the cost burden. The strategies to increase the market return are also summarized in Figure 5.

*<Insert **Figure 5** here>*

3.5. Taxonomy of production paradigms

Figure 6 provides taxonomy of production paradigms. It consists of four layers. At the first layer, four key manufacturing requirements are listed. At the second layer, the strategies for meeting these requirements, which have been discussed in sections 3.1-3.4, are shown. At the third layer, the domains of a manufacturing system, where the strategies are applied, are illustrated. At the fourth layer, various production paradigms are classified in terms of the applied strategies and domains.

*<Insert **Figure 6** here>*

Taxonomy includes the production paradigms of Lean Production (Womack et al. 1991), Just In Time (O'Grady 1988), Agile Manufacturing (Goldman and Preiss 1992, Dove 1995, Yusuf et al. 1999, Sanchez and Nagi 2001, Correa 2001), Virtual Enterprise (Camarinha-Matos et al. 1998, Katzy and Dissel 2001), Global Manufacturing (Taylor 1997), Concurrent Engineering (Prasad 1996, Shen et al. 2001), Computer Integrated Manufacturing System (Warendorf and Merchant 1986, AMICE 1988, Gunasekaran 1997, Kosanke et al. 1999), Flexible Manufacturing System (Babic 1999), Reconfigurable Manufacturing System (Aronson 1997, Koren et al. 1999), Mass Customization (Tseng and Du 1998, Fralix 2001, Davis 1987, Pine II 1992, Mckinsey 2002, Boer and Jobane 2002), Make-To-Stock (Gupta and Benjaafar 2004), Total Quality Management (Oakland 1993), Make-To-Order, Engineer-To-Order, and Assembly-To-Order (Wortmann et al. 1997).

Some paradigms, such as Reconfigurable Manufacturing System and Lean Production, can meet the requirements in different ways since their implementations fit in different strategies. Moreover, it is very difficult to tell that one paradigm is better than another without the consideration of unique situation of a specific enterprise. All of these production paradigms have their strategies to meet the specific requirements in one way or another; while none of them apply all of the strategies simultaneously to meet all requirements.

Some relevant terminologies, such as Holonic Manufacturing System (Brussel et al. 1999) and Agent-Based Manufacturing System (Shen and Norrie 1999), are not included in the above taxonomy. Although they are often used as a concept of 'production paradigm', they are dealt with 'enabling technologies', which will be discussed in Section 6.

4. Concept and Design Issues of RMS

4.1 RMS concept

Figure 6 has shown that the RMS paradigm is one of the most effective paradigms to meet the manufacturing requirements. However, RMS concept has been defined in different ways. For example, in Koren's definition (Koren et al. 1999), an 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. Although this definition can be generalized to entire manufacturing system, the authors tried to limit its scope under the shop floor level, and they treated an RMS as an intermediate paradigm between a Dedicated Manufacturing System (DMS) and a Flexible Manufacturing System (FMS). There are other existing definitions of an RMS. Liles and Huff (1990) has defined an RMS as a system capable of tailoring the configuration of a manufacturing system to meet the production demands placed on it dynamically. The concept of an RMS is also similar to the concept of "modular manufacturing" (Tsukune et al. 1993), "component-based manufacturing systems" (Weston 1999, Harrison et al. 2001, Chirm and Mcfarland 2000), "modular product system" (Rogers and Bottaci 1997), and "modular flexible manufacturing" (Kaula 1998).

Nevertheless, there is no doubt that the RMS concept has been proposed to meet the changes and uncertainties of manufacturing environment, and this objective would be achieved by reconfiguring hardware and/or software resources. System reconfigurability can be classified in terms of the levels where the reconfigurable actions are taken. As shown in Figure 7, reconfigurability at lower levels is mainly achieved by changing hardware resources, and reconfigurability at the higher levels is mainly achieved by changing software resources and/or by choosing alternatives methods or organization structures by flexible people. However, they usually work together so that system reconfiguribility can be maximized cost-effectively.

*<Insert **Figure 7** here>*

Based on the aforementioned discussion, it is reasonable to extend Koren's definition as

An RMS has an ability to reconfigure hardware and control resources at all of the functional and organizational levels, in order to quickly adjust production capacity and functionality in response to sudden changes in market or in regulatory requirements.

4.2 RMS design issues

Similar critical issues will be involved for any type of RMSs. To discuss these critical issues specifically and concretely, a reconfigurable robot system in Figure 8 is taken as an example. Its critical issues include *architecture design*, *configuration design*, and *control design*.

<*Insert* ***Figure 8*** *here*>

Architecture design determines system components and their interactions. System components are encapsulated modules. Interactions are the options when the modules are assembled. RMS architecture has to be designed to produce as many system variants as possible, so that the system can deal with changes and uncertainties cost-effectively. Architecture design is involved at the phase of system design.

Configuration design determines system configuration under given system architecture for a specific task. *A configuration* is an assembly of the selected modules; a configuration can fulfill the given task optimally. Configuration design is involved at the phase of system application.

Control design determines appropriate process variables (joint displacements and velocities etc. of a joint module), so that a configuration can be operated to fulfill the task satisfactorily. Control design is involved at the phase of system operation.

5. Architecture Design

5.1 Characteristics and requirements

As shown in Figure 9, RMS architecture is designed to possess a set of the key characteristics (Mehrabi et al. 2000a,b, 2002). RMS characteristics include '*modularity*', '*scalability*', '*integrability*', '*convertibility*', and '*diagnosability*'. *Modularity* implies that both software and hardware elements are modularized. *Scalability* means the system is scalable in terms of the product volume. *Integrability* means the system and system components are designed for both ready integration and future introduction of new technology. *Convertibility* allows quick changeover between existing products and quick system adaptability for future products. *Diagnosability* is able to identify quickly the sources of quality and reliability problems that occur in large systems. The influences of these characteristics on system requirements have been discussed by Mehrabi et al. (2000a,b).

5.2. Development of system hardware

A scenario of an RMS application is shown in Figure 9. The system consists of a reconfigurable hardware system and a reconfigurable software system. The hardware system includes reconfigurable machining systems, reconfigurable fixturing systems, reconfigurable assembly systems and reconfigurable material-handling systems. The studies on the hardware system are summarized in the following sections.

*<Insert **Figure 9** here>*

5.2.1. Reconfigurable machining systems

Modular machine tools have been on the market over a decade. The international standards had been established to standardize the design and fabrication of modular units in the seventies. The project Modular Synthesis of Advanced Machine Tools (MOSYN) has been proposed to customerize the configurations of modular machine tools (Thematic Network 2000). However, modular machine tools are traditionally used to increase product variants by the machine-tool producers, end-users often purchase machine tools with a specific configuration, and these machine tools are rarely reconfigured after their installments. Parallel Kinematic Machines (PKMs) are another type of reconfigurable machine tools (Cooke et al. 1995, Bostelman et al. 2000, Katz et al 2002, Fassi and Wiens 2000). Unfortunately, the theories and methodologies for developing commercial PKMs have not been well established. Most of available PKMs are expensive machines that provide less accuracy than conventional machines (Katz et al. 2002, Koren 1999). New class of reconfigurable machine tools has been studied at the University of Michigan. It is designed to meet the requirements of modularity, integrability, customization, convertibility, and diagnosiability, so that the machines can reconfigure frequently in the fast-changing environment (Koren et al. 1999).

5.2.2. Reconfigurable fixturing systems

Research on reconfigurable fixturing systems can be traced back to the late 1960s, when modular fixtures first came into prominence. A modular fixture is composed of many basic modules including locators, clampers and connectors. Some reconfigurable fixturing systems have applied industrial robots, since industrial robots are flexible to be programmed for different tasks (Shirinzadeh 1993, Benhabib et al. 1991). Other reconfigurable fixturing systems are integral and implemented by special materials or adjustable components (Haas et al. 2002, Valjavec and Hardt

1999). A critical review on the development of reconfigurable fixture systems has been provided (Bi and Zhang 2001).

5.2.3. Reconfigurable assembly systems

Reconfigurable assembly systems are usually robotized (Giusti et al. 1994, Arai et al. 2001, Heilala and Voho 2001, Sugi et al. 2001). The number and types of the assembly equipments can be changed to meet the requirements of the products. System reconfigurability can be further improved if a robot system itself has been modularized. In fact, modular robot design is one of the main research threads in the robotics community (Hooper and Tesar 1994, Chen 1994, Pritschow and Wurst 1996, Unsal et al. 1999). System ramp-up and dignosibility are other design issues. Arai et al. (2002) used some robots to calibrate a reconfigurable assembly system automatically to reduce ramp-up time. Mehrabi and Kannatey-Asibu (2001) have built a multi-sensor monitoring system to increase system dignosibility.

5.2.4. Reconfigurable material handling systems

A few of reconfigurable material handling systems are under development. Fukuda and Takagawa (2000) have designed a flexible transfer system for a large number of product variants. The main system components are autonomous robots. Ho et al. (1997) have developed a reconfigurable conveyor system; which allows to change the product volume in real-time. Automation Tooling System (ATS) in Canada has developed a programmable conveyor, which allows the conveyors to turn pallets from one section to another (Mellor 2002).

5.2.5. Higher level reconfigurable systems

The aforementioned systems are all at machine level or cell level. Some systems are at the shopfloor or system levels. For example, the RMS at the Tri-Way in Canada, has five machine cells, each cell includes two or three workstations devoted to a particular task (Mellor 2002, Degaspari 2002). The RMS developed by Chen et al. (2001) use various modular robots for system assembly.

5.3. Methodologies for architecture design

Architecture design takes consideration of the constraints derived from a particular application where the RMS is supposed to operate. The design complexity depends on the system level and the requirements of changes and uncertainties (Suh 1990). Numberless papers have been published on architecture design of manufacturing systems, and a few of comprehensive reviews on modular manufacturing have been provided (Tsukune et al. 1993, Rogers and Bottaci 1997, Benjaafar et al.

2002). The majority of the researchers employed some intuitive approaches, such as market studies and discussion (Koren et al. 1999, Kaula 1998, Mehrabi et al. 2000a, b, Mehrabi et al. 2002, Asl et al. 2000, Lee 1997, Zhao et al. 2000), classification (Ueda et al. 2001, Erixon et al. 1998), and interviewing (Chick et al. 2000). The concerned systems are hieratical with a stable structure (AMICE 1988, Kosanke et al. 1999, Kaula 1998, Deumeingts et al. 1992, Li and Williams 2002). Some new methodologies are under investigation. For example, Chen et al. (2001) and Bi (2002) used axiomatic designs to define general architecture of reconfigurable robot systems. Kuhnle (2001) presented a state-time model to describe the relationship between design requirements and organization changes. Asl et al. (2000) studied the stability of an RMS by analogizing it as a fluid dynamic system. Adolfsson et al. (2002) applied simulation to design component-based manufacturing systems. Tseng and Jiao (1997) and Kota and Chiou (1992) determined design requirements by assessing a multi-attributes matrix. Lee (1997) applied integer programming to determine the factory layout. Moriwaki and Numobiki (1994) proposed to use objected-oriented method to design conceptual machines.

Ueda et al. (2001) have indicated that system design of the RMS belongs to the problems with ill-defined specifications. Emergent synthesis methodologies, such as evolutionary computation, self-organization, behavior-based methods, reinforcement learning, multi-agent systems, are appropriate to obtain efficient, robust and adaptive solutions. However, their context of the design is actually ‘configuration design’. The applied methodologies will be discussed in the next section.

<*Insert* ***Figure 10*** *here*>

6. Configuration Design

As shown in Figure 10, system architecture determines available types and assembly options of system components. Therefore, system architecture determines what configuration variants a system can produce. Configuration design can be formulated as an optimization problem. In Figure 11, design variables, including the selections of module types, the number of modules, and internal adjustable parameters within a module, are used to represent a system configuration. Design constraints and objectives are derived from task specifications and business strategies. Configuration design involves *design analysis* and *design synthesis*. *Design analysis* establishes the mappings from design variables to design constraints and from design variables to design objectives. *Design synthesis* finds an optimal solution from all configuration candidates. For an

RMS, configuration design is repeatable within a life cycle of the system application. It will be operated when the task requirements are changed (Turner et al. 2000).

The methodologies for configuration design depend on the complexity of a reconfigurable system. In terms of the coupling nature of design variables to fulfill design requirements, a reconfigurable system can also be classified as an *uncoupled system*, *loosely-coupled system*, or *strongly-coupled system.* In an uncoupled system such as a computer system, each module corresponds to an individual requirement. For example, a monitor is responsible for the requirement of displaying quality and a keyboard is responsible for the requirement of typing input. A configuration is determined when all of its components are selected. In a loosely-coupled system such as a fixturing system, each component corresponds to one requirement (a clamping component is responsible for the clamping requirement), but a few of system requirements, such as tolerance and deformation, are fulfilled by all of the components. In a strongly-coupled system such as reconfigurable robot system, the function of a module does not have a direct relation with system requirements. All system modules have to be considered together to evaluate system's capability to meet the requirements.

6.1. Methodolgies for uncoupled and loosely-coupled Systems

For an uncoupled or loosely coupled system, a system component can be determined individually based on their corresponding requirements. To meet a few of system requirements, individual components need some adjustments. Configuration design of an uncoupled or loosely-coupled system is similar to the determination of a modular product. Many methods, such as feature-based methods (Perremans 1996), modular-based methods (Tsai and Wang 1999), combinatorial synthesis method (Levin 2002), entity-based methods (Hong and Hong 1998), and case-based methods (Watson 1999), can be applied. The researchers at the University of Michigan have made considerable efforts in developing a methodology for reconfigurable machine tools. In their methodology, task requirements of a machine tool are represented by matrices of motions, and the screw theory is employed to identify appropriate components. Kinematics constraints, dynamic stiffness, and accuracy, are taken into considerations in the design process (Koren et al. 1999, Moon and Kota 2000, Landers 2000).

6.2. Methodolgies for strongly-coupled systems

For a strongly-coupled system, design variables should be considered together to justify whether or not the configuration fulfill its requirements. Taking the reconfigurable robot system in Figure 11 as an example, design variables are the selections and assemblies of the modules, and design requirements are kinematic and dynamic behaviors of the robot including trajectory, time and load. There is no one-to-one relation between a design variable and a design requirement.

<*Insert **Figure 11** here*>

6.3. Methodolgies for strongly-coupled Systems

Early works have applied a sequential design procedure and most of them have considered the portion of system behaviours (Paredis and Khosla 1993, Fryer et al. 1997, Chen and Burdick 1995). However, Due to the couplings of design variables, a concurrent consideration of design variables, constraints, and objectives, is desirable to find a global optimal solution (Bi and Zhang 2000). Paredis (1996) has used the concurrent design for a fault-tolerance modular robot. Leger (1999) has considered kinematic and dynamic constraints, simultaneously in his automated synthesis.

Concurrent design can increase the problem dimension, and thus the computation is highly demanding. Two approaches have been proposed to cope with this problem: parallel computation (Paredis 1996, Sims 1994, Ramachandran and Chen 2000) and space reduction approach (Bi 2002).

6.4. Formulation of configuration design problem

In regard to the configuration design at a higher system level, people tend to employ system simulation where an approximate solution is found in time-consuming iterative process (Adolfsson et al. 2002, Banazak et al. 2003, Subbu et al. 1999). Mathematical formulation of a design problem can be applied only in a specific sub-problem. Zhao et al. (2000) have developed a design methodology based on a stochastic model. Spicer et al. (2002) have classified system configurations into pure serial lines, pure parallel lines, short serial lines arranged in parallel, and crossover short serial lines arranged in parallel. They have introduced a set of design principles for selecting appropriate system configurations. Hon and Lopez-Jaquez (2002) have taken the time factor into consideration in designing a dynamic manufacturing cell. Turner et al. (2000) have dealt with configuration design through a case study. Smirnov (1999) has proposed a constraint-based model for configuration management of a manufacturing system. Yigit et al. (2002) have applied nonlinear programming in optimizing an RMS configuration.

7. Control Design

To explain the issues of the RMS control, a reconfigurable robot system is taken as an example.

7.1. Reconfigurable and process variables

As shown in Figure 12, the system has two classes of variables to be manipulated: reconfigurable variables and process variables. Reconfigurable variables can change the robot configuration. For example, a 6 Degrees of Freedom (DOFs) trajectory with a light load can be fulfilled by a 6-DOF serial configuration, and a 3-DOF planer trajectory with a heavy payload can be fulfilled by a 3-DOF planer parallel configuration. Process variables, including the joint motions, can change the end-effector motion when the robot is operated to fulfill a task. Reconfigurable variables are determined in the configuration design. The reason why a configuration design is also regarded as a part of system control is that for a reconfigurable system, the system should be reconfigured frequently to meet quick changes, and reconfigurable variables can be changed during controlling process. Due to system reconfigurability, a new configuration has to be calibrated and verified before it is applied. The control problem during the ramp-up period is also raised so that the robot configurations can be shifted smoothly. Note that the system should also be able to identify reconfigurable factors, such as the failure of joints and the change of a task, so that the system is reconfigured at the right time.

<*Insert **Figure 12** here*>

<*Insert **Figure 13** here*>

7.2. Design requirements

Other types of RMSs have similar features with a reconfigurable robot system. RMS control can be generalized and described in Figure 13. The design requirements of an RMS control are determined as follows.

(i) The control system should be autonomous since a system level objective is decomposed into module level objectives Each module needs an encapsulated controller to fulfill its objective; the control system should be capable to integrate and coordinate the modules to implement system-level objective;

(ii) The control system should be distributed and modularized, since system components are decentralized and geographically distributed;

(iii) The control system should be open so that it can update controlling components. Controlling components might be developed on heterogeneous operation systems, languages, networks, databases, and protocols, and from different vendors;

(iv) The control system should be scalable and upgradeable because adding/removing/upgrading hardware components are needed when the functionality, capability, or enabling technologies have been changed;

(v) The control system should be self-reconfigured since the system configurations can be shifted from one configuration to another frequently, and the corresponding control system should also be self-reconfigured quickly;

(vi) The control system should be able to identify the changes of task specifications. These changes can cause system reconfiguration.

7.3. Methodologies for control design

The concepts of the control paradigms, such as holonic manufacturing (Markus et al. 1996), bionic manufacturing (Okino 1993), fractal companies (Sihn and Rist 1998), interactive manufacturing (Ueda et al. 1998), and random manufacturing (Wata and Onosato 1994), are proposed for the next-generation manufacturing systems. Bussmann and Mcfarlane (1999) analyzed the rationales to apply the agent technology in manufacturing; it seems that agent-based technologies are feasible to implement these concepts because of their capability to deal with autonomy, distribution, scalability, and disturbance. Shen and Norrie (1999), Caplinskas (1998), Tommila et al. (2001), Marik et al. (2002), Tian et al. (2002), and Kim (2002) reviewed the state of the art of the agent-based technologies in manufacturing; Langer and Alting (2000), Zaremba and Morel (2003), Bongaerts et al. (2000), Balasubramanian et al (2001), Heikkila et al (2001), and Zhang et al. (2000), proposed various control architectures for manufacturing systems control, Brussel et al. (1999) presented a fundamental work to identify various 'holons' for holonic manufacturing systems.

However, efficient methodologies are still lacking to support the collaborations in a large-scale multi-agent system. Most of the prototype systems are developed for a single machining system (Shu et al. 2000, Wang and Shin 2002, Lucas et al. 1999, Tatra et al. 1997, Tilbury and Kota 1999), or for a simplified reconfigurable system with a few of components (Bongaerts et al. 2000, Balasubramanian et al. 2001, Zhang et al. 2000, Arbib and Rossi 2000, Ottaway and Burns 2000, Zhang et al. 2002).

Open Architecture Control (OAC) provides the infrastructure to implement RMS control. Advances in the OAC development have reviewed by Katz et al. (2002), Albus (1993), Faulkner et al. (1999), Erol et al. (2000), and Pritschow et al. (2001). The hierarchical structures, which are used widely in mass production and Computer Integrated Manufacturing (CIM), could also be utilized with the consideration of time and changes. Monfared and Weston (1997), Harrison et al (2001), and Weston (1999) proposed model-driven approach based on CIM-OSA; Park et al. (2000) developed a generic control framework for modular flexible manufacturing system; Kalita and Khargonekar (2002) developed a logical controller for an RMS.

8. Summary and Furture Directions

The strategies to meet the requirements of a manufacturing system have been generalized, and these strategies can be used to compare and distinguish various manufacturing paradigms and enabling technologies. It is seen that the RMS paradigm is one of the most effective paradigms to meet some key requirements such as changes and uncertainties. But it is not the complete solution to meet all of manufacturing requirements. To our knowledge, no attempt has been made to combine an RMS with other production paradigms. Many prototype systems have been developed. Most of them are machine-level systems. These systems have been designed intuitively. A systematic design methodology is still lacking.

RMS design includes architecture design, configuration design and control design. For architecture design, most of the existing methodologies have been developed for integrated systems with a hierarchical structure, and they have not taken consideration of RMS performances such as reconfigurablility and convertibility. Little work has been conducted to quantify system requirements such as reconfigurability, so that system architecture can be designed optimally. For configuration design, due to the couplings of design variables to fulfill the objectives, design variables have to be considered simultaneously. A few of researchers have applied concurrent design methods for specific modular products and systems. These methodologies are not capable and flexible enough to deal with the complexity and scalability of a general RMS. For control design, the studies are towards two extreme applications: stable hierarchical systems and intelligent autonomous systems. However, an RMS should be an intermediate system between the two. The trade-off of control methodologies will be needed to control an RMS efficiently.

Based on our investigations and observations, some future directions can be identified:

(i) Since the RMS concept is not a complete solution for a manufacturing enterprise to meet all of the challenges, it is promising to take advantages of other technologies in an RMS. For example, the concept of Lean Production (LP) could be a supplement to an RMS, so that an enterprise can apply an RMS to optimize the utilization of the portion of resources for specific product families, and it can also reduce the waste caused by the portion of the idle resources of an RMS. Further effort is worth dealing with the waste of idle resources of an RMS.

(ii) RMS architecture is extremely important for an RMS to meet its expectation. A potential approach to develop a systematic design methodology is to extend existing methodologies such as the methodologies proposed for non-reconfigurable integrated manufacturing systems. They can be improved and extended with the consideration of time and changes. The other issue is the granularity of system modules. It is obvious that the finer the granularity of system modules are, the higher the reconfigurability of a system is. However, one has to make a trade-off among the cost, reconfigurability, and the complexity of the software system. Another untouched issue is how to help an enterprise evolve from a non-configurable system to a reconfigurable system. It is worth to note that system reconfigurability can be achieved by manipulating a set of non-configurable systems at the management level.

(iii) With respect to configuration design, further explorations will be needed to design a configuration for a heterogeneous RMS (for example, an RMS consisting of reconfigurable fixtures, robots, and conveyors) or an RMS with a highly-coupled nature (for example, a reconfigurable robot system). These explorations include the decomposition of the complexity and design synthesis when the number of reconfigurable variables is big.

(iv) With respect to control design, it combines the issues of configuration design and real-time control. A control system should be autonomous, distributed, scalable and self-reconfigurable. This increases the complexity of control design greatly. Open Architecture Control provides the infrastructure to implement RMS control, and the agent-based technologies meet most of these requirements. Future works can focus on how to coordinate modular components to achieve system objectives efficiently.

Acknowledgement

The authors wish to thank the anonymous reviewers for valuable comments and suggestions on the manuscript.

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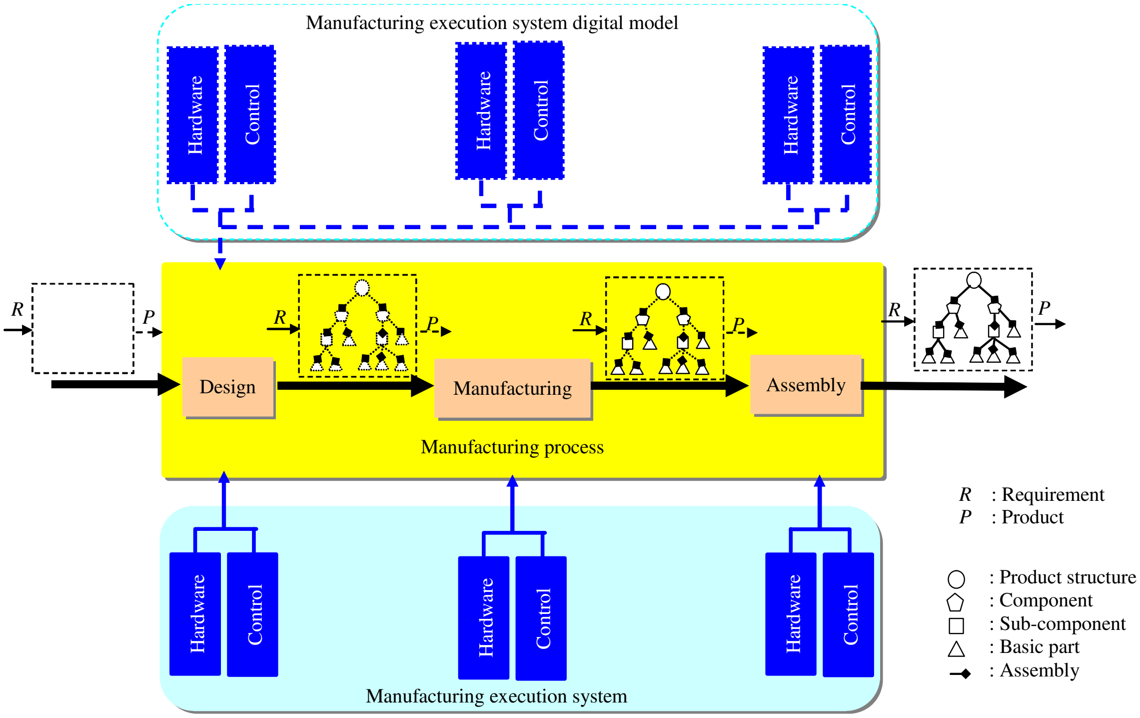


Figure 1 Manufacturing system model

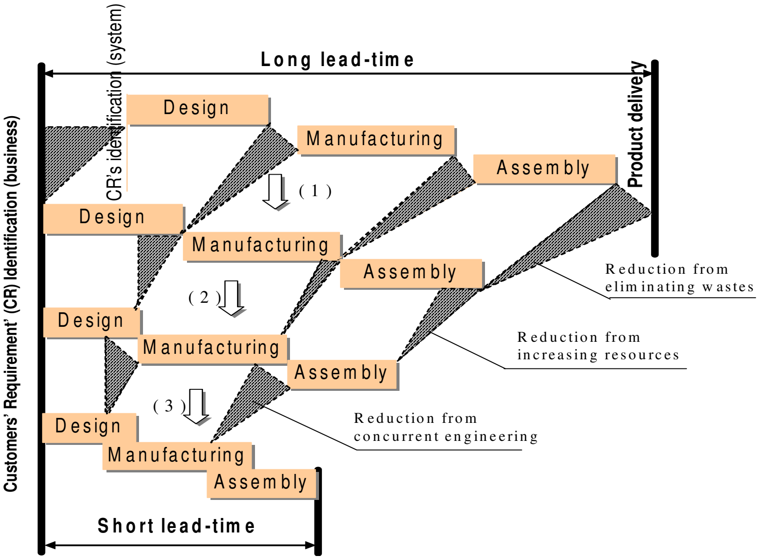


Figure 2 Strategies to reduce lead-time

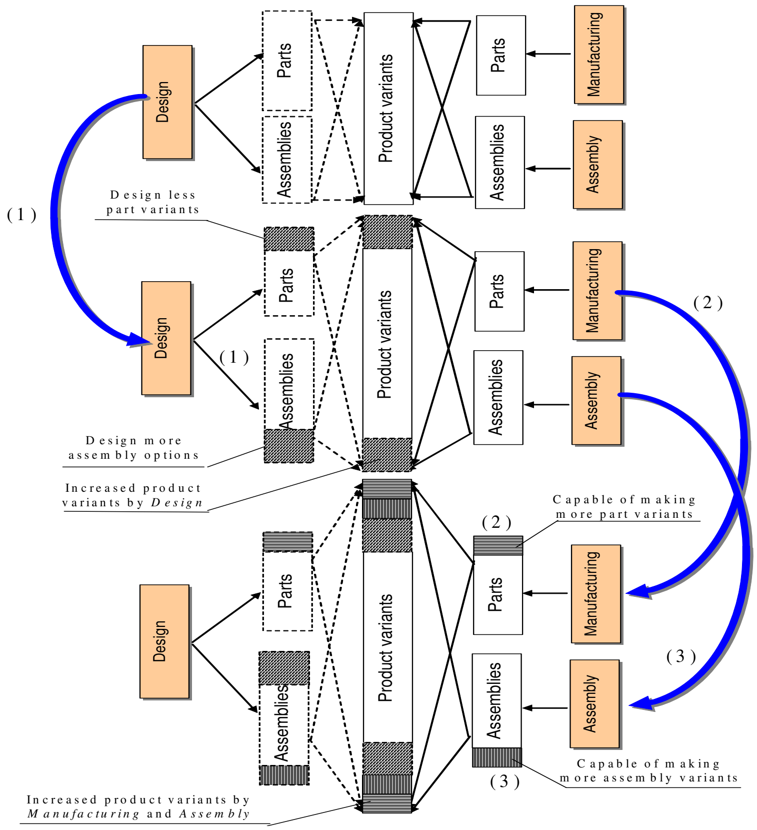


Figure 3 Strategies to increase variants

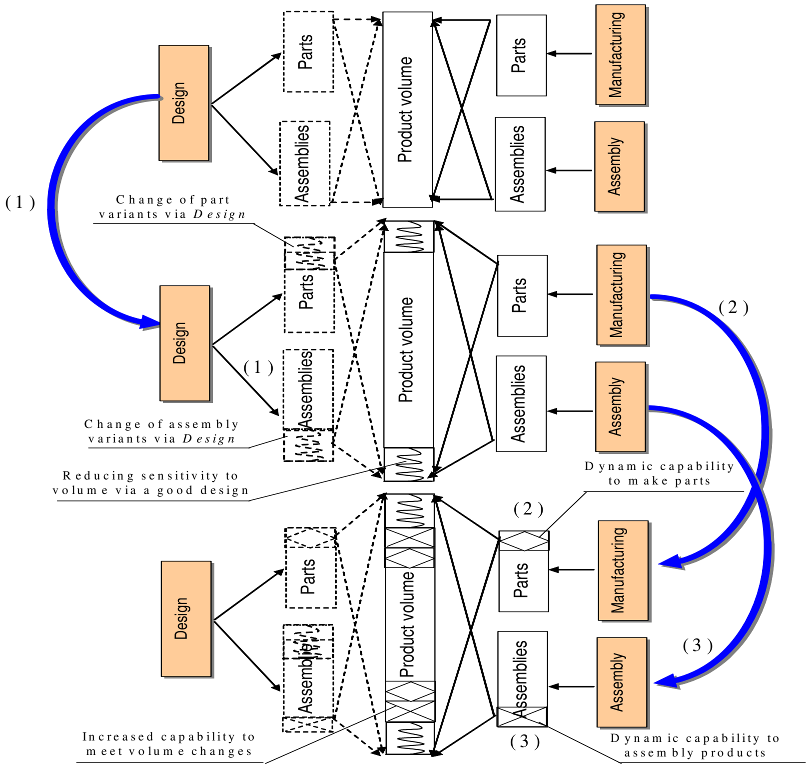


Figure 4 Strategies to deal with low and fluctuating product volumes

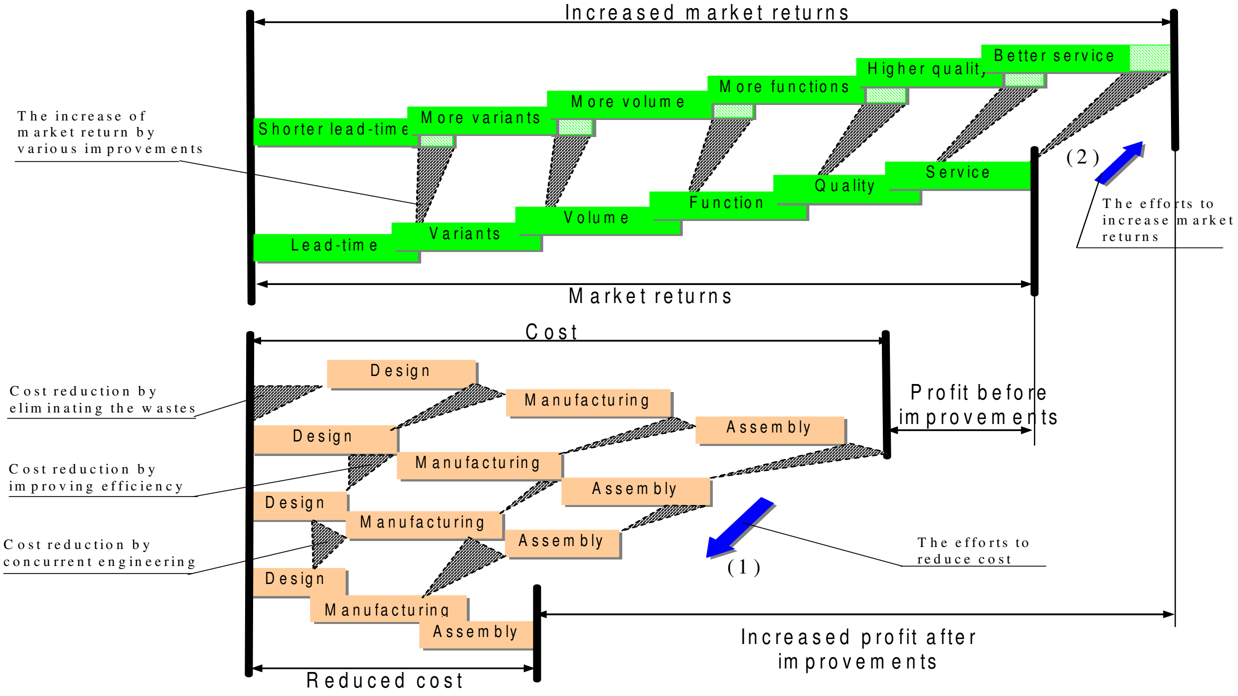
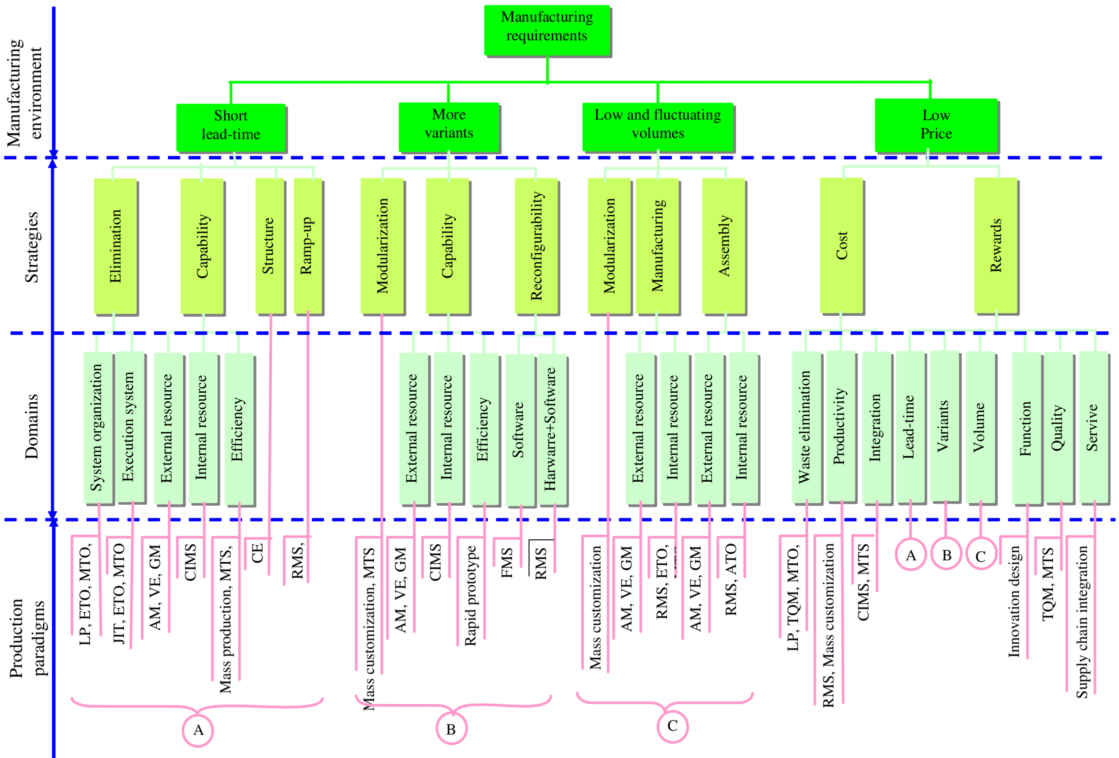


Figure 5 Strategies to reduce the cost



LP: Lean production
JIT: Just-in-Time
AM: Agile Manufacturing
VE: Virtual Enterprise
GM: Global Manufacturing
MTS: Make-To-Stock
TQM: Total Quality Management
ATO: Assembly-To-Order
ETO: Engineer-To-Order
CIMS: Computer Integrated Manufacturing System
CE: Concurrent Engineering
FMS: Flexible Manufacturing System
RMS: Reconfigurable Manufacturing System
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Figure 6 Manufacturing requirements, strategies, domains and production paradigms

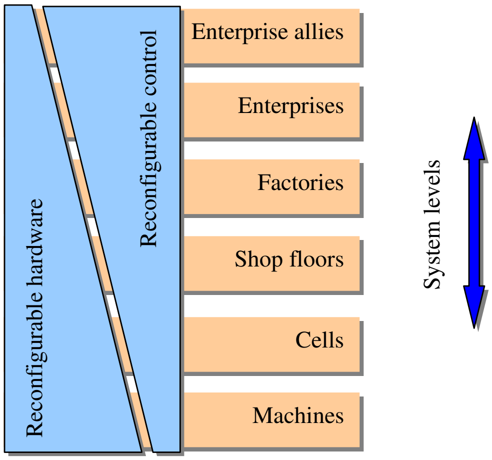

Figure 7 System organization and reconfigurable resources

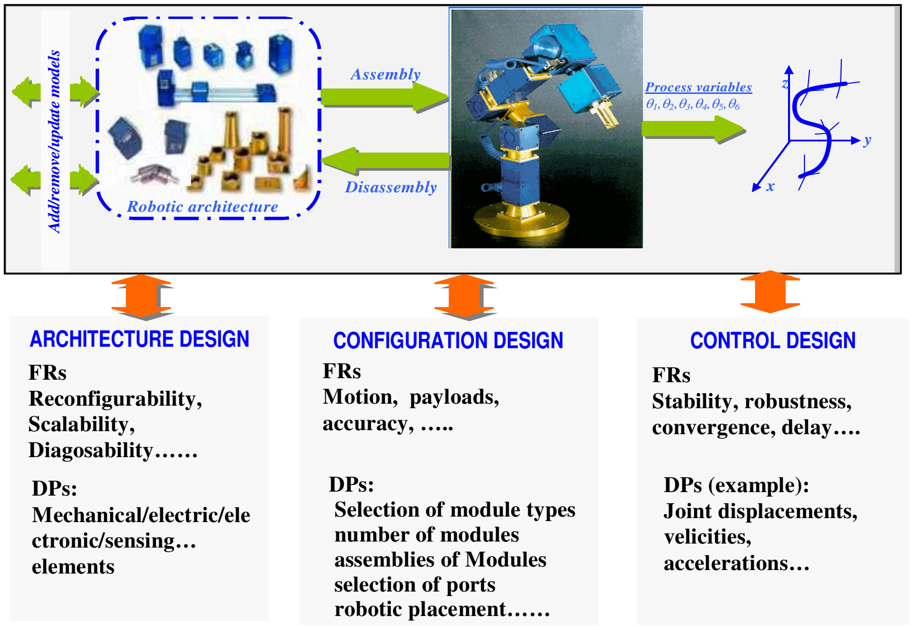

Figure 8 Design issues of an RMS

(Modular robot pictures are cited from Amtec Robotics (2006) and Chen (2001))

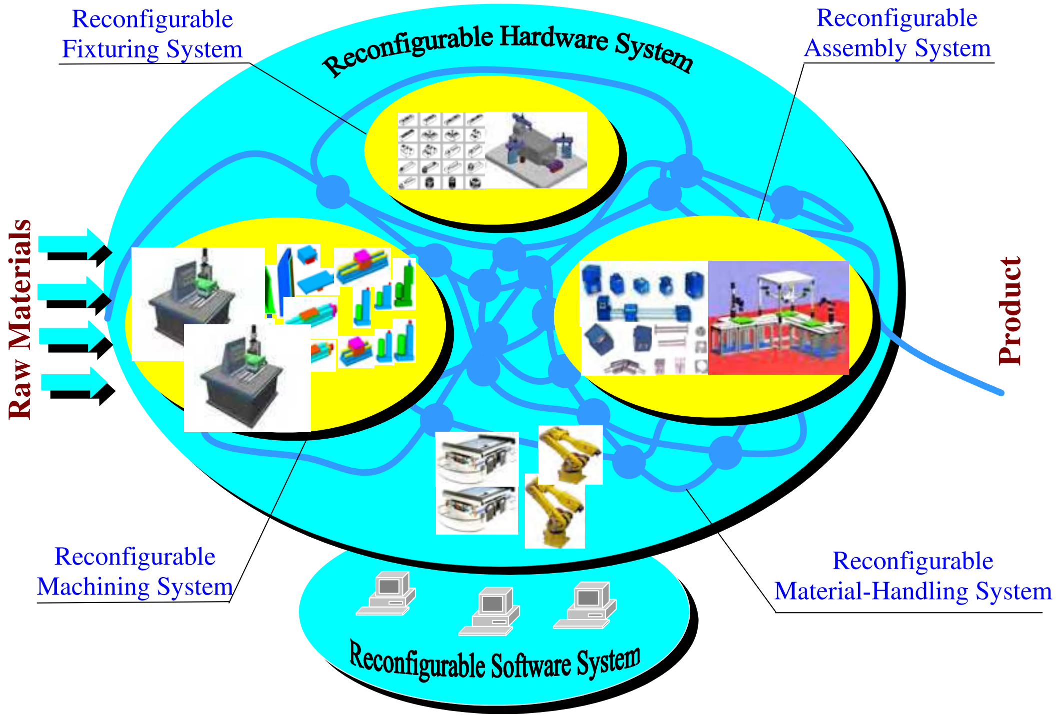

Figure 9 An application scenario of an RMS

(Modular robot pictures are citied from Chen (2001) and Amtec-Robotics (2006), Reconfigurable machine picture is cited from Koren et al. (1999))

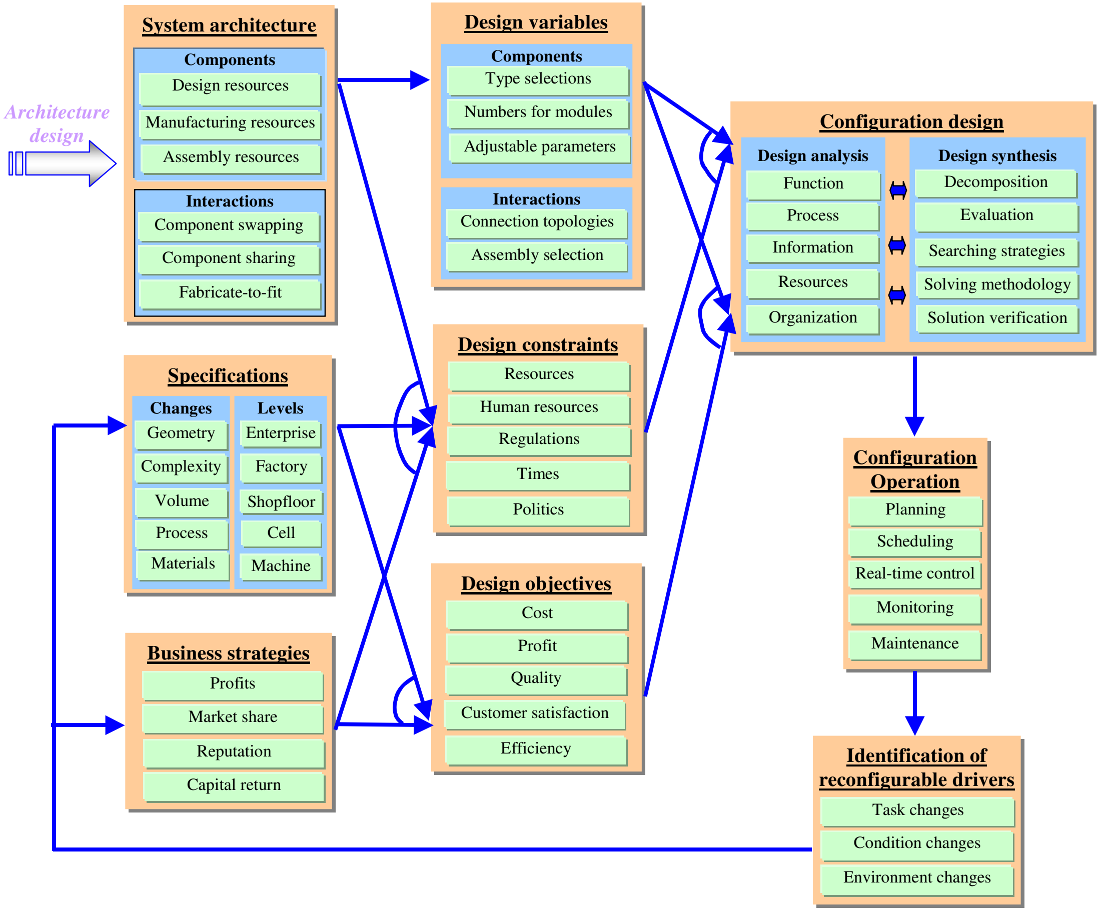

Figure 10 Configuration design in the lifecycle of an RMS

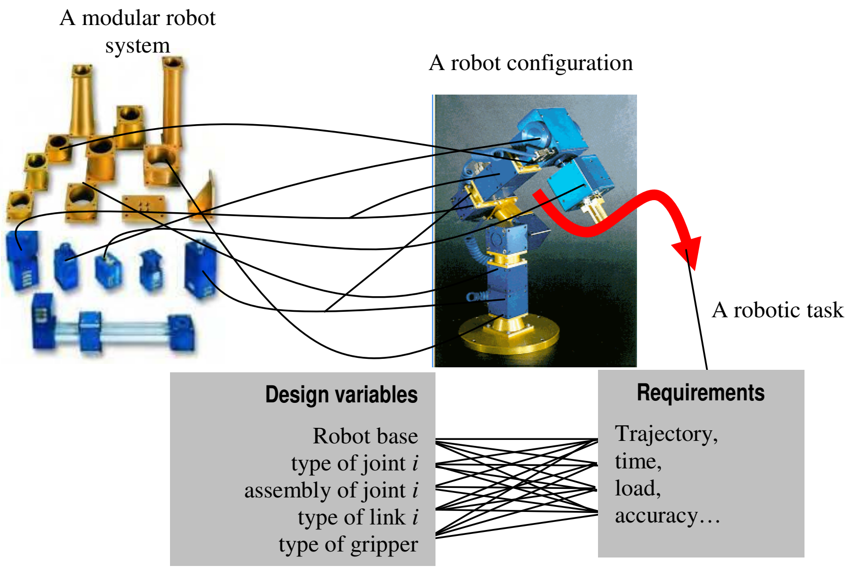

Figure 11 An example of a strongly-coupled system

(Modular robot picture is cited from Amtec Robotics (2006))

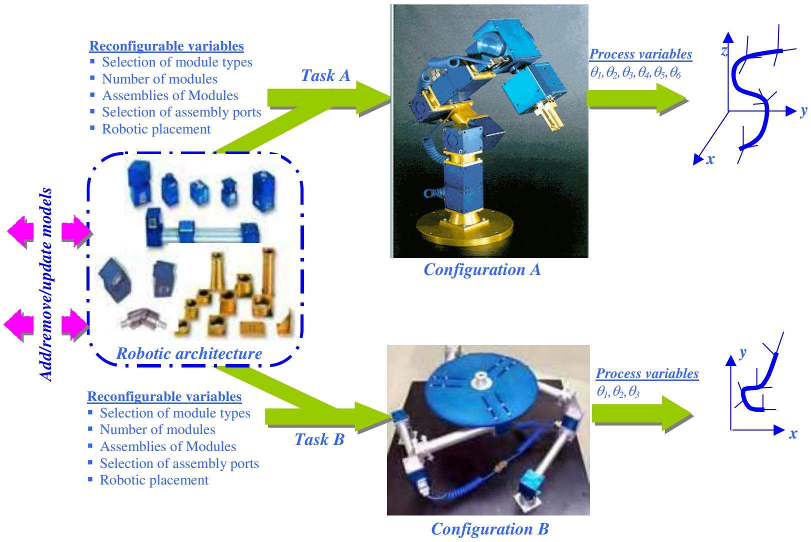

Figure 12 Control of a reconfigurable robot system

(Modular robot pictures are cited from Amtec Robotics (2006) and Chen (2001))

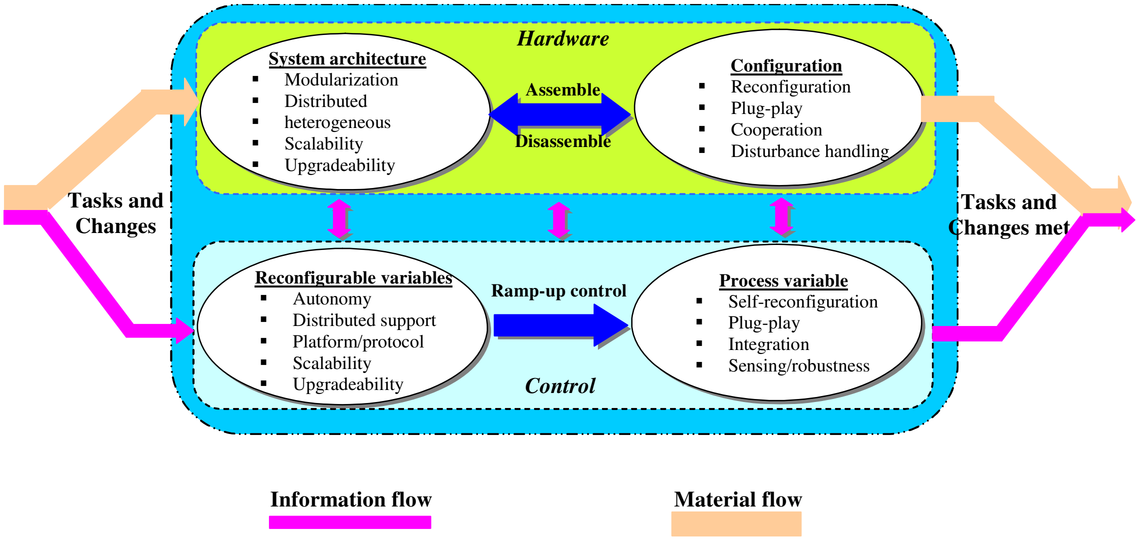

Figure 13 Requirements of reconfigurable system control