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Capacity scalability modeling and design framework for reconfigurable manufacturing systems.

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Capacity Scalability Modeling and Design Framework for Reconfigurable Manufacturing Systems

By

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ABSTRACT

Shorter product life-cycles, unpredictable demand, and customized products have forced manufacturing systems to operate more efficiently and effectively in order to adapt to changing requirements. Traditional manufacturing systems, such as job shops and flow lines, cannot handle such environments. Even Flexible manufacturing systems, although they can deal with variety of products in an efficient manner, are not the best candidates for such new environment due to their high cost and medium volume of production. To accommodate for the drawbacks of the existing manufacturing systems, reconfigurable manufacturing systems were proposed to convert quickly to production of new models with different volumes and variety.

The focus of this research will be on how to approach the design reconfigurable manufacturing systems and how to control the design process. This will be achieved first in a systematic manner through implementing system design methodology to develop an architecture that visualizes the full reconfiguration process from recognizing customer needs through the operational level. An example in the reconfigurable printed circuit board (PCB) automatic assembly industry is used to illustrate the design and control activities in the proposed architecture.

An analytical approach will follow the systematic approach. In this research only the first layer of the architecture dealing with capacity scalability is mathematically modeled. The capacity scalability model is used to develop a computer-based tool that generates optimal capacity scalability schedule and can be integrated to the architecture.

Results of using the developed tool with numerical examples revealed the need to modify cost function of the model to reflect the real case of capacity scalability in reconfigurable manufacturing systems. The modification highlighted the fact that the success of reconfigurable manufacturing systems is through responsive scalable systems in a cost effective manner. Results also showed the superiority of the generated optimal capacity scalability schedule over other capacity plans and illustrated how the developed model can deal with different demand scenarios in an optimal way.

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LIST OF ACRONYMS

C_{RT}	Reconfiguration Time Cost.
C_{HR}	Cost of Hard Reconfiguration.
C_{SR}	Cost of Soft Reconfiguration.
C_{MR}:	Cost of Human Reconfiguration.
C_O	Cost of Additional Operational Parameters.
CR	The Cost of System Reconfiguration.
C(v)	Cost Function of Capacity Scalability.
D_t	Demand at Period t.
n:	Number of Capacity Scalability Points.
RT	Reconfiguration Time.
T	Capacity Scalability Planning Time.
T_m	Time consumed During Each Design Activity in the Market Capturing Layer.
T_s	Time consumed During Each Design Activity in the System Reconfiguration Layer.
T_c	Time consumed During Each Design Activity in the Component Configuration Layer + Ramp up Time
T_P	Time for production.
S	Capacity Scalability Index.
V	Set of Feasible Capacity Schedules.
v_t	Capacity Scalability Decision Variable.
Z_t	End of Period Excess Capacity.

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Shorter product life-cycles, unpredictable demand, and customized products have forced manufacturing systems to operate more efficiently and effectively in order to adapt to changing requirements. Tougher competitive situations have led to increasing attention being paid to customer satisfaction, of which timely and customized services are the key concepts. As the product life cycle becomes shortened, high product quality becomes necessary for survival. Markets become highly diversified and global, and continuous and unexpected change becomes the key factor for success.

Traditional manufacturing systems, such as job shops and flow lines, cannot handle such environment. Even Flexible manufacturing systems, although they can deal with variety of product in an efficient manner, are not the best candidates for such new environment due to their high cost and medium volume of production.

For such tough environment and to accommodate for the drawbacks of the existing manufacturing systems, reconfigurable manufacturing systems were proposed to convert quickly to production of new models with different volumes and variety.

The focus of this thesis will be on how to approach the design of reconfigurable manufacturing systems from systematic and analytical perspectives.

1.2 WHAT IS A SYSTEM?

A system is "a collection of elements aggregated by virtue of the links of form, process, or function which tie them together and cause them to interact. All that is excluded from the system constitutes the environment" [Rubinstein, 1975].

Systems can be simply defined as a combination of elements forming a complex whole or as a set of elements embodying specific characteristics. Between the elements are relations representing the functional connections of the elements. The system has a defined boundary to its environment and all elements exist within this boundary. Each element itself might be a subsystem. The purpose of a system is to achieve defined goals [Bruns, 1988].

The science of system development (systemology) was first articulated in the late forties of the previous century by Ludwing von Bertalanffy who talked about the general system theory and stated that this theory is concerned with developing a general framework for describing general relationships in the natural and the man-made world.

Systems are composed of components, attributes and relationships. Blanchard [1990] describes components as the operating parts of a system consisting of inputs, process, and output. Each system component may assume a variety of values to describe a system state as set by control action and one or more restrictions. Attributes are the properties or discernible manifestations of the components of the system. These attributes characterize the system. Relationships are the link between components and attributes.

There are various classifications of systems. Among these classifications are: physical and conceptual systems, closed and opened systems, and static and dynamic systems.

Physical systems are those which manifest themselves in physical terms (real components), while conceptual systems use symbols to represent components, so physical systems consumes physical space while conceptual systems are organization of ideas. Closed systems are those systems that don't interact significantly with its environment; it only gives a context for the system, while open systems allow information, energy and matter to cross its boundaries; open systems interact with their environment. Static systems are systems that depend only on the current input and not on the history of inputs, on the other hand, dynamic systems change over time and their states depend on the input's history.

Cybernetics is the modern branch of the system theory and sometimes referred to as the sciences of complexity. Cybernetics can be defined as the complex, adaptive and self-regulating systems.

In this thesis the concerned systems, reconfigurable manufacturing systems, are classified under physical, open and dynamic systems.

1.3 MANUFACTURING SYSTEMS

Manufacturing is the economic term of making goods and services available to satisfy human wants. Manufacturing implies creating value by applying useful mental or physical labor. The collection and arrangement of processes and material handling equipments defines the basic design of manufacturing systems. The manufacturing system takes inputs and produces products for the customers as its output [Black, 2002].

The manufacturing system includes the actual equipment composing the processes and the arrangement of those processes and/or people. Figure 1.1 explains this definition. A Manufacturing System is a complex arrangement of physical elements characterized by measurable parameters.

Salzmann [2002] through his work with the Manufacturing Systems Team of LAI the following definition of manufacturing systems has been presented:

> "A manufacturing system is an objective oriented network of people, entities, and processes that transform inputs into desired products and other outputs; all managed under an operating policy".

Where objective is defined as the ultimate objective of the manufacturing system that should be able to help satisfy corporate goals, entities as machines, tools, floor space, software, transport equipment, suppliers, etc., inputs as Raw materials, energy, and information, outputs: Desired products, wasted materials, wasted energy, and knowledge and finally operating policy as a set of rules that determine how people, system entities, and the processes are interconnected, added, removed, used and controlled.

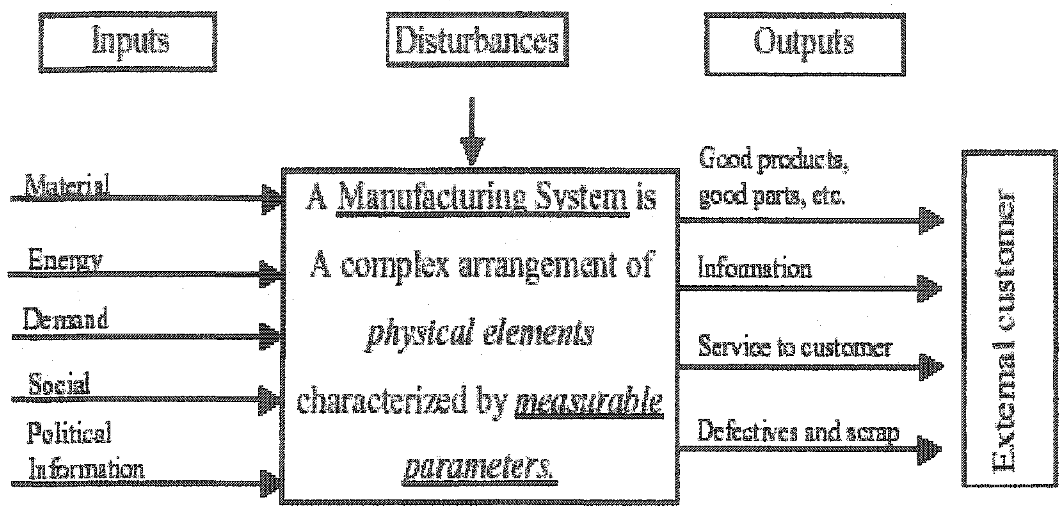


Figure 1.1 Definition of Manufacturing System [Black, 1991]

1.4 PROBLEM STATEMENT

Today, Industrial Engineers must not only prescribe the physical layout of the manufacturing system, they must also prescribe the way the manufacturing system is designed and controlled to adapt to short-term changes. Most of the manufacturing system design approaches found do not integrate the design process with how to control that design process. This results in questioning the degree of consistency of the design process to the strategic objectives of the corporation that implement the manufacturing system.

The reconfigurable manufacturing systems are the most recent manufacturing environment developed to adapt for today's dynamic market. Thus the classical manufacturing design approaches or frameworks are not sufficient to capture such dynamic systems. Even the new design approaches failed to capture the full reconfiguration process for such systems and to explain how the new suggested technology for these manufacturing systems can be implemented in the design process.

Many manufacturing system design frameworks in practice are characterized by a lack of formal processes. This is because most of the existing frameworks or approaches do not provide analytical models for the design procedure they address. Most of these frameworks act like guidelines for the manufacturing system designers. This problem is clearer when it comes to reconfigurable manufacturing systems especially when modeling is required to address the design of the new technology of such systems like modularity and scalability.

Therefore, there is a need to develop an integrated systematic approach for the design of reconfigurable manufacturing systems that capture the full process of reconfiguration and its control. The approach should reflect the objectives of these systems and should adapt to the dynamic characteristics of such systems. Also there is a need to go beyond the systematic approach to the analytical modeling of such an approach to give it a practical validity.

This thesis will address these needs by developing architecture for the design of reconfigurable manufacturing systems and how to control that design process. Further more, an analytical approach to model the first layer of the architecture that deals with the capacity scalability aspect of these systems is carried out. The full modeling of the architecture is left for further research.

1.5 RESEARCH OBJECTIVES

The objective of this research has two stages. The first stage is a systematic approach that deals with the big picture of the reconfigurable manufacturing systems. The objective of the first dimension is to develop architecture for the design of reconfigurable manufacturing systems. The architecture should enhance the ability of manufacturing engineers to:

- Visualize the full reconfiguration process from recognizing customer needs or anticipated needs through the component and operational level.
- Develop a systematic approach or guidance for the design of reconfigurable manufacturing systems through different levels of the system.
- Control the design process of reconfigurable manufacturing systems to ensure that the system fulfills the strategic objectives of the corporate.

The second stage of the research is a more analytical approach. A good approach for design is the approach that can be modeled to be practically applied; however modeling the different architecture layers is beyond the scope of the thesis. The objective of this dimension is to model the first layer only of the proposed architecture that deals with the market demand capturing and delivering these demands as capacity levels for the system to be reconfigured. As a result, the objective is to develop a capacity scalability modeling tool that generates optimal capacity policy or schedule in the reconfigurable manufacturing systems. Such modeling will point out for the validity of the architecture to be practically implemented.

1.6 RESEARCH APPROACH

The research approach followed in the thesis is as follows. An intensive literature review is conducted to explore the various frameworks and methodologies found for the design and control of different types of manufacturing systems. Also different system engineering tools will be investigated. The result of the state of the art will unveil the need for an integrated approach for the design and control of reconfigurable manufacturing systems.

An architecture for the design of reconfigurable manufacturing systems and how to control that process will be developed through adopting the system design methodology used for computer software. Such methodology was not adapted to the reconfigurable manufacturing systems environment before.

An analytical approach for one of the layers of the developed architecture will be carried out through modeling the first layer. For the modeling of that layer in the architecture a mathematical approach based on the properties of convex sets and concave functions together with what is known as the regeneration theory is implemented. After formulation of the model a computer based tool is developed using dynamic programming techniques. The software used for the tool will be the MATLAB package as it is considered a powerful tool for dynamic programming problems. The developed tool will be used to investigate different demand and capacity scenarios for reconfigurable manufacturing systems.

1.7 STRUCTURE OF THE THESIS

This thesis begins with a review of manufacturing systems in chapter 2. The chapter will introduce the reconfigurable manufacturing systems and their enabling technologies. Practical reconfigurable examples on the system level as well as the machine level are presented.

In chapter 3, a review of existing approaches to manufacturing system design and control is conducted. In addition, the review will include various system engineering tools that can be applied for the manufacturing system design. The review categorizes the various approaches by relating them to the general systems engineering design process.

Chapter 4 presents the proposed architecture for the design of reconfigurable manufacturing systems. Each layer of the design module is explained using $IDEF_0$ model. Following the explanation of the design process, the control of the design module of the architecture is described. The last part of the chapter is an application of the architecture in a reconfigurable automatic printed circuit board (PCB) assembly environment.

Chapter 5 describes in detail the modeling of the market capture layer through approaching the capacity scalability problem in reconfigurable manufacturing systems. A review for the capacity scalability problem is first presented, followed by the theoretical background of the model then the model formulation and finally a computer-based tool is developed and used to generate some numerical results that will be used to modify the model. Chapter 6 summarizes the work performed and identifies future research areas.

CHAPTER 2

EVOLUTION OF MANUFACTURING SYSTEMS

2.1 INTRODUCTION

The history of the manufacturing systems shows how these systems evolved from classical paradigms starting from Mass Production to the modern paradigms like Agile Manufacturing. This evolution over the years was in response to an increasingly dynamic and global market with greater need for globalization and competitiveness.

The nature of manufacturing system and its paradigms will also evolve in response to changes in the technological, political, and economic climate. The following factors will be the most important to the development of manufacturing:

- The competitive climate, enhanced by communication and knowledge sharing, will require rapid responses to market forces.
- Sophisticated customers, many in newly developed countries, will demand products customized to meet their needs.
- The basis of competition will be creativity and innovation in all aspects of the manufacturing enterprise.
- The development of innovative process technologies will change both the scope and scale of manufacturing.
- Environmental protection will be essential as the global ecosystem is strained by growing populations and the emergence of new high-technology economies.
- Information and knowledge on all aspects of manufacturing enterprises and the marketplace will be instantly available in a form that can be used for decision-making.
- The global distribution of highly competitive production resources, including skilled workforces, will be a critical factor in the organization of manufacturing enterprises.

ElMaraghy, W., [2001] summarized the factors that lead to the evolution of manufacturing systems in Figure 2.1.

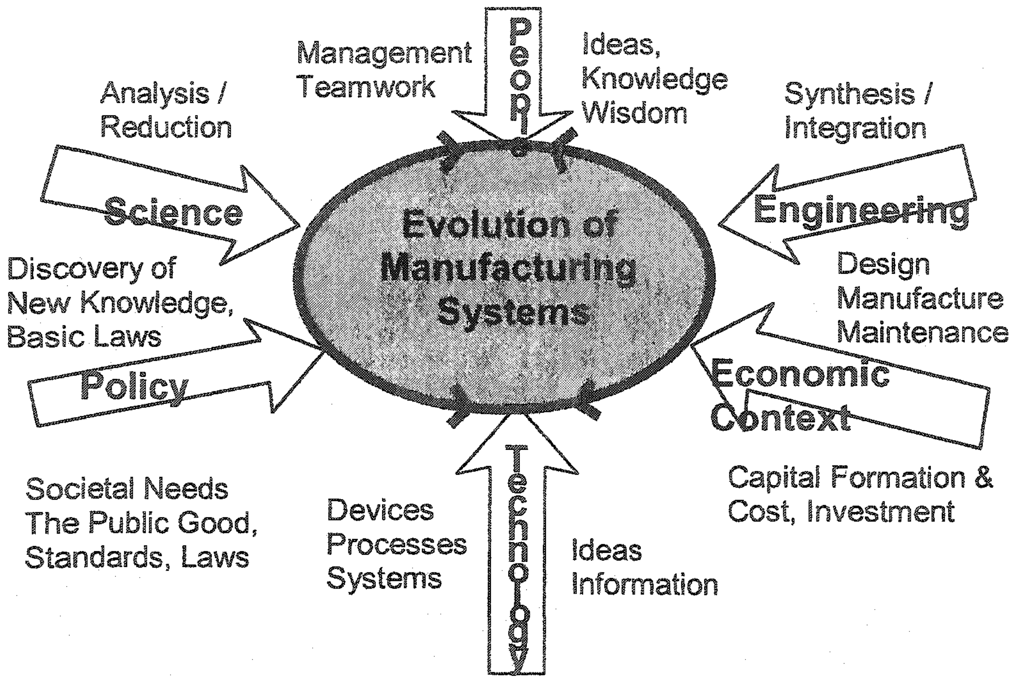


Figure 2.1 Factors Affecting the Evolution of Manufacturing Systems [ElMaraghy 2001]

In the following sections an overview of the different manufacturing paradigms will be presented. The manufacturing paradigm is usually composed of two dimensions. The first dimension is the business one that includes the strategies and objectives that guides and controls the manufacturing systems, while the second dimension deals with the enabling technology of that paradigm. Viewing the manufacturing systems from that perspective will clarify many of the interrelations in manufacturing systems terminologies like lean, agile and other business strategies with terms as dedicated, flexible, reconfigurable and other technological terms.

2.2 MASS PRODUCTION

It is the classical paradigm of manufacturing systems and sometimes it is named after its enabling technology which is the dedicated lines. The production of long runs of standardized goods for a mass market was introduced into the United States at the beginning of the 20th Century. The first industrialist to make full use of this system was Henry Ford and as a result it became known as Fordism. This has been described as "the mass production of standardized goods, using dedicated machines and moving assembly lines, employing unskilled and semi-skilled labor in fragmented jobs, with tight labor discipline, in large factories" [95].

Initially it took 14 hours to assemble a Model T car. By improving his mass production methods, Ford reduced this to 1 hour 33 minutes. This lowered the overall cost of each car and enabled Ford to undercut the price of other cars on the market. Between 1908 and 1916 the selling price of the Model T fell from $1,000 to $360. Following to the success of Ford's low-price cars, other companies began introducing mass production methods to produce cheaper goods.

In mass production dedicated lines were designed for the specific product. It use transfer lines technology with fixed tooling and automation. Its main objective is to cost effectively produce a specific part type at a high volume and required quality.

The swift trend towards a multiplicity of finished products with short development and production lead times has lead many companies into problems with inventories, overheads, and inefficiencies. They are trying to apply the traditional mass-production approach without realizing that the whole environment has changed. Mass production does not apply to products where the customers require small quantities of highly custom, design-to-order products, and where additional services and value-added benefits like product upgrades and future reconfigurations are as important as the product itself.

2.3 LEAN MANUFACTURING SYSTEMS

Lean Manufacturing is a term that embraces many of topics of both business and technology as just in time (JIT), minimizing work in place, pull systems of production control, flexibility and setup time reduction. Lean can be defined as doing more and more with less and less human effort, less equipment, less time and less space, while coming closer and closer to providing customers with what exactly they want. It can be also defined as the adaptation of mass production in which workers and work cells are made more flexible and efficient by adopting methods that reduce wastes in all forms [Groover, 2000].

The Lean manufacturing is based on four principles [Groover, 2000]:

- Minimize waste
- Perfect first-time quality
- Flexible production lines
- Continuous improvement

All four principles are derived from the first principle of minimize waste. Waste includes production of defective parts (perfect first-time quality), production of more than the number of items needed, unnecessary inventory (JIT), unnecessary processes steps, unnecessary movement, unnecessary transport of materials and workers waiting (JIT).

Lean production is lean because the manufacturing system use less of everything compared to traditional manufacturing system [Hunter, 2002].

The implementation of the Lean paradigm leads to the evolution of what is called group technology and its cellular manufacturing systems. No doubt that the Japanese industries are the best to implement this manufacturing paradigm and Toyota company comes on the top of all Japanese industries in the optimum accomplishment of the Lean manufacturing.

2.4 CELLULAR MANUFACTURING SYSTEMS

- This manufacturing technology could be classified under lean manufacturing paradigm, however others classifies it as an independent paradigm named as group technology or GT.

Group Technology, is a manufacturing philosophy in which similar parts are identified and grouped together to take advantage of their similarities in design and production [Groover, 2000]. Similar parts are arranged into part families where each part family posses similar design and/or manufacturing characteristics. The GT is best applied if the plant currently uses traditional batch production and a process type layout and also if the parts can be grouped into part families.

The basic idea of cellular manufacturing, CM, is to divide a manufacturing system into several subsystems called cells based on their similarities as mentioned. The first to introduce this idea explicitly was Burbdge in 1963.

Companies which have implemented the CM concept, have witnessed a number of benefits including: reducing material handling cost, reducing setup time, decreasing work in process, improving product quality, increasing job satisfaction, process planning and production scheduling is simplified and finally tools, fixtures and setups are standardized [Chen, 1995].

The grouping of parts into families is the main obstacle to the efficient implementation of CM. This could be achieved by visual inspection (least accurate), parts classification and coding and finally production flow analysis. Also the re-arrangement of production machines into machine cells is sometimes another obstacle for the CM implementation as it is time consuming, costly to plan and accomplish the re-arrangement and the machines are not producing during the changeover.

2.5 COMPUTER INTEGRATED MANUFACTURING SYSTEMS CIM

CIM is the integration of the total manufacturing enterprise through the use of integrated systems and data communication coupled with the new managerial philosophies that improve organizational and personal efficiency [ElMaraghy, 2003]. It is concept, roadmap, strategies not a system, thus it lies on the business or strategic dimension of the manufacturing system paradigm. However, CAD, CAPP, CAM and other technologies are considered the enabling technologies of that manufacturing paradigm.

CIM is concerned with the integration of different machine centers through a material handling system, computers system through networks, all company data through database, computer system software and finally, manufacturing activities through networking [ElMaraghy, 2003].

Full implementation of CIM results in the automation of the information flow through every aspect of the company organization. Figure 2.2 shows a robot in a CIM and figure 2.3 describes the different CIM implementation components.

Figure 2.2 Robot in a CIM Factory [91]

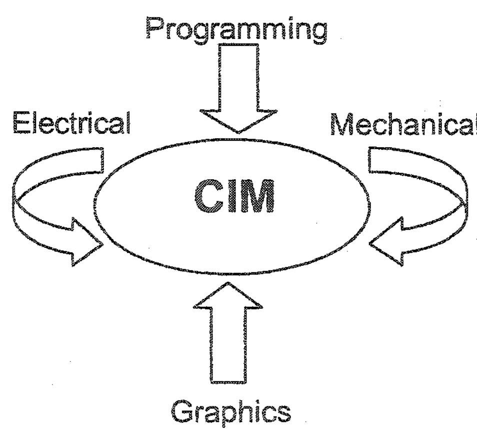


Figure 2.3 CIM Major Components

It is generally held that CIM will only produce successful outcomes, if appropriate human resources and organizational structures accompany the technology installed. The importance of determining the organizational options within a company, before adopting a specific type of technology, is also stressed. Clearly the existing company culture or corporate philosophy of a company is likely to have a bearing on its willingness to change its attitude towards innovation. Table 2.1 summarizes the major benefits of CIM [91]

Table 2.1 Major Benefits of CIM

Tangible Benefits	**Intangible Benefits**
Higher quality	Greater Flexibility
Reduced Inventory	Meet competitive pressure
Less Floor Space	Shorter Throughput and Lead Time
Eliminate paper	Increased Learning
	Faster Response to Market Shifts

CIM implementation process is carried out in three steps. The first step is the assessment of the enterprise in the areas of technology, human resource and system. The second step is the simplification of processes and elimination of waste. The third step is the real implementation with performance measure of previous listed benefits [ElMaraghy, 2003].

The extent to which the firm is able to take advantage of the capabilities and power of future CIM will be dependent on its ability to identify and overcome these obstacles: Organizational Barriers, strategic barriers, human barriers, system barriers, evaluation and justification and finally performance measurement Barriers

Future CIM systems will apply computer-augmented systems to every aspect of the firm. Future CIM will not only affect the operation of such direct activities as manufacturing, engineering, and quality assurance, but it will also influence the operation of such support activities as accounting and finance. Increasingly, these support activities will become more closely linked to direct activities in both time and place.

2.6 FLEXIBLE MANUFACTURING SYSTEMS

FMS is the natural evolution of the lean manufacturing paradigm as request for more responsive manufacturing systems increased due to new market challenges as was described before. FMS is an arrangement of machines, cells and robots under the control of computer [Ostwald, 1996]. FMS is the most automated system of the machine cell types (usually CNC) implemented in group technology. The reason it is called flexible is that it is capable of processing a variety of different parts simultaneously at the various stations and mix of part styles & quantities of production can be adjusted in response to changing demands patterns [Koren et al., 1999].

To say that a system is flexible, it should be capable of identifying and distinguishing among the different part or product styles processed by the system. It also should be capable of quick change over of operating instructions and physical setup. The main components of the FMS are the workstations, material handling system, computer control system and human resources.

In a typical manufacturing system, the flexibility could be one of the following types with each have its different details [ElMaraghy, 2003]:
Machine flexibility, Production flexibility, Mix flexibility, Product flexibility, Routing flexibility, Volume flexibility and Expansion flexibility.

Another Important fact about the flexibility of a manufacturing system is its level of flexibility and number of machines. The level of flexibility is either a dedicated FMS (which is designed to produce a limited variety of parts style and the complete universe of parts to be made is known in advance) or random-order FMS (which designed to large number of parts with high variety subjected to day-to-day change). As For the number of machines, the manufacturing system could be a single machine cell, a flexible manufacturing cell or flexible manufacturing cell [Groover, 2000].

It is very important to mention that one of the major prerequisites for the implementation of the FMS (after being dedicated for mid-volume and mid variety production application) is that the manufacturing system is implementing what is called families of parts or group technology. The reason for such a prerequisite is that the similarity between the parts is the base of flexibility as the more there are similar or common features between the parts the easier and smoother the process planning, scheduling, setup changes and other manufacturing parameters are changed.

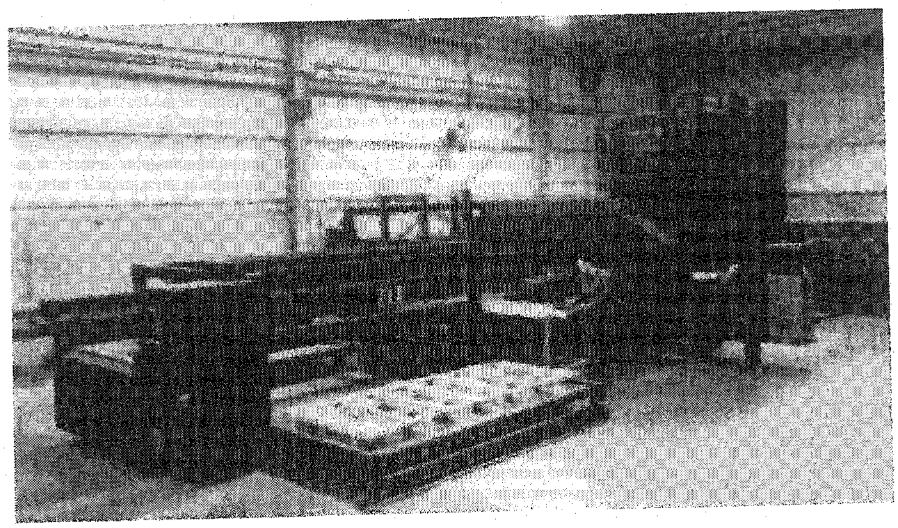


Figure 2.4 An FMS System [Salzman, 2002]

The major draw back of the FMS is its expensive cost. The cost of the general purpose numerically controlled machines and other programmable automation is very high compared to the utilization of its capacity and capability. Another drawback of the FMS is that its throughput is relatively lower than that of dedicated machines because of the single tool operation of the CNC machines [Koren et al., 1999]. This combination of the previous drawbacks makes the choice of the FMS is not desirable for some manufacturers. To overcome such problem the evolution of a new manufacturing paradigm is expected which is the Reconfigurable Manufacturing Systems RMS which will be discussed in this thesis in details.

2.7 CUSTOMIZED PRODUCTION MANUFACTURING SYSTEMS

Mass Customization is the customization and personalization of products and services for individual customers at a mass production price. Stan Davis in Future Perfect company first conceived the concept. Joseph Pine then further developed it in his book Mass Customization.

Mass Customization is a new manufacturing paradigm that lies in the business dimension and it is based on creating variety and customization through flexibility and quick responsiveness. It moves the focus from buying on price (because all goods and services appear to be much the same), to one of buying on satisfied needs and wants, at a competitive and affordable price. A company engaged in Mass Customization actually seeks to fragment the market through economies of scope. This is in contrast to a mass producer who seeks to consolidate and reduce choice through economies of scale.

Mass Customization processes integrate the design and sales activities before the production stage. Customers become actors within the design process. They are first engaged in dialogue to design their unique products that precisely meet their requirements. This dialogue can be overt or hidden, perhaps behind a question and answer session. Design can include simulation so that customers can trial the product under varying situations. Design aspects can include not only the product or service, but also its delivery and its on-going servicing. Once customers have designed their product, confirmed the purchase and settled the financial aspects, only then do you build and deliver the product or service [93].

With some service products like insurance Mass Customization involves an ongoing customer relationship. It allows customers to continually assess and amend their investment portfolios. This involvement can happen on any day of the week, at any time and from any place. It may be done by the customer themselves, their agent, the supplier, or any combination [93].

Mass Customization is the outcome of one to one targeting and promotion. Early adopters of mass customization need to identify suitable participants. Typically those who are more educated, can articulate their needs, are skilled with technology, have more complex lives, and have higher disposable incomes. These lead consumers to become a good source of product ideas that can be offered to the less adventurous customer. Another possibility is the implementation of user friendly interfaces that hide the design process and so are less intimidating for the followers.

The major advantages of Mass Customization are:

- By providing tailored products to meet particular needs, you make comparative shopping difficult and you shift the focus from price to benefits.
- While it is possible to manufacture at a mass produced price, you have the option to charge a premium while still retailing below the price of a custom product. This in turn will open your product to a wider market.
- Mass customization allows the ordinary man or women in the street to acquire a product that has been produced to meet their own particular needs yet at a competitive price - thus providing exceptional value for money.

Implementing this new paradigm from a manufacturing perspective requires a very flexible and responsive manufacturing system technology. This paradigm complies totally with the reconfigurable manufacturing systems that will be discussed in this thesis.

2.8 AGILE MANUFACTURING

Agile manufacturing is often confused with lean production, flexible manufacturing or CIM; however, this is not the case. Agile manufacturing is a business concept and its aim is to place the company ahead of its competitors. The goal of agile manufacturing is to combine the organization, people and technology into and integrated and coordinated whole. Knowledge and highly skilled, flexible, motivated labor are crucial resources for an agile corporation. On top of this a new form of organizational structure is needed, which incites non-hierarchical management styles, stimulates and supports individuals and brings about cooperation and teamwork. To achieve all of these changes, advanced computer based technologies is needed. A company can benefit from agile manufacturing only if it has a strategy of agility that will allow it to formulate a change plan to implement agility and be competitive.

Lean or world-class manufacturing is being very good at doing the things you can control. Agile manufacturing deals with the things you cannot control. Agility is the ability to thrive and prosper in an environment of constant and unpredictable change. Agile manufacturing as a philosophy is applied on the enterprise level (not only in the manufacturing level as in the reconfigurable manufacturing systems) in order to ensure that the whole enterprise is well responsive to the changing dynamic market.

Agile manufacturing is the ability to accomplish rapid changeover between the manufacture of different products. Rapid changeover is further defined as the ability to move from the manufacturing of one product to the manufacturing of a similar product with a minimum of change in tooling and software. Rapid changeover enables the production of small lot sizes, allowing for `just-in-time' production. Approaches such as Rapid Prototyping (RP), Rapid Tooling (RT), and Reverse Engineering are helping to accomplish rapid changeover between the manufacture of different assemblies [96].

In order to implement agile manufacturing we need to have a flexible organization. Implementation of lean manufacturing and CIM are also crucial to agile manufacturing, but these paradigms alone are not enough to achieve agile manufacturing. We also need to integrate flexible technologies with highly skilled, knowledgeable, motivated and empowered workforce with the help of organizational and management structures. These management structures will then stimulate cooperation within and between companies. Thus agile manufacturing is supported by three primary resources: innovative management structures and organizations, a skill based knowledgeable and empowered people and flexible and intelligent technologies [93].

To successfully implement agile manufacturing we need a lot more than just technology. Most importantly we need changes in attitudes, work practices, organization and people's skills. Over the years the manufacturing paradigms have followed the interventionist model, where humans intervenes technology when something goes wrong. We should be moving towards a more participatory model, where people can participate in the decision- making process even when it would be possible to use automated techniques. In order to achieve this, we need to implement concurrent engineering and human centered manufacturing systems in our corporations [93].

An agile enterprise is a fast moving, adaptable and robust business. It is capable of rapid adaptation in response to unexpected and unpredicted changes and events, market opportunities, and customer requirements. Such a business is founded on processes and structures that facilitate speed, adaptation and robustness and that deliver a coordinated enterprise that is capable of achieving competitive performance in a highly dynamic and unpredictable business environment that is unsuited to current enterprise practices. An Agile approach requires ability to easily reconfigure strategies, structures and processes and to continuous review company market positioning and the business environment [90].

As a conclusion it can be said that at the moment no known corporation has completely implemented agile manufacturing. Many companies have however started to move towards a more agile corporation.

2.9 RECONFIGURABLE MANUFACTURING SYSTEMS

2.9.1 Definition

Reconfigurable machining system (RMS) is a new class of manufacturing systems recently proposed which aims at combining the high throughput of dedicated manufacturing lines (DML) with the flexibility of flexible manufacturing systems (FMS). An RMS can simultaneously manufacture multiple product types with high throughput comparable to a DML, making it an ideal choice for the high-volume production of product families.

The Engineering Research Center for Reconfigurable Machining Systems at the University of Michigan, Ann Arbor defines Reconfigurability as: A Reconfigurable Manufacturing System (RMS) is one designed at the outset for rapid change in its structure, as well as its hardware and software components, in order to accommodate rapid adjustment of production capacity and functionality needed in response to new market circumstances; to produce a new part of the same part family.

The aim of RMS is to reconfigure systems, machines, and controls for cost-effective, rapid response to changes in market demand and products. The new reconfigurable manufacturing paradigm provides exactly the functionality and capacity needed, exactly when needed. Reconfigurability is defined as the ability to adjust the production capacity and functionality of a manufacturing system to new circumstances through rearrangement or change of the system's components. "Components" could be machines and conveyors in whole systems, mechanisms in individual machines, new sensors, or new controller algorithms. "New circumstances" may be changing product demand, producing a new product on an existing system, or integrating new process technology into existing manufacturing systems.

ElMaraghy, H. [2003] explains the dimensions of the reconfiguration of the manufacturing systems through classifying the reconfiguration process to physical configuration and logical configuration. Examples of physical configuration (sometimes called hard configuration) include layout configuration, adding or removing of machines, adding or removing of machines tools or components and material handling system configuration. Examples of logical configuration include reprogramming of machines, re-planning, rescheduling and re-routing. These classifications of system reconfiguration, in addition to human involvement reconfiguration, will be the basic foundation for the system reconfiguration design and control architecture presented in this thesis.

Urbani et al. [2001] defines the reconfigurability of a system as "the ability to adapt to expected or unexpected demand changes through consecutive system's and/or system component's structure modifications which also guarantee efficient functionality use" According to this definition, the more a system can produce wide mixes at different volumes through modifications of dedicated configuration the more reconfigurable the system. In order to be able to take reconfigurability of a system into consideration Urbani divided system life cycle into successive production period *T*. Each one of these periods corresponds to a known *productive objective* (mix and volumes) which is realized in one *configuration*.

Urbani explained the relation between the reconfigurability of a manufacturing system and the dedication and flexibility of that system using the time horizon figure (Figure 2.5) stating that one period T ends, and the following starts, when the corresponding productive objective changes so that the first configuration is no longer able to realize it.

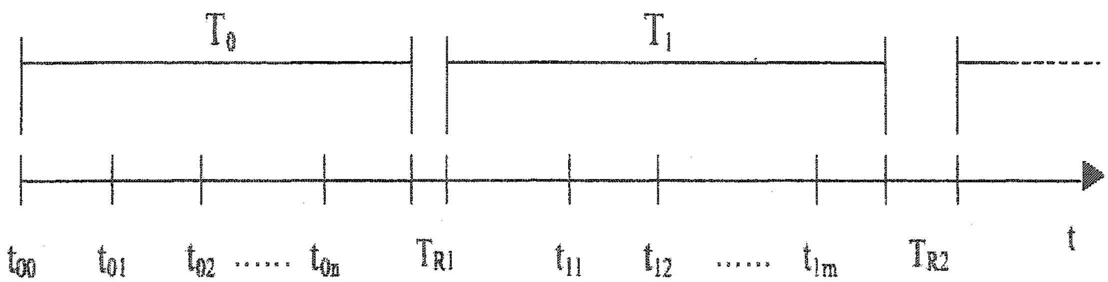


Figure 2.5 Time Horizon for Generically Reconfigurable Manufacturing Systems

To reconfigure from configuration T0 to configuration T1 a period TR is needed. Each period T can be divided into sub-periods t, which represents different mixes and/or volumes which can be manufactured by the same configuration. In such a scheme, then, we can take both flexibility and reconfigurability, expected and unexpected changes into consideration. Such a scheme may represent both FMS and RMS and DTL. Flexibility increases T and n, m. A dedicated solution implies long T and very poor n, m. Reconfigurability decreases TR and makes T shorter through the possibility of higher efficiency, i.e. higher reconfigurability allows producing wide mixes at different volumes through consecutive dedicated configurations.

2.9.2 Implementation of RMS

To achieve a high level of Reconfigurability the system should posses the following key characteristics: *modularity*, which means to design all system components (both software and hardware) to be modular; *integrabilty*, which means to design systems and components for both read integration and future introduction of new technology; *customization*, which means to design system capability and flexibility (hardware and control) to match the application or the product family; *convertibility*, which allow quick changeover between existing products and quick system adaptability for future products; and finally *diagnosability,* which is the quick identification of sources of quality and reliability problems in the system [Mehrabi et al, 2000]. Modularity, integrabilty and diagnosability reduce the reconfiguration time and effort, while customization and convertibility reduce cost [Koren et al., 1999].

Thus, RMS is designed at the outset of rapid change in its structure, as well as its hardware and software components, in order to quickly adjust its production capacity and functionality in response to sudden, unpredictable changes in market demand as well as introduction of new products or new process technology [Koren et al., 1999]. This design characteristic is shown in Figure 2.6.

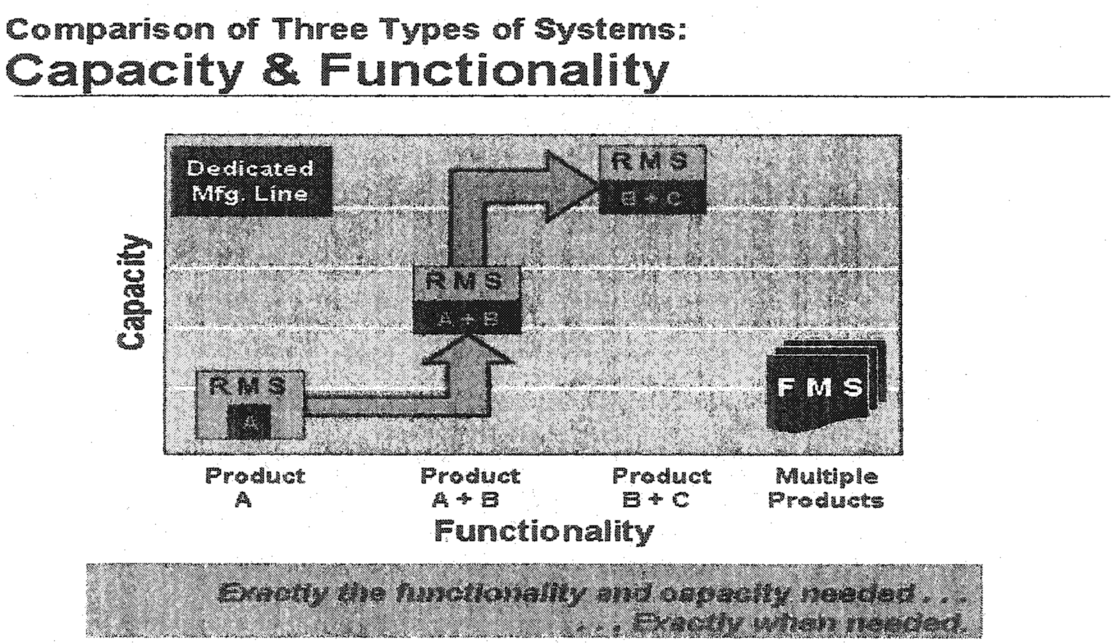


Figure 2.6 Capacity and Functionality Scalability in RMS [Koren et al., 1999]

From the system perspective, reconfigurability is achieved by recombining or changing particular manufacturing units or machines into new compounds. Thus it is possible to meet new demands, for example with respect to work sequences and capacity by parallel or serial arrangement of the manufacturing units. A reconfigurable manufacturing system should offer alternatives to the user, it has to be multi-functional. This means that the manufacturing system can produce different work pieces with different functions and in different configurations.

2.9.3 Practical Examples of RMS

It is difficult to find a practical example of a complete reconfigurable manufacturing system as the complete implementation of these systems is still in the research phase. However there are few examples on the system level for "partially" reconfigurable systems found in some research laboratories or in real industrial field. As for the machine level there are quite more examples and actually much more developed.

An example of a system that is considered reconfigurable is in the wood industry. The manufacturing system is composed of (together with other machines) reconfigurable through feed machine for the edging of furniture parts. The implementation of this type of reconfigurability depends on the number of variants. Manufacturers of fitted kitchens produce more than 1000 variants per day and, therefore, need faster conversions than mass producers. Figure 2.7 shows this reconfigurable machine [Heisel, 2003].

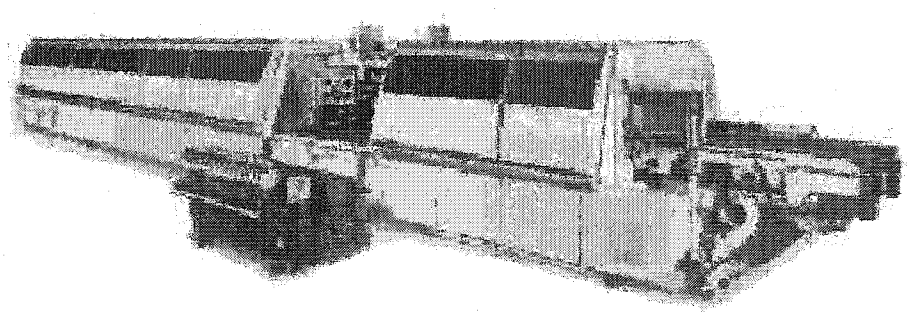


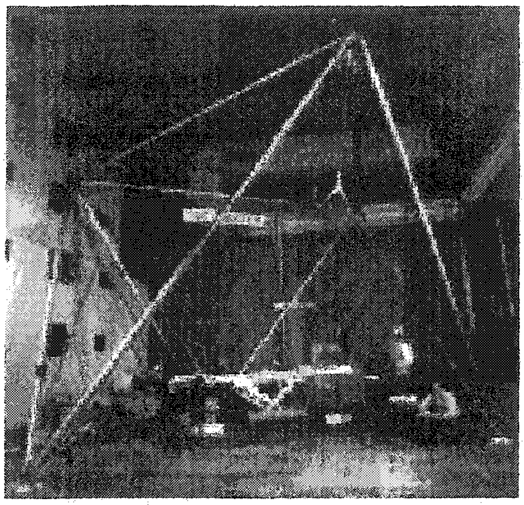
Figure 2.7 Reconfigurable Through Feed Machine for the Edging of Furniture Parts [Heisel, 2003]

The Toyota engine factory in Texas USA is another good example of moving towards reconfigurability on the system level. The reason for that as stated by the facility manager is the short life cycle of the engines. Ten years ago, the life cycle for Toyota engine was around 10 years, thus it was feasible to have a dedicated line for each type of engines. However, this is no more cost effective and the solution proposed by Toyota was to redesign the manufacturing system to be reconfigurable. This was achieved through standardizing part of the system and modularly designing the rest of the system to be changed with different types of engines. Practically speaking the system is physically reconfigured by reconfiguring the jigs and cutting tools of some machines and logically reconfigured through installing different NC machines programs according to the type of engine. This is integrated with human configuration for the new tasks as well as decreasing the preparation time.

There are various examples for reconfigurability on the machine level. Parallel Kinematics Machines (PKM) are considered a good example of reconfigurable machines. Cable-based machines are an example of reconfigurable PKM machines. The main advantage of these machines is that the length of travel for a cable is large compared to the size of the actuator. Also, a cable-based system can be reconfigured relatively easily and quickly to handle changes in mounting configurations at various work sites. In addition, they scale well in both size and payload capacity to allow application to a large variety of tasks. Since the winches and winch controllers for all six axes are identical, these systems are very modular and easy to maintain. Another alternative for reconfigurability is the location of the control and actuator package. There are two distinct configurations. One configuration locates the winches and control equipment on or near the ground, and the cables are simply redirected over pulleys that form the overhead triangle (Figure 2.8a). This configuration allows a passive suspended platform. Another configuration places the actuation and control equipment directly on the suspended platform (Figure 2.8b). There is typically a power tether draped to the platform. Control commands may be generated from an onboard computer or radio linked from an off-board location. Cable-based machines can either be self-supported (Figure 2.8a) or facility-mounted (Figure 2.8b). Self-supported machines use a structural frame to provide the elevated mounting points that form the overhead triangle [Bostelman et al., 2000].

Another commercial reconfigurable machine is the Masco SuperCenter machine [94]. Reconfiguring the machine can get the production volume advantages of a dedicated machine and the flexibility of running many different parts through the machine.

(a)



(b)

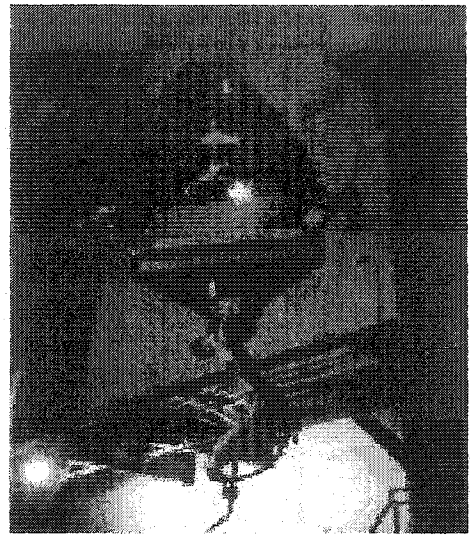


Figure 2.8 RobCrane Prototypes. (a) Supported from six-meter octahedral frame. (b) Supported from facility ceiling/walls [Bostelman et al., 2000]

The facility can run a six cylinder crankshaft one week and then run an eight cylinder crankshaft the next. Or run a transmission shaft one day and a camshaft the next. The machine design is based on plug-and-play modular configuration. Each station is a separate module that can be relocated, removed or replaced as the need arises.

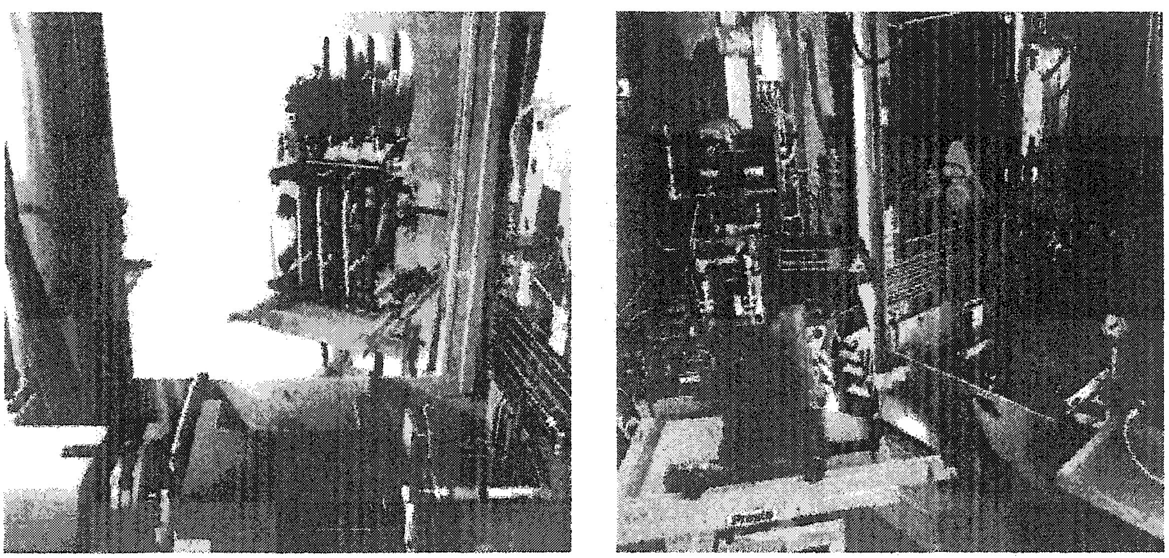


Figure 2.9 Masco Super Center Reconfigurable Machines [94]

Besides the commercial reconfigurable machines there are quite few examples of these machines that are within the academic research laboratories. The Polypod Robot is one example of these machines, Figure 2.10, which was developed at Stanford University and the University of Michigan reconfigurable machine tool, Figure 2.11.

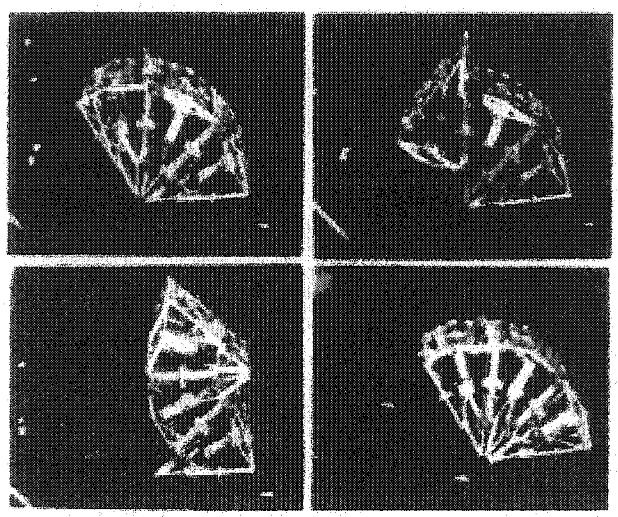


Figure 2.10 Polypod Reconfigurable Robot [88]

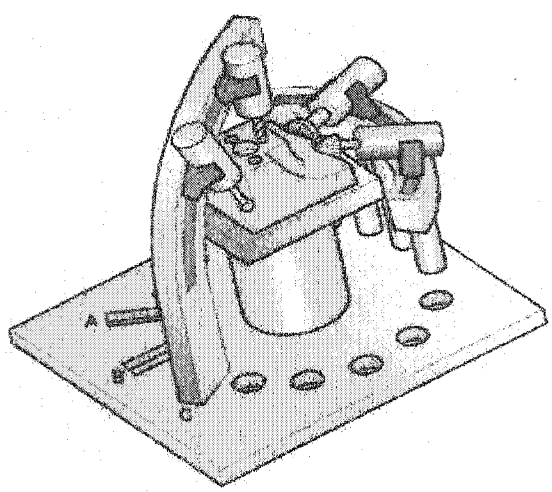


Figure 2.11 Reconfigurable Machine tool [85]

2.10 CHAPTER SUMMARY

Moving from mass production to lean manufacturing to flexible manufacturing systems and finally introducing reconfigurable manufacturing systems indicates that the evolution of manufacturing systems is always functional of the changing market characteristics. Today's market is becoming more complex in the sense of the needs of customer. Modern customers are no more attracted by lower prices, however; they are expecting products of high quality, more customized and still at lower prices. Such sophisticated requirements lead to a high competitive market where classical manufacturing systems cannot be of a great advantage. For such new environment reconfigurable manufacturing systems were introduced.

Reconfiguration is a fast-growing research field in manufacturing that spans from system-level design issues to modular machines, reconfigurable control, and rapid ramp-up methods after reconfiguration. The National Research Council [84] mentioned that Adaptive, Reconfigurable Manufacturing is priority number one for future systems. In the rest of the thesis the design of reconfigurable manufacturing systems and how it is controlled will be explored from a systematic perspective.

CHAPTER 3

LITERATURE REVIEW

3.1 INTRODUCTION

Systems engineering is basically a structured approach to think about and work with systems. Hitomi finds four characteristics of systems engineering in the literature [Blanchard and Fabrycky, 1998]:

(1) A top-down approach that examines how individual system elements work together to influence overall system performance. The bottom-up approach is complementary in that it deals with individual elements first and then considers the relationships among the elements. Both, the top-down and bottom-up approaches assume that systems are hierarchical in nature.

(2) A life-cycle orientation that addresses all phases of a system from conceptualization, rough design, detailed design, and operation to phase out.

(3) System design starts with the definition of system requirements, relates these requirements to design decisions, and performs system evaluations relative to the requirements.

(4) System design requires an interdisciplinary approach to understanding and handling the system complexity.

Manufacturing system as defined in chapter 1 is a collection of components (machines, equipments, people, etc.) bound by common material and information flow and working together to transform raw material into marketable goods, [Chryssolouris, 1992].

Manufacturing system design applies a system engineering process to create and operate a manufacturing system from the definition of the system needs and requirements to the phase out of the system [Linck, 2002].

Manufacturing system design is the process of defining the behavior and the structure of a manufacturing system [Duda, 2000]. Behavior for a system describes WHAT the system is to do independent of HOW the system will do it. As for the structure of a system; it is the organization of the components that make up the system including the number of these components, their arrangement and their interrelation. According to Cochran [2001]; manufacturing system design covers all aspects of creating and operating a manufacturing system. Creating the system includes equipment selection, physically arranging the equipment, work design (manual and automatic), standardization, design of material and information flow, and so on. Operation includes all aspects that are necessary to run the created factory.

The design of manufacturing systems is an inherently complex task. It starts with the definition of system requirements and ends with operation of the system. Many people from various organizational levels and disciplines have to cooperate to create and operate a successful manufacturing system.

Manufacturing system design methodology refers to the theoretical analysis of the methods and processes used to develop and/or describe a manufacturing system. It is a set of instructions, rules, and/or guidelines that defines the process of achieving a specific task. A manufacturing system design framework is a conceptual structure used to group ideas that guides the designer of the system to achieve his design objectives.

In this chapter various frameworks and approaches for the design and control of different manufacturing systems environment will be reviewed, in addition to some of the system design tools that will be also explored. Finally, a comparison of these frameworks and approaches will be done as a summary of the review and followed by some comments concerning the future needs for the manufacturing systems design and control approaches.

3.2 MANUFACTURING SYSTEM DESIGN FRAMEWORKS

3.2.1 Manufacturing System – Product Matrix Framework

Hayes and Wheelwright [1979] developed a framework for thinking about the relationship between product and manufacturing system characteristics (or can be called configuration). The system is illustrated in Figure 3.1.The rows of the matrix represent different configuration (or process structure) of the manufacturing systems, ranging from job shop system to one based on continuous flow of material. The columns represent the product structure and characteristics from a volume and variety perspective. The positions along the diagonal of this matrix represent the natural position of the system.

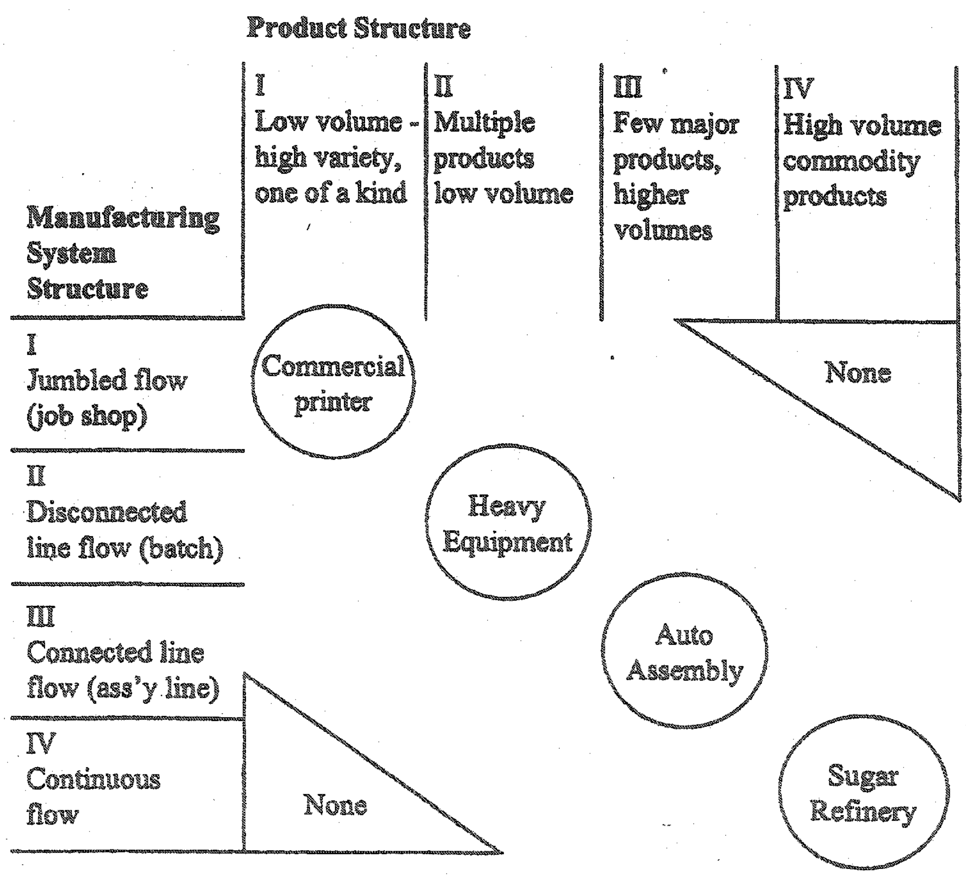


Figure 3.1 Manufacturing System – Product Matrix [Hayes and Wheelwright, 1979]

3.2.2 Miltenburg Framework for Selecting a Manufacturing System

Miltenburg [1995] extended the previous matrix and developed a more structured approach to configuration selection based also on the relation between different configurations and the corresponding product mix (volume and variety). He also rated these configurations in terms of their manufacturing outputs (ability to meet their strategic objectives). Figure 3.2 represent Miltenburg framework.

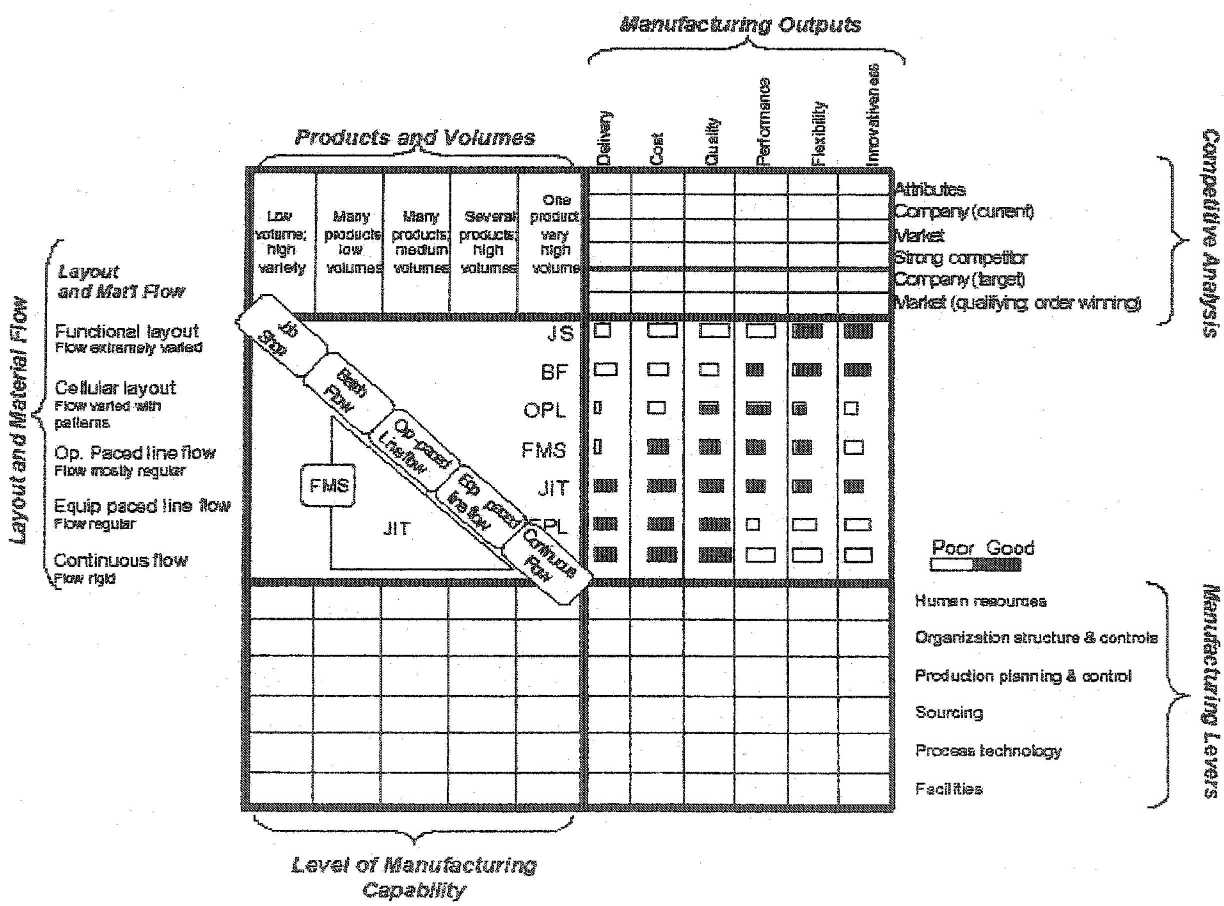


Figure 3.2 Framework for Selecting a Manufacturing Strategy [Miltenburg, 1995]

The framework is very useful in analyzing the present position of a company and deriving an improvement strategy. It shows the impacts of strategic decisions on manufacturing systems such as increasing production volume or changing production technology. A shortcoming of the framework is that it treats the configurations as discrete choices and does not provide guidance on how to combine advantages of different configurations. The framework also does not assist the actual design of the manufacturing it is limited to high- level strategic choices.

3.2.3 Black Graph

Black [1991] established similar correlations between production volume and mix and system configuration. The graph is not considered as a design framework; however it helps the manufacturing system designer to select the suitable kind of manufacturing system to design. The relationships, however, are only useful for a very high- level selection of possible configurations. First, there is significant overlap between the different configurations as shown in Figure 3.3. Second, many existing manufacturing systems show characteristics of several configurations. Third, it is assumed that basically two variables (production volume and mix) are the main determinants for the system configuration.

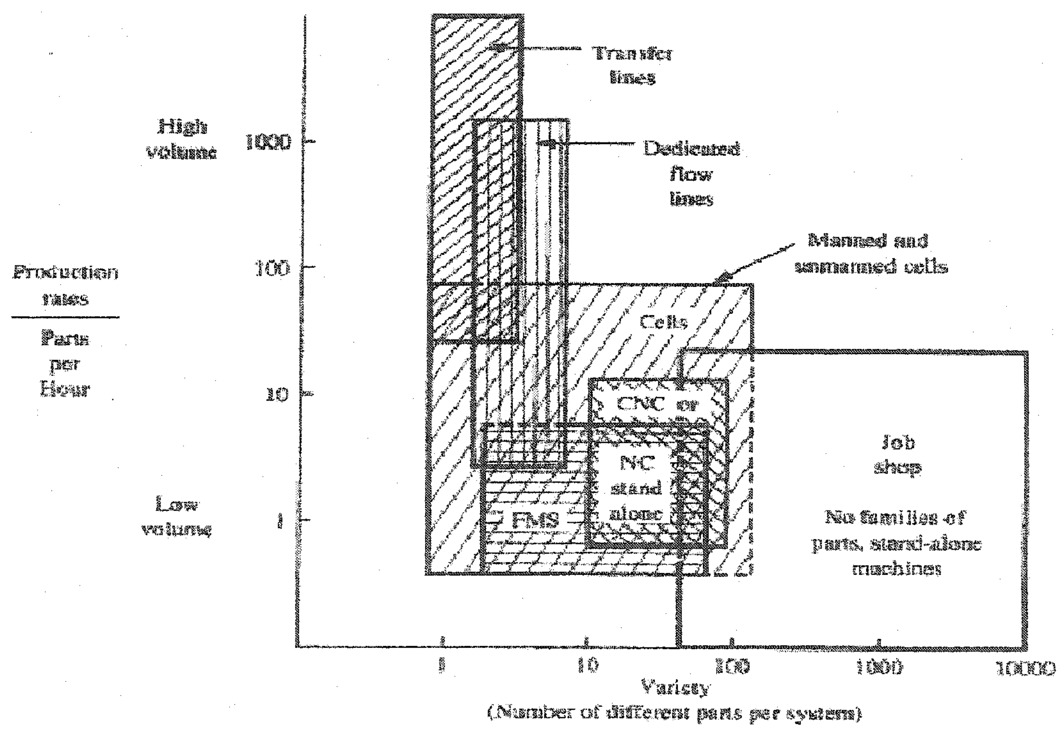


Figure 3.3 Relationship between Product Rate/Mix and System Configuration [Black, 1991]

3.2.4 Chryssolouris Graph

Chryssolouris [1992] developed a simple graph shown in Figure 3.4 that provides a general guidance of selecting a manufacturing system configuration as a function of lot size. He based his graph over a thorough review of the advantages and disadvantages of different configurations from the perspective of product mix, volumes, inventory, scheduling and flexibility. He didn't include the FMS as he considers it a hybrid of job shop and lean cell configuration which leads to the following important point. Chryssolouris states that systems' structures often occur as combinations or in modified forms. That is the selection of a configuration is just a starting point for the rest of the manufacturing system design process, and the resulting system design may end up being different from the predefined configuration.

The last point is the main reason for considering the previous four manufacturing systems selection approaches within the survey of the manufacturing system design frameworks although they do not represent a real design approach.

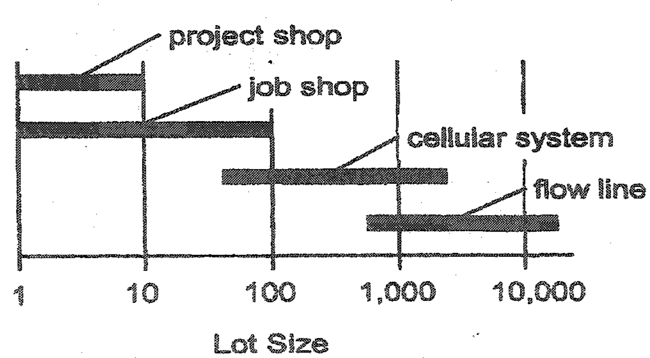


Figure 3.4 Manufacturing System Configuration Selection Based on Production Lot size [Chryssolouris, 1992]

3.2.5 Design by Philosophy (Holistic Approach)

This approach for designing manufacturing systems is based on a design philosophy that guides the designers through all the stages of the manufacturing system design process. An example of that approach is what happened in Toyota where all the enterprise shares a common vision of the characteristics of an ideal system design.

3.2.6 Purdue Enterprise Reference Architecture PERA

The Purdue Enterprise Reference Architecture (PERA) provides a framework for examining manufacturing system design from the definition of enterprise objectives to the design of individual tasks [Williams, 1993]. PERA distinguishes five phases: concept phase, definition phase, design phase, installation phase, and operations phase. PERA links information architecture and a manufacturing architecture with a human-organization architecture. The PERA framework is illustrated in Figure 3.5.

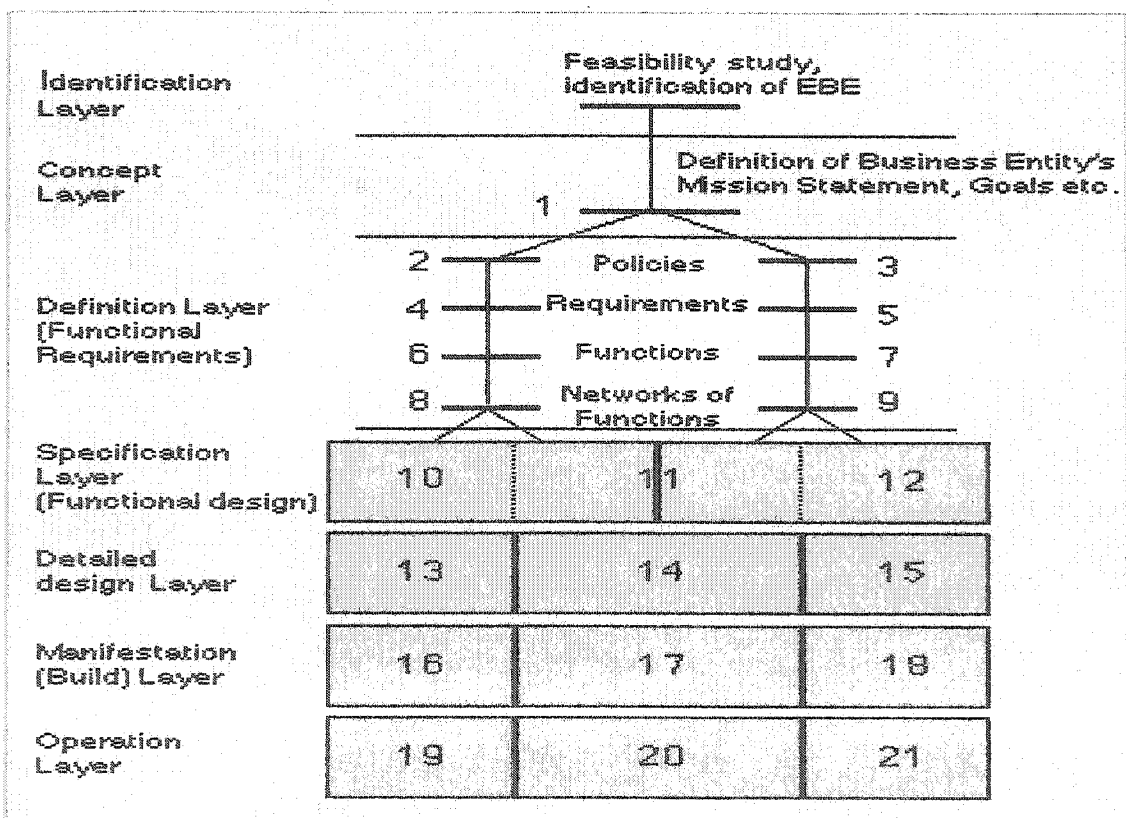


Figure 3.5 PERA Life Cycles Layers [Williams, 1993]

Although PERA provides a useful framework to convey the complexity of manufacturing systems, the overall application process remains undefined. The PERA methodology is good for the "master planning", and it has a detailed implementation guide. However, it does not have any tools and methods for identifying the information requirements in order to develop necessary software and hardware system to support the operation

3.2.7 Toyota Production System (TPS) Frameworks

There are many frameworks that were developed to capture the merits of what Toyota's production system succeeded in achieving. Among these frameworks are:

- Sakakibara et al. [1993] developed a framework for Just-in-Time (JIT) manufacturing. The core Just-In-Time manufacturing framework is shown in Figure 3.6. The framework is based on academic and practitioner literature and provides a valuable summary of research with respect to the Toyota Production System. The upper and lower parts of the framework show how manufacturing strategy, management, and organizational aspects interrelate with each other. The main focus of the framework is on the middle part and deals with continuous improvement and problem solving activities.

- Monden [1983) developed a framework to show how elements of TPS support the high-level objectives and also recommend an implementation order for these elements. The intent of the framework is to show relationships between system goals and means. The idea is to start with the means at the bottom and to move upward to achieve the ultimate goal of increasing profits. Monden provides a bottom-up approach for manufacturing system design based on methods and concepts observed at Toyota, the system is shown in Figure 3.7. The framework is useful in clarifying the interrelationships between those concepts. However, the distinction between means and goals is unclear.

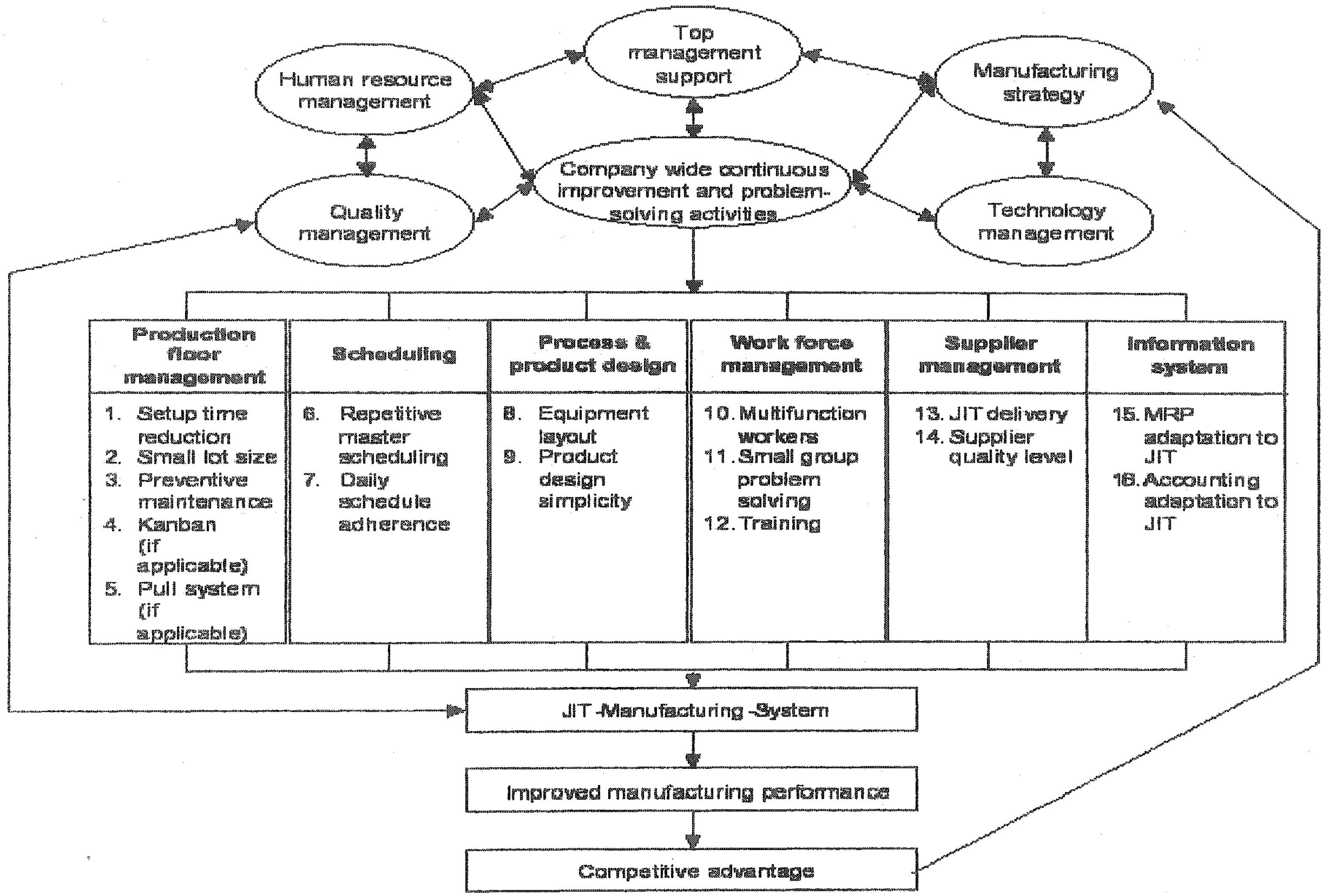


Figure 3.6 Core Just in Time Manufacturing Framework [Sakakibara et al., 1993]

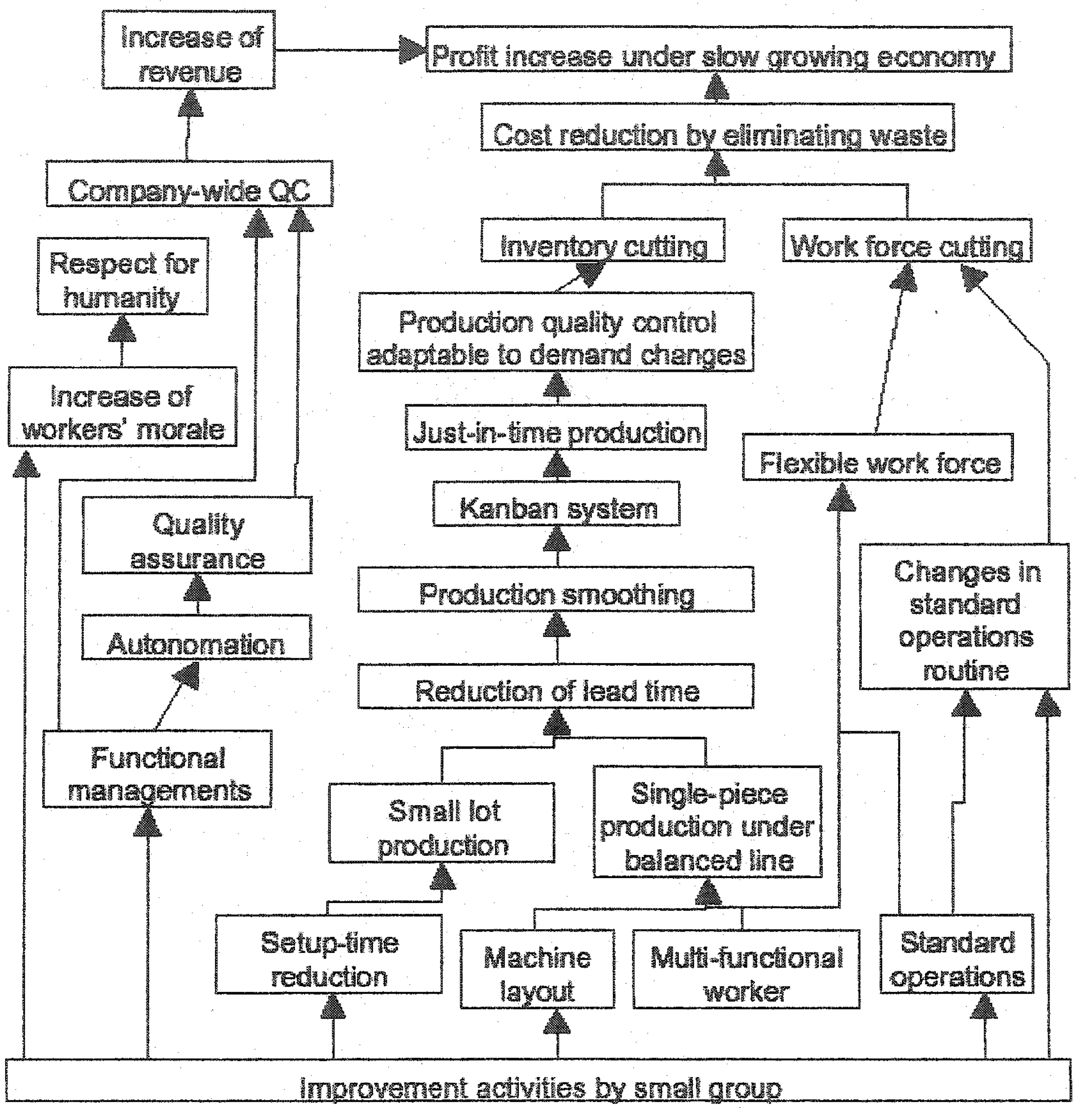


Figure 3.7 Implementation Steps for Toyota Production System [Monden, 1983]

- Lean Manufacturing Framework (TRW Automotive) shown in Figure 3.8 is an extension of the TPS basic concepts of just in time and jiodoka was developed by Suzuki [1999] to show the design methods that contribute to their achievements. Also the framework shows how these design methods succeed in the waste elimination purpose of lean manufacturing. This elimination leads to the achievement of the high-level goals of cost reduction the improvement of productivity.

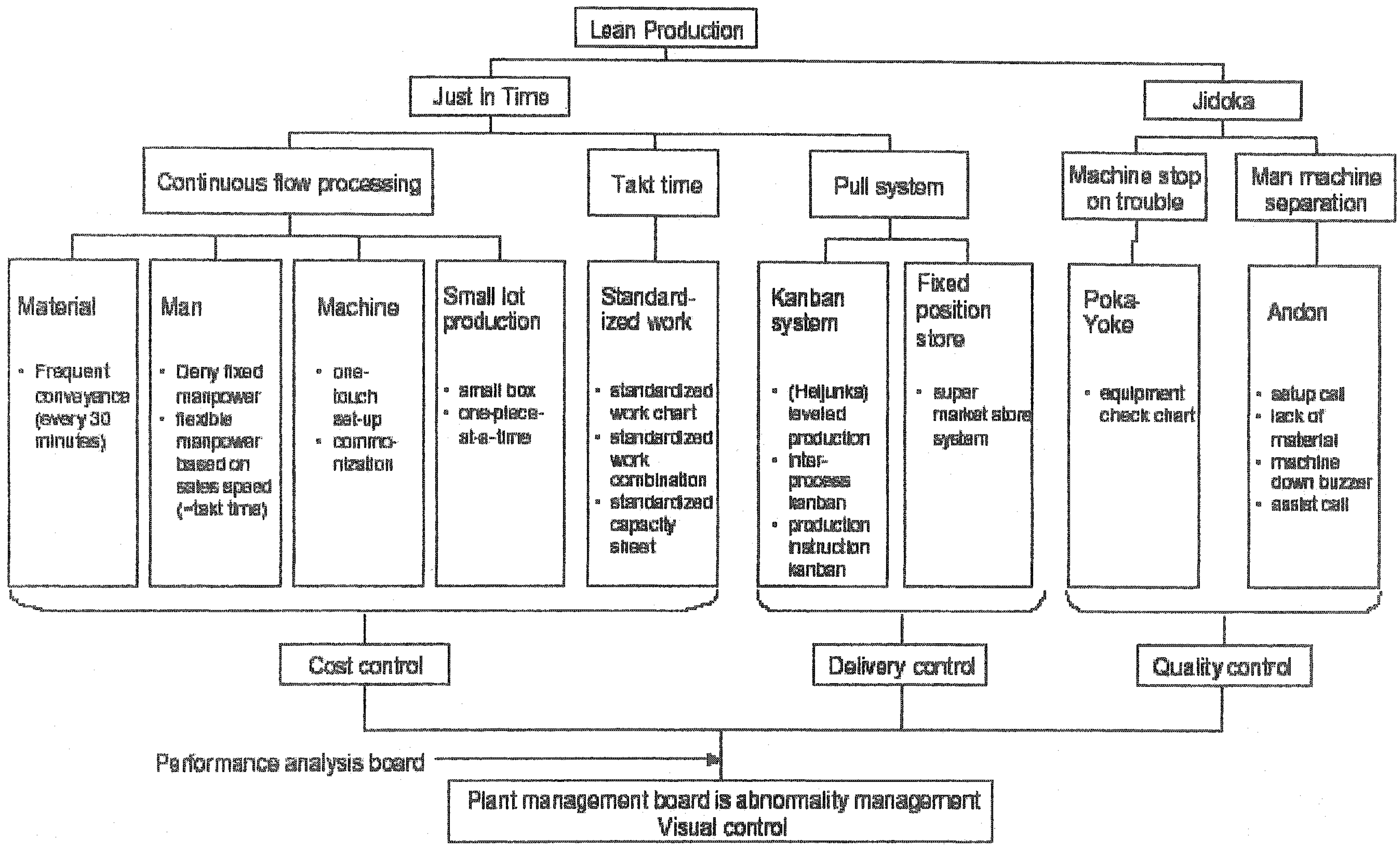


Figure 3.8 Lean Production Framework [Suzuki, 1999]

TPS related research is mostly empirical and descriptive. The frameworks discussed here attempt to help system designers create a manufacturing system that can emulate manufacturing efficiency of the system observed at Toyota. In terms of systems engineering, the focus of the frameworks is on operational aspects of system design

3.2.8 Hierarchy of Manufacturing Objectives

Hopp and Spearman [1996] developed hierarchy of manufacturing system objectives through a decomposition approach of manufacturing system design requirements. The hierarchy shown in Figure 3.9 focuses on operational practices such as reduction of variability, utilization considerations, service rate, and inventory. The two high- level goals of low costs and high sales lead to conflicting practices at lower levels. For example: low inventory is desirable to reduce costs, while high inventory ensures meeting delivery demands to achieve high sales. The hierarchy is not intended to be a manufacturing system design framework. It illustrates how operations management relates to overall manufacturing system objectives. Furthermore, the hierarchy points out the presence of trade-offs in the operation of manufacturing systems.

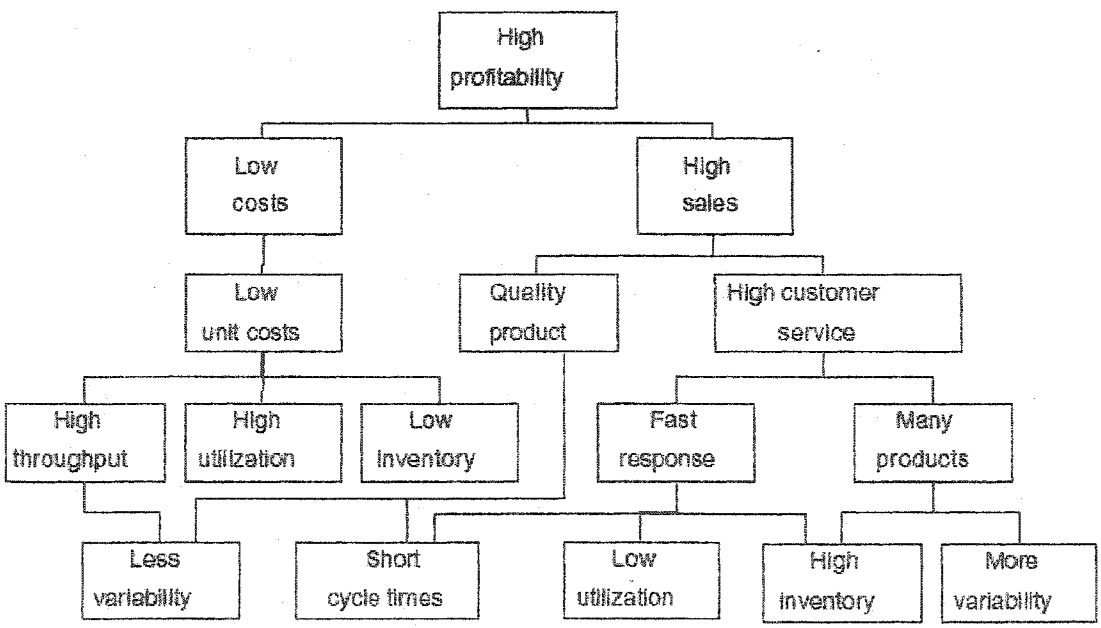


Figure 3.9 Decomposition of High Profitability for Manufacturing Systems

[Hopp and Spearman, 1996]

3.2.9 Framework for Unified Manufacturing Systems Management

Wu [2000] tried to develop a comprehensive framework for the design of manufacturing and supply systems. The framework attempts to provide a unified approach to the design and operation of manufacturing and supply systems. The framework consists of three main areas, the three interfaces between the areas, and three layers of architecture that overlay all three areas. For example, Wu aims to delineate a clear link between the strategic positioning of a company (i.e., MSA-Manufacturing/ Supply Strategy Analysis) and the best structure of a manufacturing system to support strategic objectives (i.e., MSD-Manufacturing/Supply Systems Design). MSO performs plan, monitor and control functions and reflects activities normally associated with MRP/ERP systems. Wu states that the overlapping regions shown in Figure 3.10 still represent areas where further research is needed to achieve an integrated manufacturing system management framework.

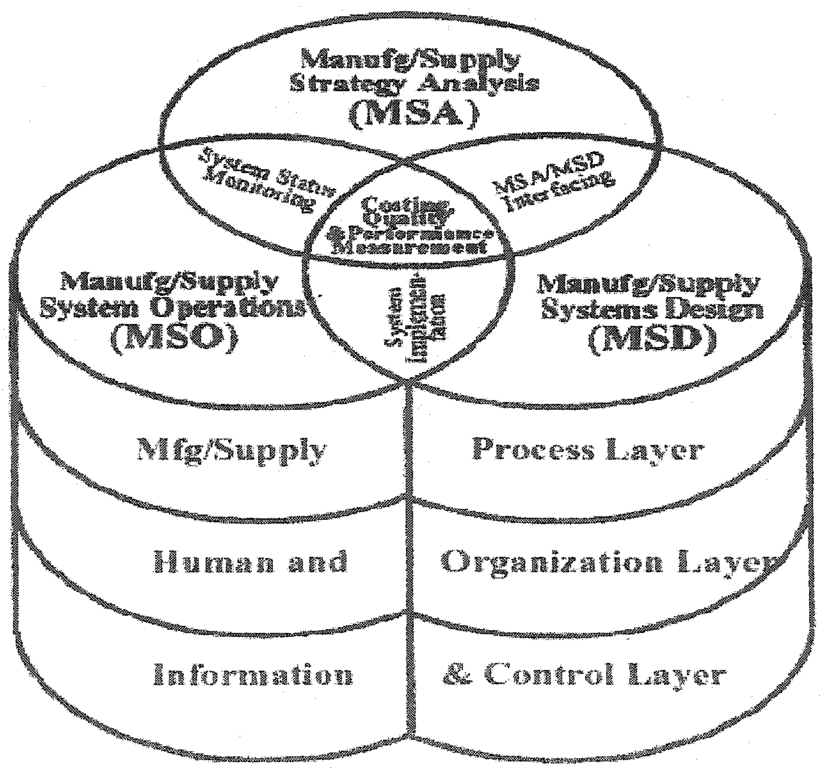


Figure 3.10 Structure for Unified Manufacturing System Management UMSM [Wu, 2000]

3.2.10 The Vee Model

Forsberg et al [1992] developed the Vee Model that addresses the technical aspect of the project cycle and represents the sequence of project events. The project could be the design of manufacturing systems or any part of the manufacturing subsystem. The model is illustrated in Figure 3.11.

The left side of the Vee is a representation of the evolution of user requirements into functional requirements through the process of decomposition and definition. The downward iterations include engineering studies, requirements understanding modeling, feasibility demonstrations, and with-if analysis, and descend to the level of the system under investigation such as subsystem or piece parts as examples. The right side of the Vee represents the integration and verification of the system components into successive levels of assembly. The upward iterations ensure that the technical baseline, as it evolves, continues to be satisfactory to the customer or market requirements.

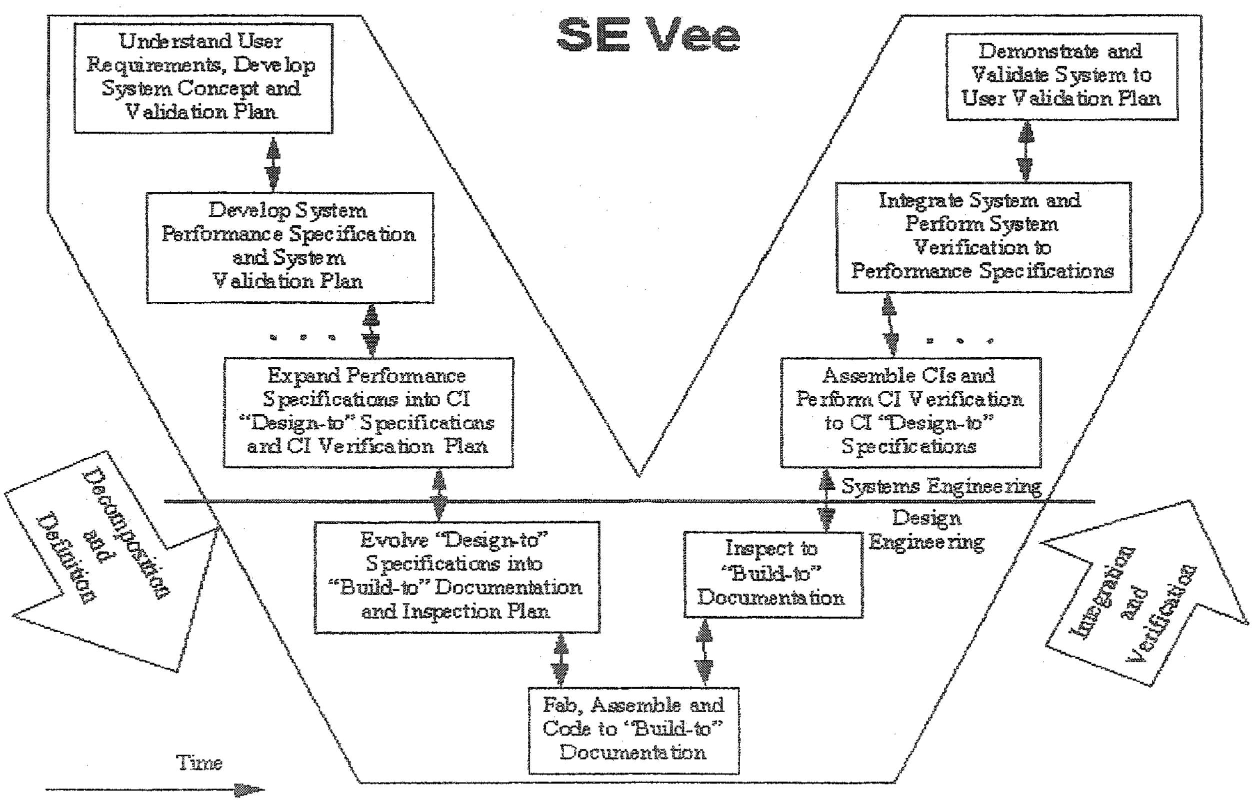


Figure 3.11 The Vee Model [Forsberg, 1992]

3.2.11 Factory Design Procedures

System design procedures provide a detailed step-by-step guide for factory design. The approach presented by Kettner is one of the standard and classical procedures in German research and industry [Kettner et al., 1984]. The goal of the procedure is to provide a logical sequence and time sequence of main planning steps for designing a factory. Kettner subdivides the tasks into six phases as shown in Figure 3.12 and describes supportive tools for each phase such as organization charts, layout, planning tools and workstation design.

The procedure is very comprehensive and covers all systems engineering phases except the operational phase. The general structure is very intuitive in the way that it divides the complex task of factory design into different phases with an increasing level of detail. However, the procedure fails to provide linkages between the phases making it difficult to understand how decisions at later design phases affect the achievement of requirements from earlier phases.

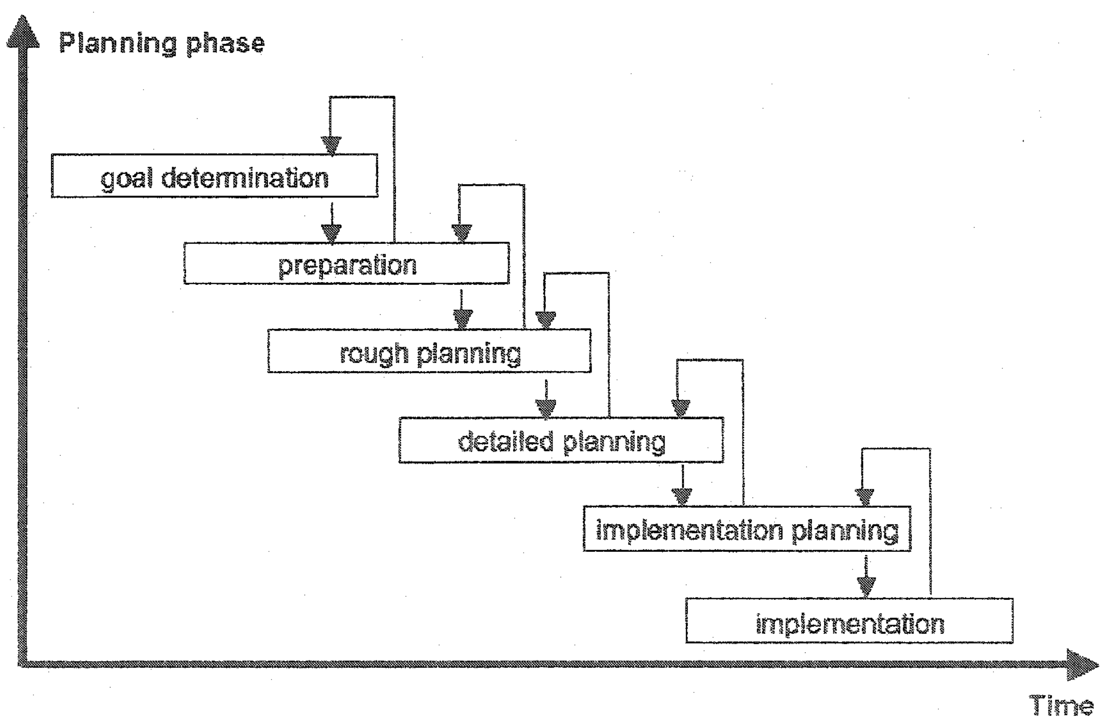


Figure 3.12 Factory Design Procedure [Kettner et al, 1984]

3.2.12 Lean Aerospace Manufacturing System Design

The lean manufacturing center at MIT developed a general framework for the design of lean manufacturing systems. The center focuses on how to implement this approach to the aerospace industry to design a lean aerospace factory. Figure 3.13 describes the design framework.

The Framework is of the diagonal type and it specifies the inputs to the design process in a sequential way and classifies the input into internal input that develops the manufacturing strategy that will control the design process and external input that comes from the other world. The framework highlights the different activities that are associated with the design process and when to improve the design [88].

This framework is very general and does not specify any exact design procedures and how these steps in the framework interact together and also does not show how the improvement process of the design (to be lean) is carried out.

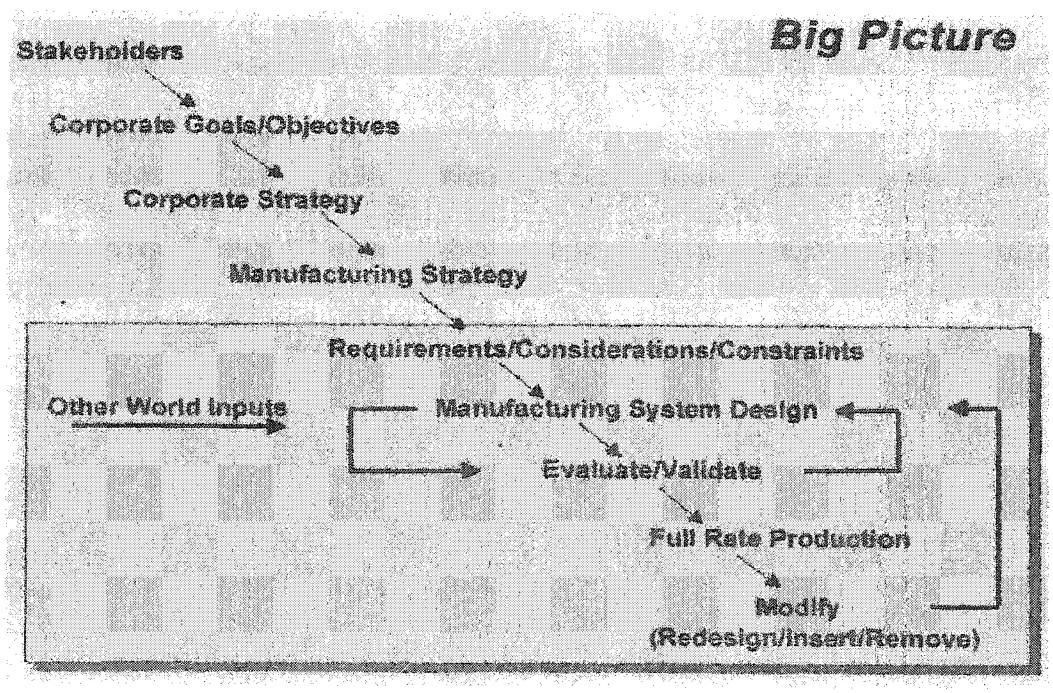


Figure 3.13 Lean Manufacturing Systems Design

3.2.13 Application of Axiomatic Design in Manufacturing Systems

Axiomatic design was developed to provide a structured, scientific approach for the generation and selection of good design solutions [Suh, 1990]. While there are many steps in the manufacturing system design process, the axiomatic design process focuses on the generation of requirements and the selection of means for achievement. In fact, one of the central ideas of axiomatic design is the importance of distinguishing between what (objectives) is to be achieved by the manufacturing system and how (means) it will be achieved. In axiomatic design terminology, the objectives of the design are expressed as Functional Requirements (FRs) and the solutions are expressed as Design Parameters (DPs). The design process is one of selecting the best set of DPs to satisfy the FRs.

The two axioms of axiomatic design are used to select the best set of possible design parameters. The two axioms are as follows [Suh, 2001]:

1. Independence Axiom: Maintain the independence of the functional requirements.
2. Information Axiom: Minimize the information content of the design

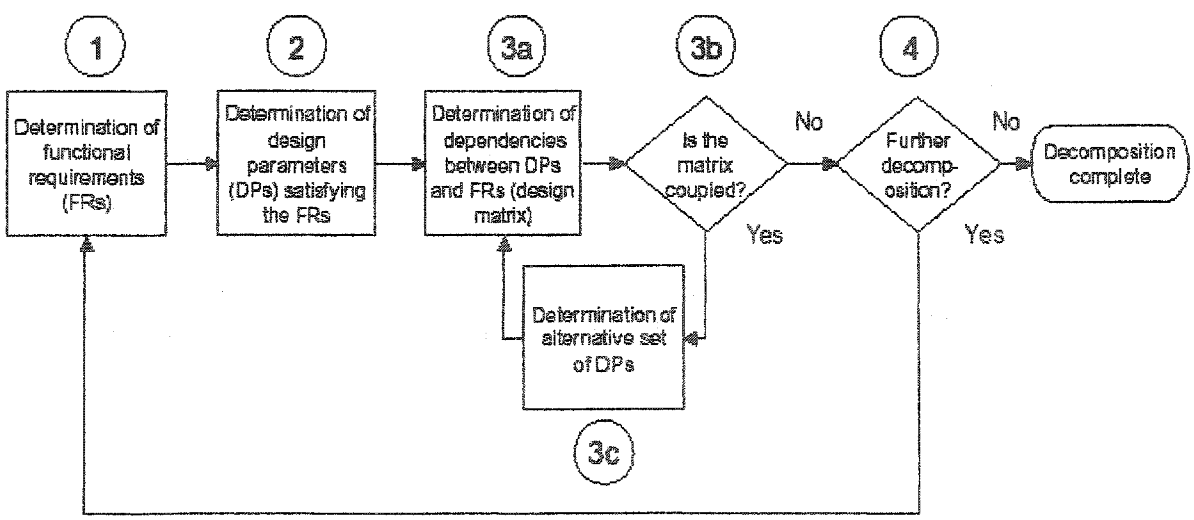


Figure 3.14 Implementation of Axiomatic Design in the Manufacturing System Design

Gu et al. [2001] presented a method for design of manufacturing systems by combining the axiomatic design approach and systematic design approach. The methodology explains how design axioms are used during different design stages, and also provides a step-by step approach for the design of manufacturing systems. The proposed design methodology divides the design process of manufacturing systems (MS) into four phases:

- Phase I: Definition of design requirements of MS
- Phase II: Conceptual design of MS
- Phase III: Configuration design of MS
- Phase IV: Detailed design of MS

At each phase, design axioms can be used to assist the designers in analyzing and evaluating design solutions. The proposed methodology is shown in Figure 3.15.

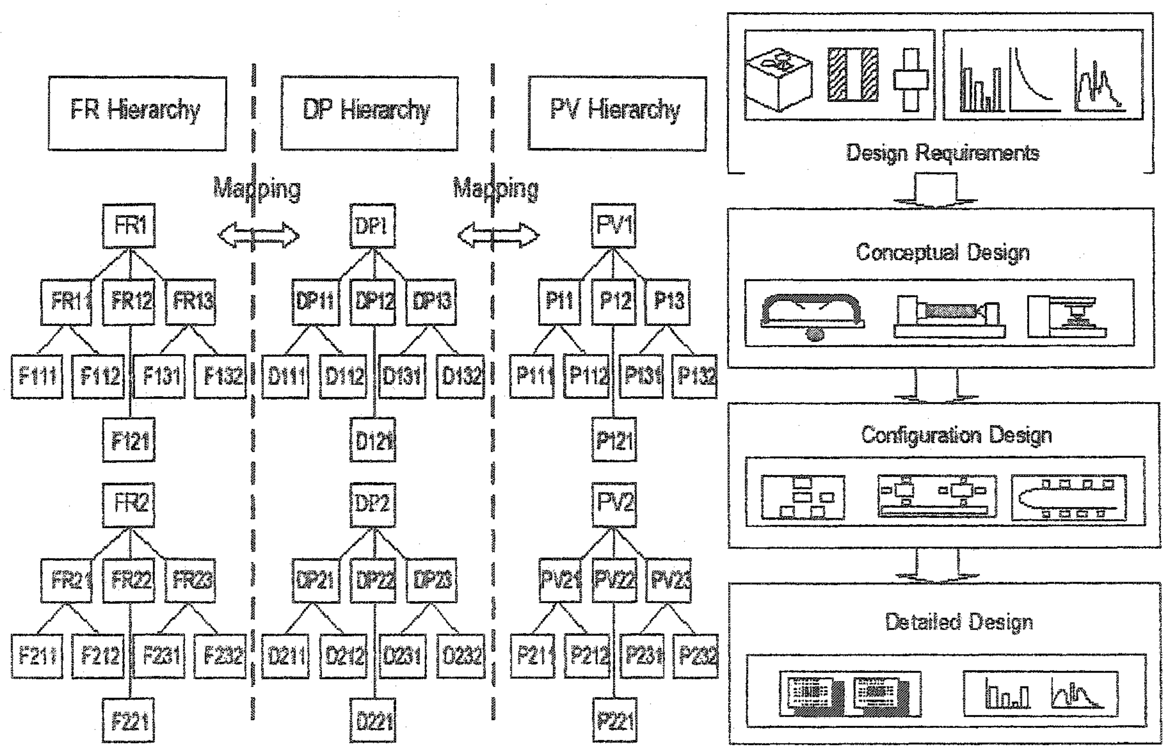


Figure 3.15 Combining Axiomatic Design and Systematic Design Process for the Design of Manufacturing Systems [Gu et al., 2001]

3.2.14 Manufacturing System Design Decomposition MSDD

Cochran et al. [2000] integrated axiomatic design approach with the concepts of several design frameworks as TPS and others and developed the MSDD approach that is shown in Figure 3.16. The motivation for developing the Manufacturing System Design Decomposition (MSDD) is the desire to have an approach that can link the upper level objectives of a system to the operational level decision making process to guarantee that every operational design parameter is consistent with the higher level objectives.

The focus of the decomposition is on specific activities and decisions that are likely to be under the control or influence of the group of engineers, managers, and operators responsible for designing and running a manufacturing system. Thus, the decomposition is limited to the shop-floor level. Once a set of DPs has been determined, the next step is to decide if further decomposition is necessary. In the case of the MSDD, decomposition proceeds for as long as it is possible to do so without limiting the usefulness or range of applicability of the decomposition. When further decomposition is needed, the next step is to develop the next level of FRs. By following a downward path in the MSDD), one can see this alternation back and forth between FRs and DPs. The decomposition process resulted in six main areas: quality, identifying and resolving problems, predictable output, delay reduction, operational costs, and investment. Linck [2001] applied the MSDD approach to practical case studies.

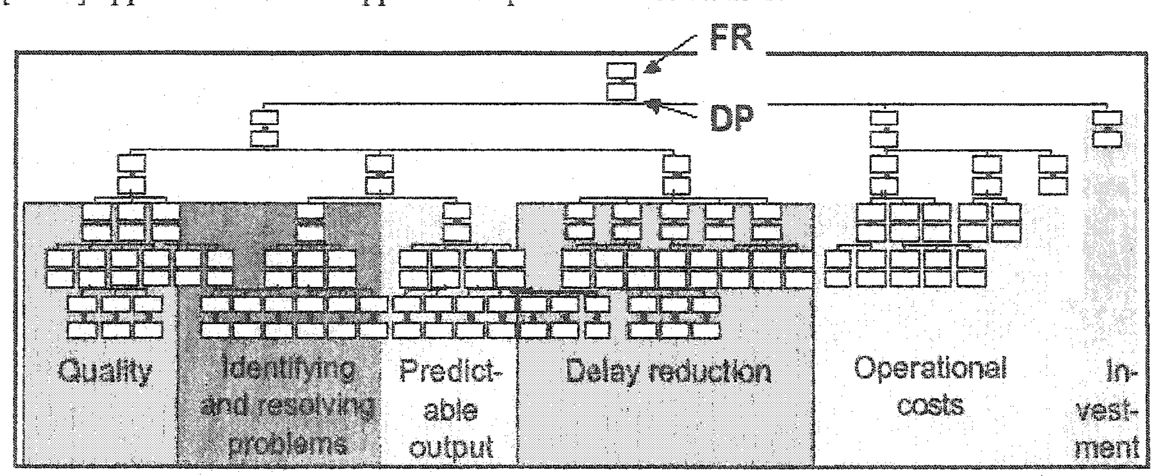


Figure 3.16 Manufacturing System Design Decomposition [Cochran, 2000]

3.2.15 Core System Engineering Technical Process

Oliver et al. [1997] developed that process to represent the engineering tasks that support a system in all phases of its life cycle, the system is illustrate in Figure 3.17. Steps 2-4 are made concurrently and all the steps are performed repeatedly, both over time as the system and its environment evolve and at various details. Oliver also expanded the part of trade-off analysis into more detailed process. This process represents a structural approach to the design of complex systems.

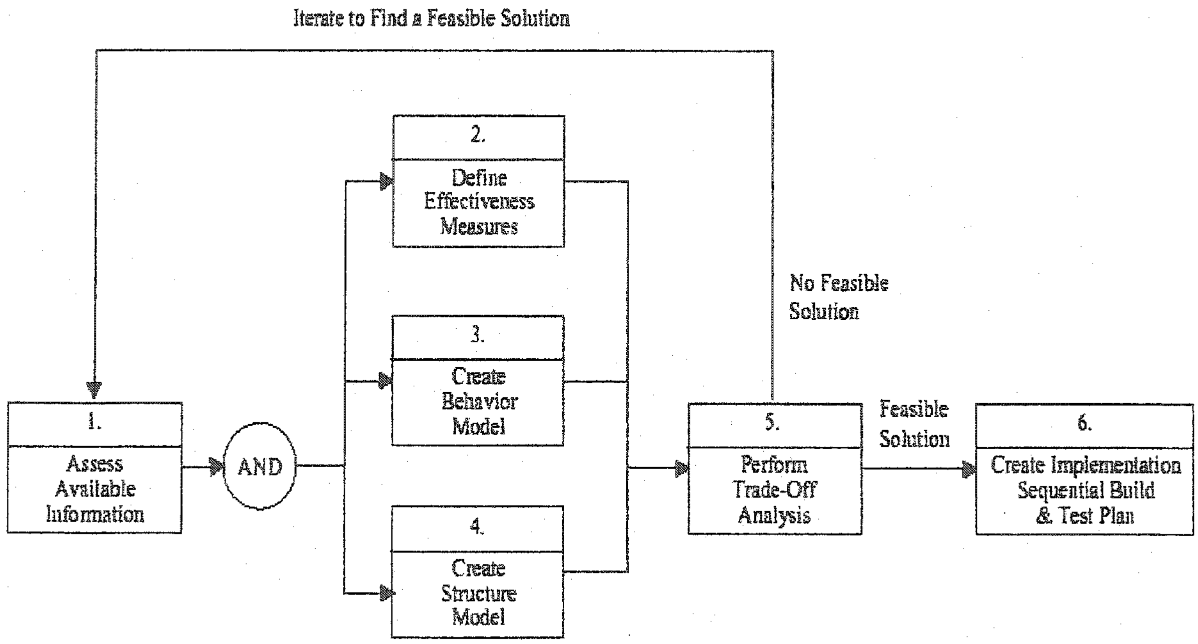


Figure 3.17 Core System Engineering Technical Process [Oliver et al, 1997]

Duda [2000] modified the core system framework into Core Manufacturing System Design Process where he implemented the previous process elements to the design of the manufacturing systems shown in Figure 3.18. In the first step the manufacturing strategy is determined followed in step 2 by defining and prioritizing the key measurements that will be used to evaluate and compare different designs. He also integrated the axiomatic design process in the modified model through using the axiomatic approach in determining the manufacturing system requirements FRs (step 3) & to model the manufacturing system structure DPs (step 4). In Step 5 designers are encouraged to identify and analyze the trade offs that exist among different designs. In the final step the selected design implementation plan is created. The framework could be applied at different level of detail; however the framework does not present any clue about the implementation plan of the selected design.

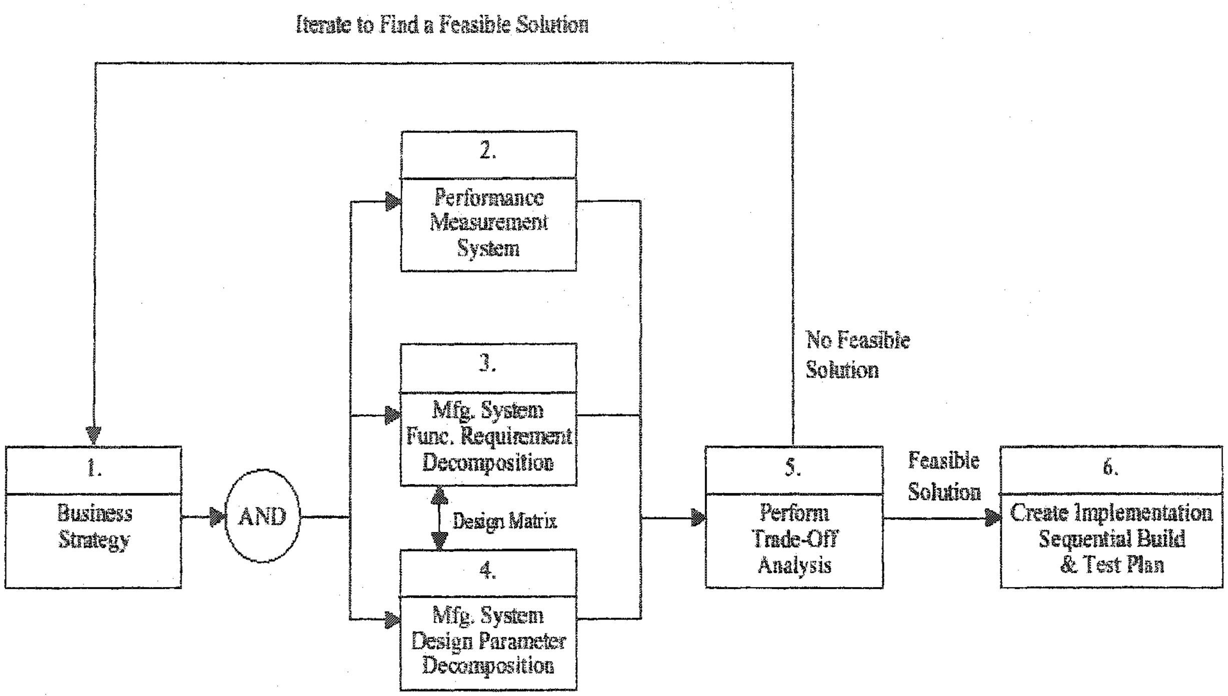


Figure 3.18 Core Manufacturing System Design Process [Duda, 2000]

3.2.16 Combining Information System with Manufacturing System Design

Katzen, J. [2003] talked about the role of the information flow in designing manufacturing systems and how traditional design approaches did not include the information flow from the early design stage. He introduced an improved manufacturing systems design methodology shown in Figure 3.19 that differs from the traditional methodologies in two aspects. The first aspect is that the traditional methodologies wait until the concept is fully developed and then modifies the design to accommodate outside requirements and practical limitation. The improved methodology requires the design team to solicit input from other areas during very early stages and thus decrease time, resources and complexity of the design process. The second aspect is that the improved methodology includes stages that consider the design of the information flow system. This ensures that the information system becomes an important component of the whole manufacturing system.

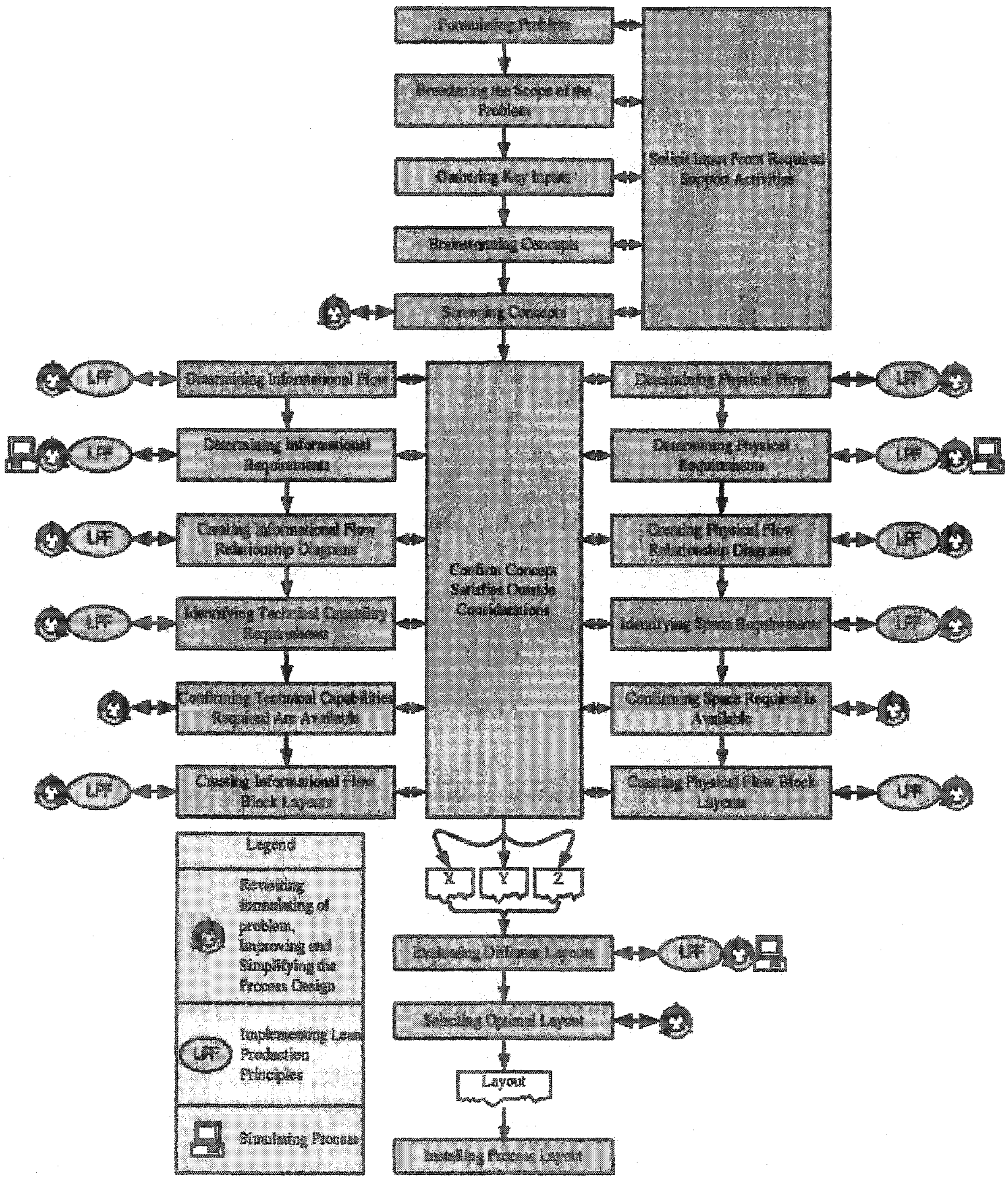


Figure 3.19 Improved Design Methodology [Katzen, 2003]

Shukla [2000] presented a pyramid that summarized the scope of different manufacturing systems design frameworks and methodologies and the objective of each scope of these frameworks and methodologies as shown in Figure 3.20. The system design pyramid helps to indicate probable causes of frequent failure in achieving enterprise objectives through the design and implementation of manufacturing systems. Shukla states that the blank base of the pyramid indicates that very few design methodologies address enterprise issues simultaneously with the rigorous implementation support.

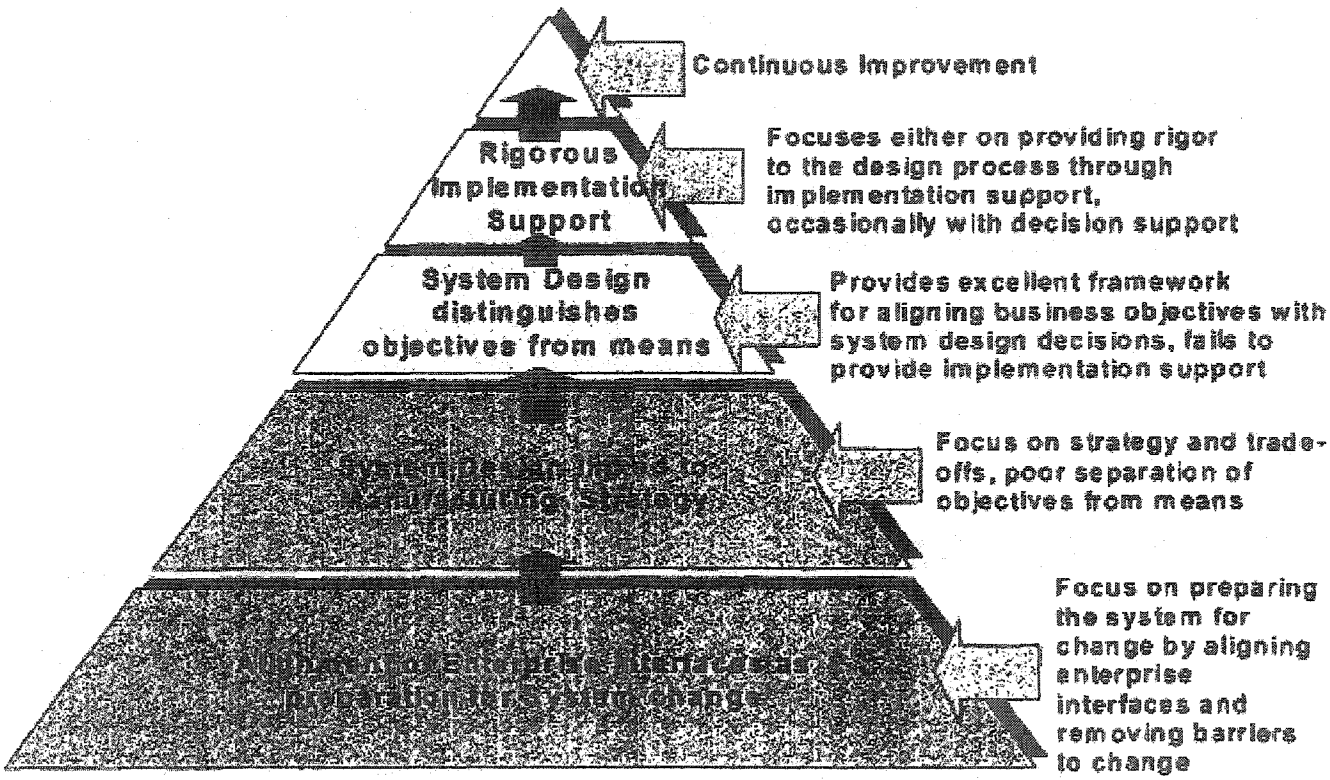


Figure 3.20 Pyramid Classification of Design Methodologies [Shukla, 2000]

3.2.17 Design Frameworks for Special Types of Manufacturing Systems

There are plenty of design approaches that dealt with special types and activities of manufacturing systems. Although such approaches are beyond the focus of the thesis literature review, however in this section we will give some examples of these attempts.

3.2.17.1 Integrated Architecture for Process Manufacturing Systems

Chengen Wang, et al. [2002] developed an integrated architecture for process manufacturing systems. The architecture aimed on the process industry encompasses view models, flow models and object oriented models, which support the design of manufacturing systems through their life cycle stages.

The models provided can be directly converted into application programs coded in object oriented languages. In addition an information infrastructure based on Corba standards is proposed. Five view models are defined – Product, Function, Information, Organization and Resource - from which four flow models can be derived as relations between the function view and the other four views. These flow models are Material Flow, Information Flow, Work flow and Cost Flow. Using the view models in the requirements analysis or view design stage leads to the flow models in the preliminary or process design stage. The latter stage is followed by the entity design stage concerned with data bases, infrastructures, multi-agent systems and object designs. [Chengen, 2002].

3.2.17.2 A Framework for Distributed Manufacturing Applications

Lieatou, P. et al. [2000] developed architecture for the development of distributed manufacturing applications is based in the Holonic manufacturing systems and Bionic manufacturing systems concepts and uses an agent based approach to implement those concepts.

A modular architecture for a generic agent based in six main modules and a knowledge database that contains all relevant (local and global) information to the behavior of agent. All modules interact together, and two of them interact with the external environment. The Physical communication module allows the interaction with other agents, for example to exchange data or to receive orders. The Operational control module allows the interaction with the process, i.e. the execution of the allocated tasks [Lieatou, 2000], the system is illustrated in Figure 3.21.

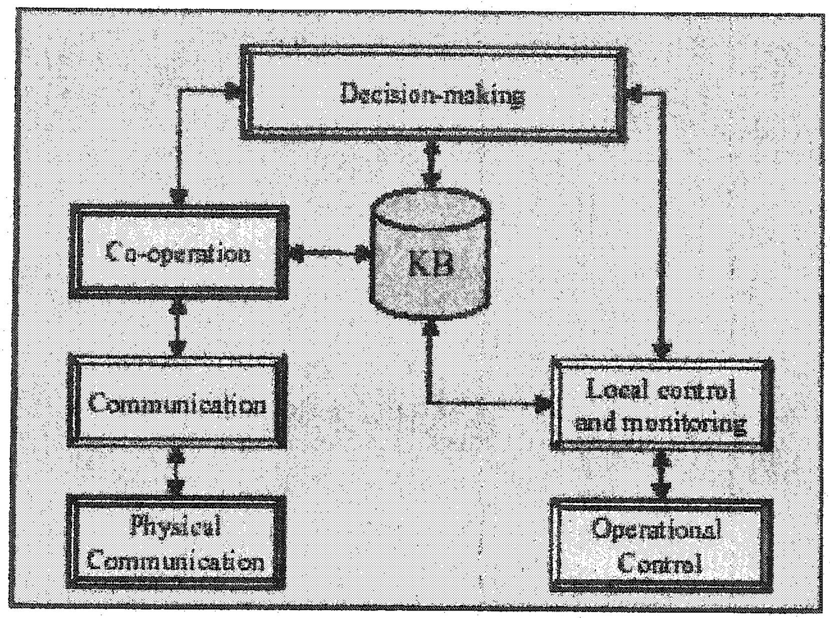


Figure 3.21 Generic Architecture for Distributed Manufacturing Systems [Lieatou, 2000]

3.3 MANUFACTURING SYSTEM DESIGN TOOLS

System designers have a large choice among various tools that support the manufacturing system design task. However, those tools are often difficult to link with each other.

3.3.1 Systems Engineering Tools Applied to Manufacturing System Design

The strength of system engineering techniques is well suited to design manufacturing systems. There are various system engineering techniques and one of the most suitable ones for the design objective is the integrated computer aided manufacturing definition, IDEF. IDEF is a tool that can describe the structure of information and organization in manufacturing systems through different levels ($IDEF_0$ – $IDEF_4$ and recently up to $IDEF_7$) for top-down functional structure, database, simulation, processes and finally software. Wu [1992] applied $IDEF_0$ for the design and analysis of manufacturing systems.

Other techniques like Zachman Framework for system design can also be used for better understanding of manufacturing system design process. The framework divides the different activities into focus categories answering the questions what, how, where, who, when and why. Also these activities are investigated through different perspectives including the conceptual, logical and physical levels. ElMaraghy [2000] applied a Zachman like framework for the analysis of agile manufacturing.

Numerous other tools support manufacturing system design at various stages. Operation management (OM) assists quantitative evaluation and analysis of systems ranging from broad applications, such as supply chain management, to detailed job sequencing. OM defines close boundaries in order to express problems mathematically. Due to the quantitative nature of OM, its application is most beneficial during later phases of system design when design constraints become better defined. From the manufacturing system design perspective, OM provides tools for well-defined sub-problems [Linck, 2002].

Simulation evaluates potential designs in terms of performance and feasibility. Various simulation packages are available to assess potential system configurations (Quest, witness, ProModel etc.). They enable an intuitive understanding of the system's dynamic behavior.

Facility layout planning determines the physical organization of a production system. The objective is to minimize material handling costs considering two constraints; floor area requirements and physical building restrictions. Facility planning is mainly a combinatorial optimization problem with well-defined boundaries to enable the formulation of algorithms. It is used during preliminary and detailed planning phases. Meller and Gau [1996] provided a comprehensive literature review of facility layout planning. They point out that the optimization of material handling can cause sub-optimality from the system perspective. They conclude that future research must concurrently address facility layout and manufacturing system design issues.

KOMPASS is a recently developed method, which supports the consideration of human aspects in the design of manufacturing systems [Grote et al., 2000]. The method consists of an analysis and design tool and is based on criteria derived from the field of work psychology. The analysis tool evaluates an existing system with respect to the work system, the individual work tasks, and the human-machine interaction. The method supports all five phases of the system engineering process, but is limited to human considerations.

3.3.2 Value Stream Mapping

A value stream is a compilation of all the actions required to bring a product through the main flow essential to every product or service, from raw material to delivery to the customer. The goal is to identify and eliminate the waste in the process- waste being any activity that does not add value to the final product.

Value stream mapping is a paper and pencil tool that helps the system designer to see and understand the flow of material and information as a product or service makes its way through the value stream. Value stream mapping is typically used in Lean. A value stream map takes into account not only the activity of the product, but the management and information systems that support the basic process. This is especially helpful when working to reduce cycle time, because you gain insight into the decision making flow in addition to the process flow. The basic idea is to first map your process, then above it map the information flow that enables the process to occur. Figure 3.22 is an example of the value stream mapping map.

3.4 MANUFACTURING SYSTEM CONTROL FRAMEWORKS

3.4.1 GRAI Method

The Graphe a Resultats et Activites Interlies (GRAI) model has been developed to provide a general description of a manufacturing system with the focus on system control

[Doumeingts et al., 1993]. The model distinguishes three sub-systems of manufacturing systems: the physical system transforms material etc. into output products, the decision system ensures that the system objectives are met, the information system contains all information the decision system needs.

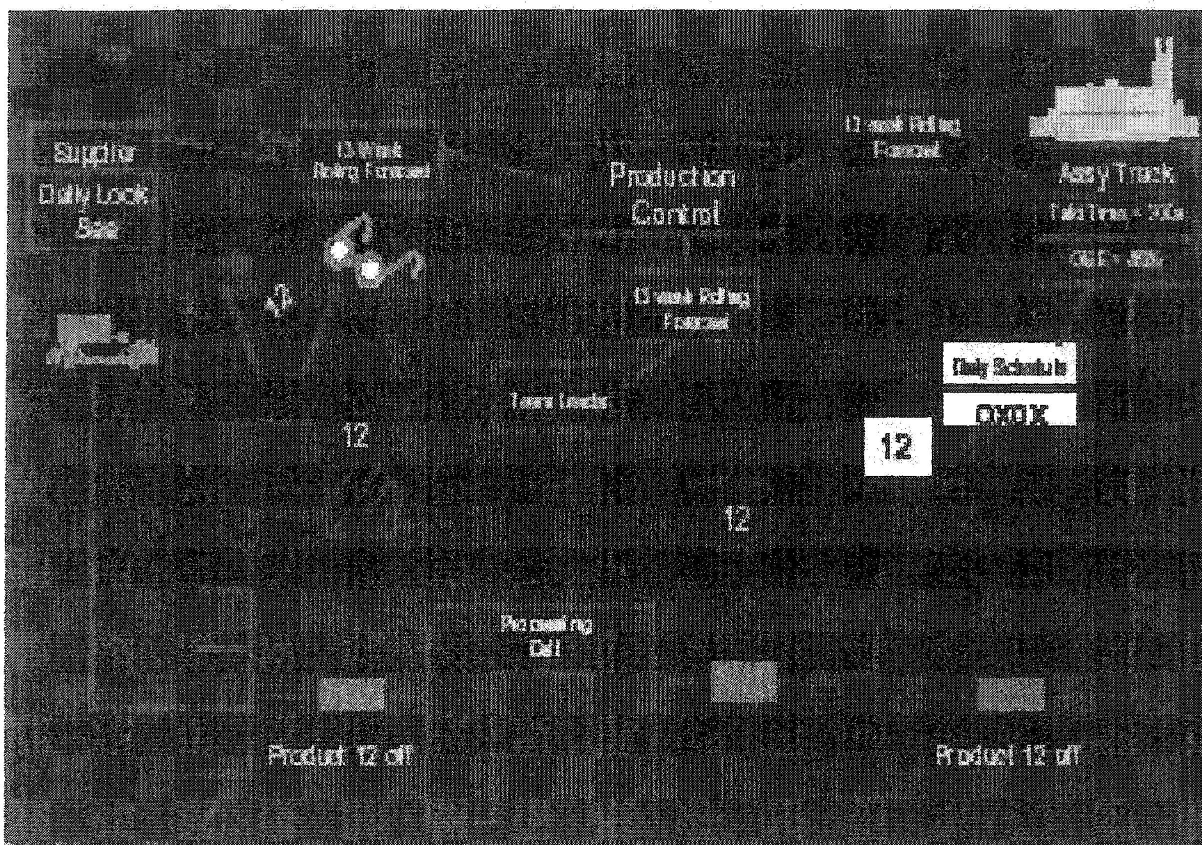


Figure 3.22 Value Stream Mapping [32]

The goal of the GRAI model is to structure the control and analysis of manufacturing systems in the early design phases. The GRAI model uses two main tools: GRAI grid is a top-down approach to identify decision centers. Decision centers are functional areas (planning, purchasing etc.) that make decisions to coordinate the system. GRAI grid determines the time horizon in which decisions are made relative to a predefined set of functions. The second tool, GRAI net, is a bottom-up approach to model activities and decisions made in the system. The GRAI model is useful in designing the control structure of systems with the focus on computerized solutions. A recent extension of

GRAI is the GRAI Integrated Method (GIM), which applies existing tools such as $IDEF_0$ to integrate decision, information and physical systems.

3.4.2 CIMOSA Model

The goal of CIMOSA is to model business processes and enterprise objects of a CIM environment [Vernadat, 1993]. The main function of CIMOSA is to develop an executable model of some part(s) of the enterprise and then use the model to control the CIM system operations. It is focused on the control part of manufacturing systems and provides only limited support for the physical design. Tools of the framework are designed to capture system requirements in a structured way. High- level requirements are decomposed into lower- level activities.

3.5 CHAPTER SUMMARY

3.5.1 Tables of Comparisons

To summarize the review of the manufacturing systems design frameworks, two tables are presented. Table 3.1 discusses the scope of each framework and to what environment of manufacturing systems it was applied. Table 3.2 locates each framework based on systems engineering process. This location helps to visualize where each process fits in the engineering design process and what the things that each framework lacks are.

3.5.2 Comments for the Literature Review

1) Manufacturing System design is characterized by a lack of formal design processes to link objectives and means. The numerous tools for manufacturing system design frameworks range from strategy frameworks (e.g. product-process-matrix) to manufacturing operations. Most frameworks (except for axiomatic based approaches), however, do not recognize the separation of the objectives and

the means throughout the entire detail of system design-from strategy to the operational level.

2) Some of the previous frameworks lack the quantification or the modeling of its various dimensions. It is understandable that the aim of the design framework is to tie ideas together and act as guidance for the specific manufacturing system it address; however the modeling of the framework will give it a practical validation. Such validation is what really manufacturing system research is looking for.
3) The control of the manufacturing system design process is not recognized as key element in most of the design frameworks. This leads to questioning the feasibility and applicability of many of these design approaches in practice.
4) Very few approaches provide a complete coverage of all manufacturing systems design phases as shown in Table 3.2. However, each approach provides valuable support for a certain manufacturing system design phase.
5) Lean manufacturing is mainly focused on system operation and improvement without formally stating system requirements.
6) Most models failed to offer performance measurement parameters that can help to judge the effectiveness and the efficiency of these models or to be used to control the design process.
7) None of the reviewed frameworks was applied to the reconfigurable manufacturing systems environment.

From the previous literature review, one can claim that there is a need to develop an integrated framework for the design and control of Reconfigurable Manufacturing Systems. The framework should link the objectives of the reconfigurable manufacturing systems, such as responsiveness and cost effectiveness, to the different levels of the reconfigurable manufacturing system design process (e.g. configuration level or operational level). This link could be established in a control module of the framework through some performance measurement parameters which could traditional or should be developed. The framework should be modeled or integrated to existing models in order to have the merit of being practically used.

Table 3.1 Scope of Manufacturing Systems (MS) Frameworks and its Application Environment

MS Scope\MS Environment	**Job Shop**	**Dedicated lines**	**Lean Production**	**FMS**
MS Design	Vee Model [1992] Factory Design [1984] Axiomatic Design [1990] MSDD [2000]	Hierarchy of MS objectives [1996] Vee Model [1992] Factory Design [1984] MSDD [2000] PERA [1993] Axiomatic Design [1990]	Hierarchy of MS objective [1996] Vee Model [1992] Factory Design [1984] MSDD [2000] PERA [1993] Monden [1983] Suzuki TRW [1999] JIT Framework [1995]	Hierarchy of MS objectives [1996] Vee Model [1992] Factory Design [1984] MSDD [2000] PERA [1993] Gu et al [2001] Axiomatic Design [1990]
MS Selection	MS product matrix [1979]. Miltenburg [1995]. Chryssolouris [1992]. Black Graph [1991]	MS product matrix [1979] Miltenburg [1995] Chryssolouris [1992] Wu (UMSM) [2000] Black Graph [1991]	Miltenburg [1995]. Chryssolouris [1992]. Wu (UMSM) [2000] Black Graph [1991]	Wu (UMSM) [2000] Black Graph [1991]
MS Control			GRAI Method [1993]	GRAI Method [1993] CIMOSA Model [1993]
MS Design and Control		Manufacturing System Core [2000]	Manufacturing System Core [2000]	Manufacturing System Core [2000]

Table 3.2 Manufacturing Systems Design Frameworks and Tools Relative to System Engineering Process

Approach/Author	Conceptual Design	Preliminary Design	Detailed Design	Implementation	Operation
MS product mix framework (1979)	X	X			
Miltenburg (1995)	X	X			
Black Graph (1991)	X	X			
Chryssolouris (1992)	X	X			
GRAI (1992)	X	X			
Wu (2000) UMSM	X	X	X		
Gu et al (2001)	X	X	X		
The Vee Model (1992)	X	X	X		
Core Manufacturing System Model (2000)	X	X	X		
PERA (1993)	X	X	X	X	X
CMOSA (1993)			X	X	
Kettner (1984)	X	X	X	X	X
Katzen (2003)	X	X			
KOMPASS (2000)			X	X	X
MSDD (2000)	X	X	X	X	X
Axiomatic Design	X	X	X		
Facility planning	X	X			
Suzuki (1999)	X	X	X		
TPS frameworks	X	X	X		
Monden (1989)	X	X	X		
Sakakibara (1993)	X	X	X		
Value Stream Mapping (1998)	X	X			
Hierarchy of MS objectives(1996)		X	X		

CHAPTER 4

DESIGN AND CONTROL OF RECONFIGURABLE MANUFACTURING SYSTEMS

4.1 INTRODUCTION

As discussed in chapter two, reconfigurable manufacturing systems are designed at the outset for rapid change in its structure, as well as its hardware and software components, in order to quickly adjust its production capacity and functionality in response to sudden, unpredictable changes in market demand as well as introduction of new products or new process technology.

The design and control of such systems is still in the developing phase. Numerous efforts were done on exploring and developing the reconfigurable manufacturing systems components such as the machines, controllers and layouts [Choren et. al, 1996, Mehrabi et al., 2000, and Urbani et al, 2001]. However, there is no approach till now for the analysis and design of the full reconfiguration process starting from capturing the market demand through system specification and selection and till the physical implementation of the new reconfiguration and the parameters that control the design process.

In this chapter a systematic approach for developing a comprehensive architecture that recognizes the different aspects of reconfigurable manufacturing systems design and its control process is presented. The focus of the architecture will be on the big picture of the design process of these systems. The chapter starts by explaining the system design methodology that was used to develop the architecture, followed by explanation of the design module and the control module of the architecture in details. Finally the proposed architecture is applied to a reconfigurable automatic assembly plant to illustrate the use and the different features of the architecture.

4.2 SYSTEM DESIGN METHODOLOGY

In this section an introduction about system design methodology is presented. A system in this section refers to software packages. Software development can be perceived as the problem of implementing a set of diverse, incomplete, and conflicting requirements expressing the concerns of different stock holders within a single system or corporation [Heckel, A. and Engels, G. 2002]. Accordingly, we can claim that a problem of developing a design framework for a manufacturing system is very close to software development in a system sense.

The system design methodology involves the structural representation of requirements. It is composed of the following steps [Ellman, T. 2000]:

- Decide on the overall system architecture.
- Divide the system into subsystem
- Assign responsibilities to subsystems
- Decide what performance characteristics will be optimized
- Make tentative resource allocation.

Subsystems are identified by the services that they provide. A subsystem should have a small, well defined interface to the rest of the system.

System decomposition into subsystems is carried out in two ways. The first is where the system is divided into ordered hierarchy of layers and each layer calls upon lower layers for services and waits for the results. The second method of decomposition is called partitions where the system is divided into unordered set of partitions and these partitions run concurrently, and exchange information asynchronously. If both techniques are used in the system development, then the architecture is called a mixed architecture. Figure 4.1 (a-c) show these different system decomposition approaches.

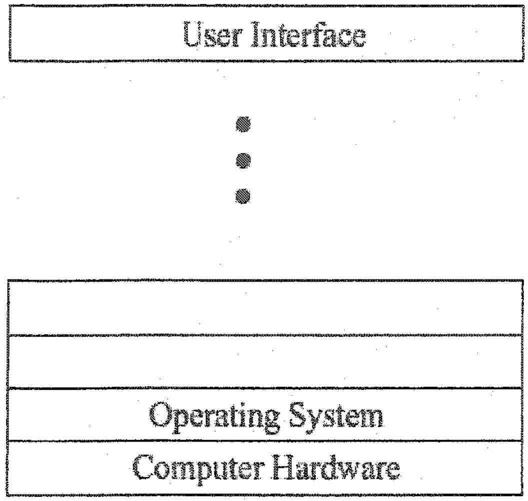


Figure 4.1 (a)

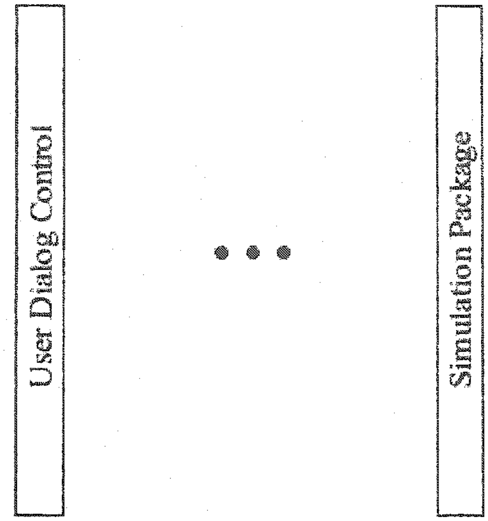


Figure 4.1 (b)

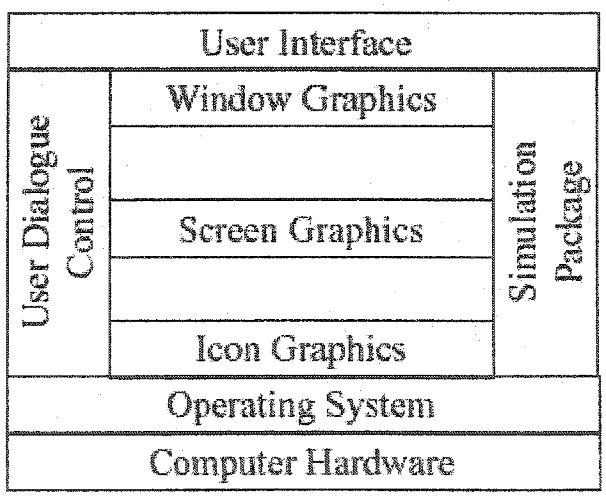


Figure 4.1 (c)

Figure 4.1 [Ellman, T. 2000]: (a) Layered architecture, (b) Partitioned architecture, and (c) Mixed architecture.

The services (information) of different layers are controlled in either open or closed manners. In open architecture, a layer may use the services of any layer lower than it in the hierarchy. In closed Architecture, a layer may use only the services of the layer immediately below it in the hierarchy.

It is significant that there is a common ground between the approach for software systems design and manufacturing system design. Both approaches focus on customer requirements as the base for the design process. Decomposing the system into subsystems and identifying the relationships (interfaces) between different subsystems of the software is a typical approach for designing complex systems like manufacturing systems. The information control patterns is another very similar aspect between both systems design approaches especially when talking about the control aspect of the manufacturing systems. Thus within the context of manufacturing systems, architecture is a set of models or modules which describe what a manufacturing system consists of and how it functions [Williams et al., 1993].

The definition of architecture helps in explaining why such modeling approach is very helpful in the description of manufacturing systems from a holistic point of view. The definitions are as follows:

- IEEE: In general, the purpose of developing systems architectures is to discover high-level frameworks for understanding certain kinds of systems, their subsystems, and their interactions with related systems. Architecture isn't a blue print for designing a single system, but a framework for designing a range of systems over time, and for the analysis and comparison of these systems. By revealing the shared components of different systems at the right level of generality, an architecture promotes the design and implementation of components and subsystems that are reusable, cost-effective, and adaptable.
- ISO (International Standardization Organization) Definition: The architectures are used to express system components and interfaces between these components. The system architecture is used in manufacturing systems to connect design, control, planning and data. The architecture approach is applied in the open

architecture control of manufacturing systems. It realizes the benefits of increased intelligence of manufacturing systems.

- ASME (American Society for Mechanical Engineers) defines architecture as a tool that emphasis on understanding and enhancing the creative design process.

Based on these similarities between the two approaches and the definitions of architecture, the system design methodology for computer software was considered as the methodology for the design and control of reconfigurable manufacturing system that this thesis focuses on. Thus, mapping the previous principles resulted in developing the proposed open mixed architecture for the design and control of the reconfigurable manufacturing systems of this thesis.

Figure 4.2 shows the architecture for the design and control of the reconfigurable manufacturing systems. The architecture is composed of two modules; the first module describes the design process of the reconfigurable manufacturing systems through its different levels, and the second module describes the control parameters that control the design process at each level. The design module is based on the different phases that the reconfiguration process of these systems passes through, while the control module is based on performance measurements that reflect the strategic objectives and constraints indicated by the high-level decision makers at each level.

The architecture as shown is considered open for that its information flow is accessible through any layer and between the design and control modules. The information flow should be open for a successful control over the design process. The architecture is also considered a mixed architecture as it is composed of both hierarchal layers (for the different design and control levels) and two partitioned layers resembling the design and control modules.

The architecture is made of three layers. The first layer is the market demand capture (or interface) layer, which deals with demand and how it is transferred as system requirements. The second layer is the system layer, which is responsible for system

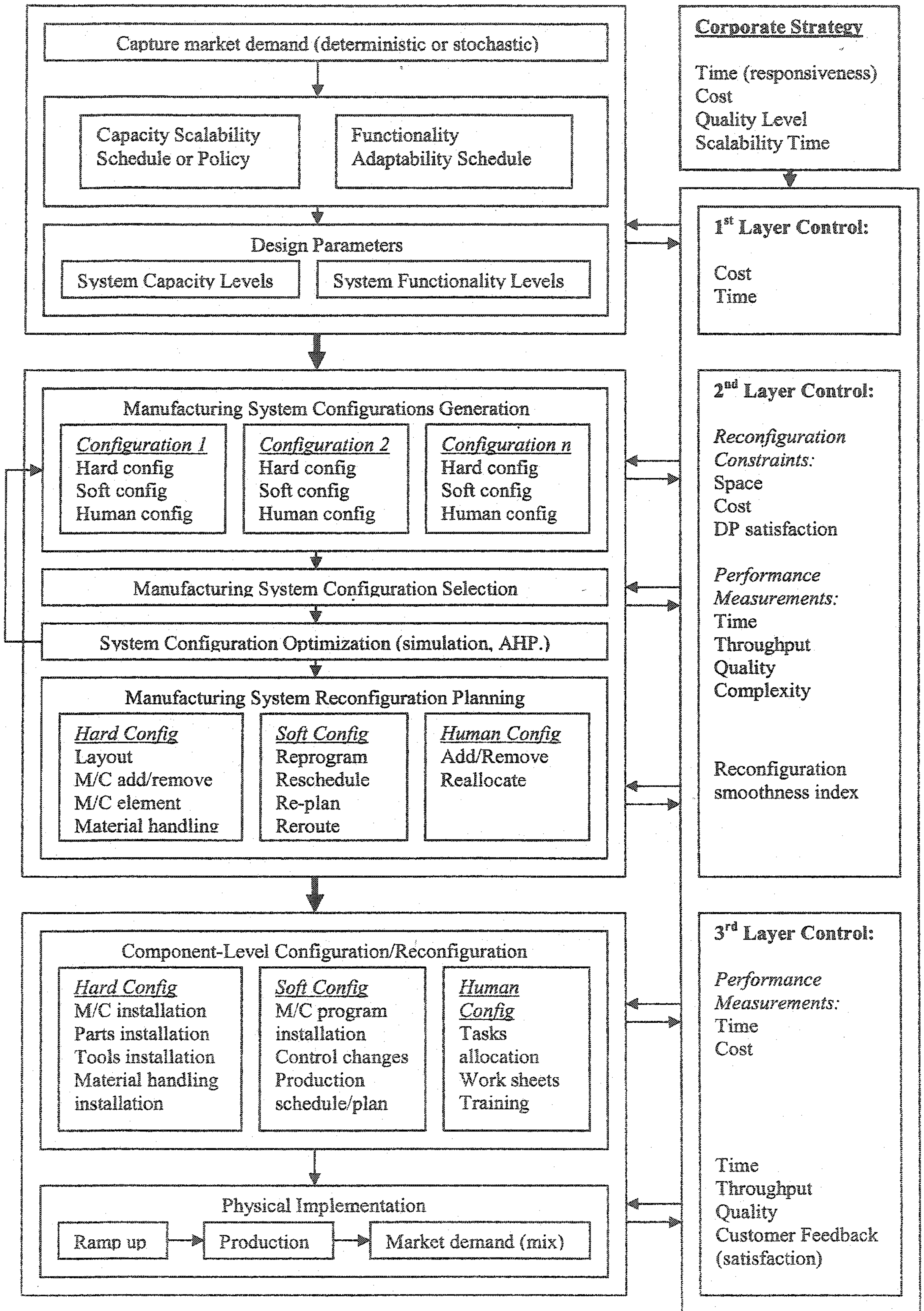


Figure 4.2 Open Mixed Architecture for the Design of RMS

configuration development (reconfiguration process). Finally, the third layer is the component layer, which describes the reconfiguration process on the component or operational level. In the following sections each layer, with both its design and control aspects will be discussed and explained.

4.3 DESIGN OF RECONFIGURABLE MANUFACTURING SYSTEMS

In this section the design process of reconfigurable manufacturing systems will be discussed through explaining the different layers of the proposed architecture in the previous section (see Figure 4.2). Each process in each layer of the architecture will be explained and elaborated with the aid of the $IDEF_0$ model to explain the input, output, controller and mechanism of each of these processes.

4.3.1 Market Capture Layer

This layer describes how the reconfigurable manufacturing system interacts with different market demand profiles. The demand profile could be deterministic or stochastic as in a typical dynamic market environment that reconfigurable systems are designed to adapt with. After capturing the customer needs (demand), it is transferred into required capacity (to adapt to different volumes of products) and functionality (to adapt to variety of products) levels. Reconfigurable manufacturing systems are designed to have scalable capacity and adaptable functionality which means that the manufacturing system is modularly designed to be able to increase or decrease its capacity physically by adding or removing capacity modules like machines, axes, spindles…etc. or logically through rerouting, extra shifts…etc. and its functionality by adding or removing functionality modules like tools, fixtures, software…etc.

However, practically speaking no system can continuously change with each instant of market change as the definition of the reconfigurable manufacturing systems entitles due to large cost and system constraints. There is a need for extensive research to make the main objective of reconfigurable manufacturing systems that they are continuously scalable and reusable be practical and feasible. In our opinion the feasible capacity scalability policy in reconfigurable manufacturing system is the policy that balances between the costs of scalability while maintaining the responsiveness level required by such reconfigurable systems. In this thesis the modeling of such a policy will be developed in chapter 5 as will be discussed.

The main objective of this layer is to capture the customer needs to develop the required capacity and functionality level plan or schedule that will act as the design parameters or inputs to the system configuration layer to start the (re)configuration of the system. This objective is achieved through a capacity scalability tool that is controlled by the cost and time requirements and leads to the development of the required scalability policy at the minimum time and with the minimum cost. The market capture layer is explained as an $IDEF_0$ model in Figure 4.3.

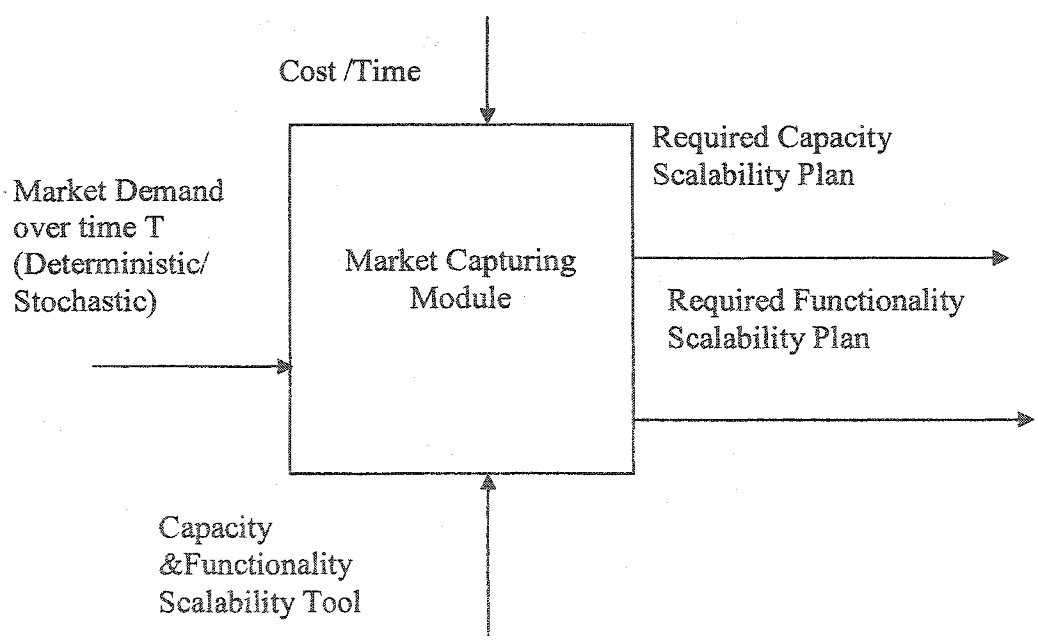


Figure 4.3 $IDEF_0$ Representation of the Market Capture Layer

4.3.2 System Configuration Layer

System configuration classically meant the layout of the machines (parallel, series and hybrid) and material handling equipments and focused on the efficiency of material flow. New trends in system configuration design extend this definition to a much bigger picture to include what can be called as the topology of the system. Topology of the system includes information like number of stages within the system, number of stations within a stage, steps assigned to stages and precedence relationships between stages [Son 2000].

For reconfigurable manufacturing systems some research were done to investigate the generation of system configurations (with both the classical and the modern definition) through developing some tools and methodologies and evaluated these configurations with specified performance criteria [Spicer et. al. 2002, Zhong et. al., 2000, Koren et. al., 2001, Xiaobo et. al., 2000 and Son, 2000]

In the proposed design architecture the configuration of the system will be expressed through three dimensions; the physical (or hard) configuration, the logical (or soft) configuration and the human configuration. Examples of each of these dimensions were presented in section 2.9.1 in chapter 2.

This layer is the heart of the reconfigurable manufacturing systems design process. The required capacity and functionality levels from the market capture layer are taken as inputs to a previously developed system configurator tool that generates different system configurations satisfying the scalability policy needs. In addition, the process plans of the required mix are also considered as inputs to the system configuration generation tool to supply enough information about the state of the raw materials, machines and required operations. The architecture successful implementation is function of its ability to integrate different number of these tools and methodologies to this layer. The system configurations generation process is explained as an $IDEF_0$ model in Figure 4.4.

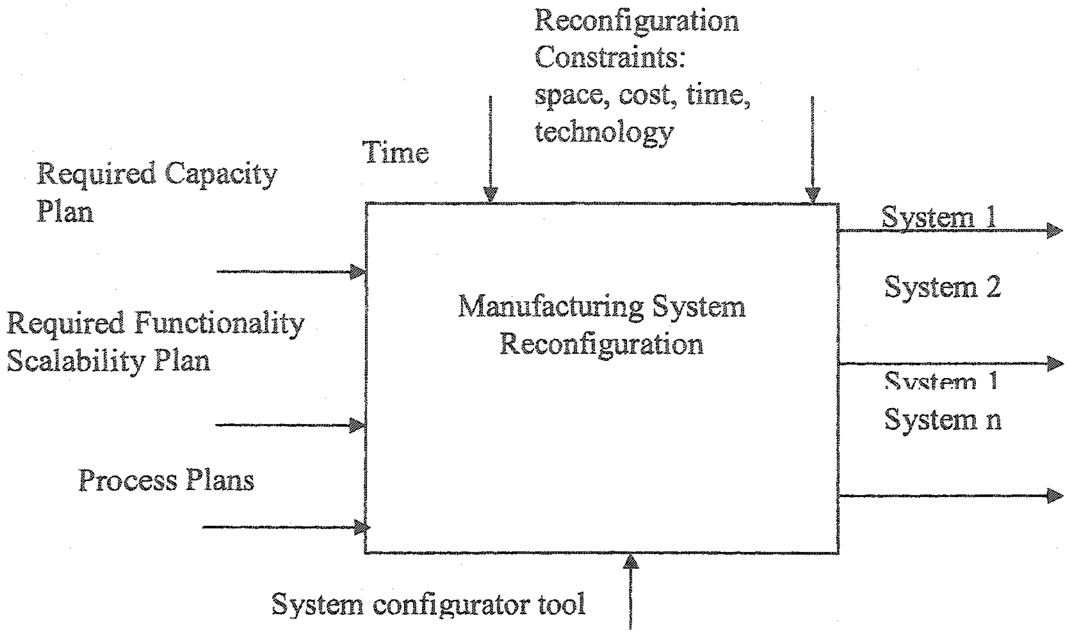


Figure 4.4 IDEF$_0$ Representation of System Configurations Generation Process

After different configurations have been generated, the selection of the best feasible configuration among the generated ones is carried out. This selection process is based on predetermined performance measurements such as quality, throughput, complexity or any other performance measurement criterion. The selection process is usually combined with the generation process in the same tool or methodology of the system configuration generation. The system configuration selection process is explained as an IDEF$_0$ model in Figure 4.5.

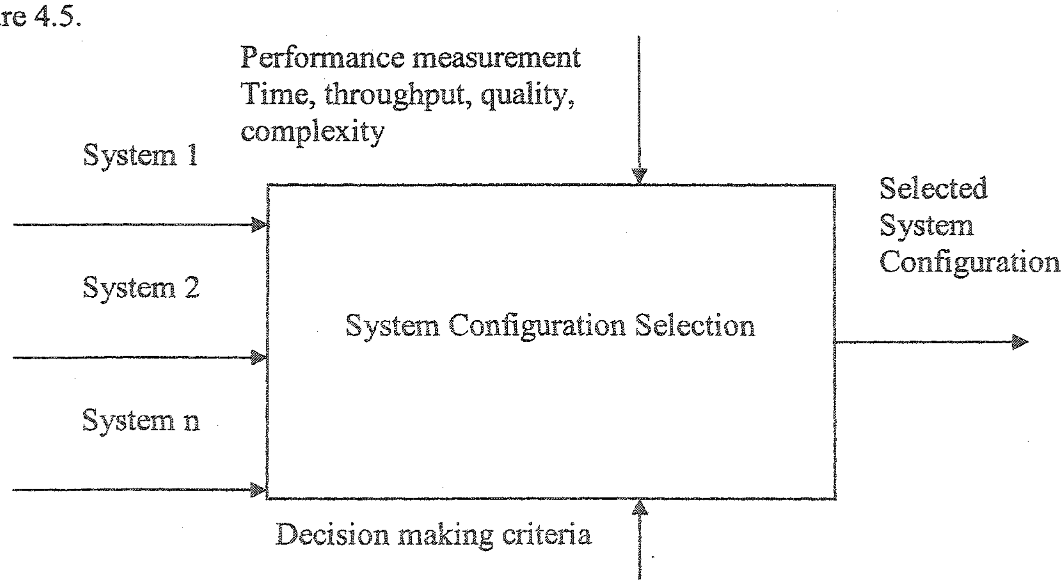


Figure 4.5 IDEF$_0$ Representation of System Configuration Selection Process

Furthermore, the selected configuration is optimized and simulated to better improve and visualize that configuration. Sensitivity analysis and other system evaluation tasks are done in this step using different tools like analytic hierarchy process AHP or any other tool. Again in practice, this process must be combined with the system selection process and it also provides feedback to the configuration generation procedure. The process is explained as an $IDEF_0$ model in Figure 4.6.

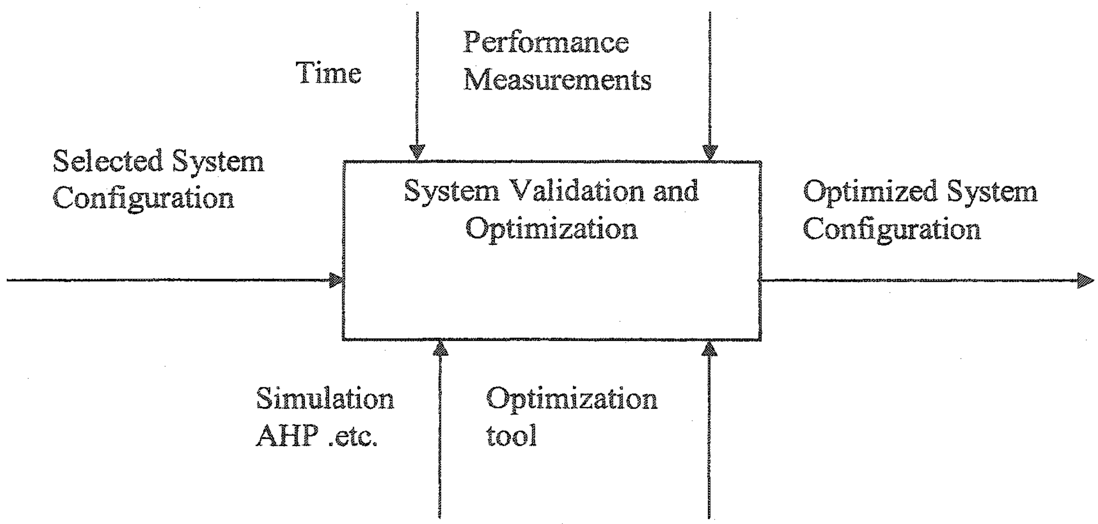


Figure 4.6 $IDEF_0$ Representation of System Configuration Optimization

After a system configuration is generated there should be also system reconfiguration planning for smooth and efficient system reconfiguration to suite the new configuration. This planning is done through planning over the three stated configuration dimensions (hard, soft and human). An index to measure the degree of smoothness is a research area that should be explored in order to maintain successful control over the reconfiguration process. The system reconfiguration planning process is explained in $IDEF_0$ model in Figure 4.7.

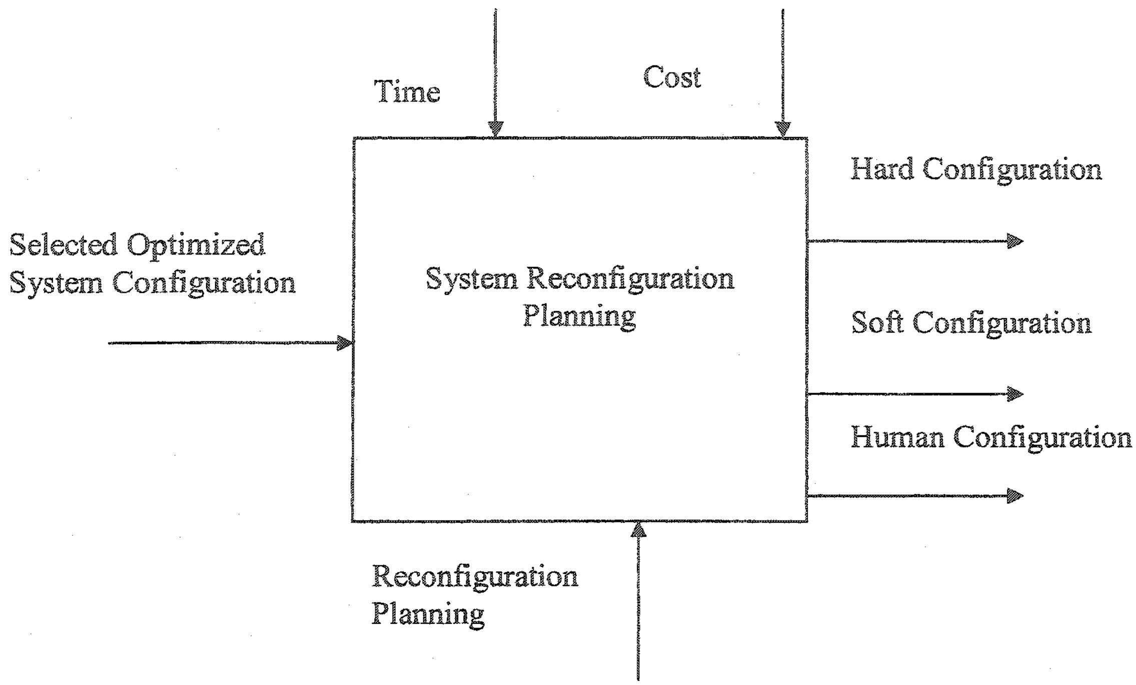


Figure 4.7 $IDEF_0$ Representation of the System Reconfiguration Planning Process

4.3.3 Component Configuration Layer

This layer in the reconfigurable manufacturing systems design process deals with physical implementation of the selected generated configuration. This layer is considered the operational level of the reconfigurable manufacturing systems thus it is integrated with the previous design layers to complete the full picture of the reconfiguration process. The implementation is carried out over the mentioned system components (physical, logical and human).

Physical or hard component-level (re)configuration includes machine(s) installation/removal, parts and tools installation/removal (like axes, tables, spindles…etc.), material handling equipments adding or adjusting and all other physical components reconfiguration of the selected system configuration.

Soft component-level (re)configuration includes changing the required programs to the machines, performing the required control changes for the new configuration and implementing the production schedule or plan that was developed from the system-level soft configuration.

As for the human configuration on that level, it includes tasks allocation, work sheets (as this is the operational level) and executing the required training for the newly hired or reallocated personnel to achieve the multi skill labor level essential for successful reconfigurable manufacturing systems.

Integrabilty (the ability to integrate modules rapidly and precisely), modular design, convertibility (the ability to transform the existing functionality to suit new production requirements) and machine open control architecture are the major enabling technologies responsible for the success of the real physical implementation of the reconfigurable manufacturing systems. The component-level configuration layer is explained by $IDEF_0$ model in Figure 4.8.

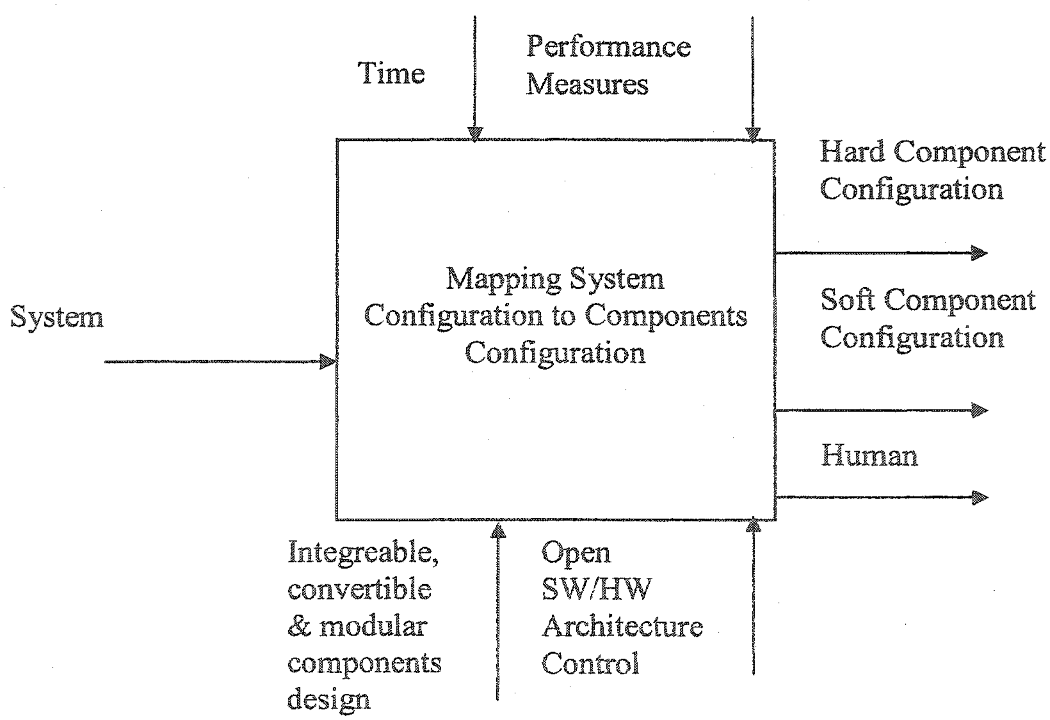


Figure 4.8 $IDEF_0$ Representation of the Component Configuration Layer

After components reconfiguration, the new (re)configured system should ramp-up in minimum time in order to be able to meet the responsiveness strategic advantage of the reconfigurable manufacturing systems. The ramp-up time is the time following the installation and before the system reaches the full-volume production at the required quality level. Mehrabi et al. [2000] suggests two ways to reduce the ramp-up time in reconfigurable manufacturing systems using two complementary methods; first, diagnostics based on process knowledge and statistics embedded in components and propagating to the system level, and second, a new real-time part dimension measurement technology combined with systematic calibration of machines. Integration of both techniques will lead to intelligent root cause analysis of quality problems and decrease ramp up time.

Finally production of the product mix required (market demand) that was captured by the market interface layer is carried out. The final physical implementation of the new (re)configured system is explained by $IDEF_0$ model in Figure 4.9. The complete $IDEF_0$ representation of the proposed architecture is shown in Figure 4.10.

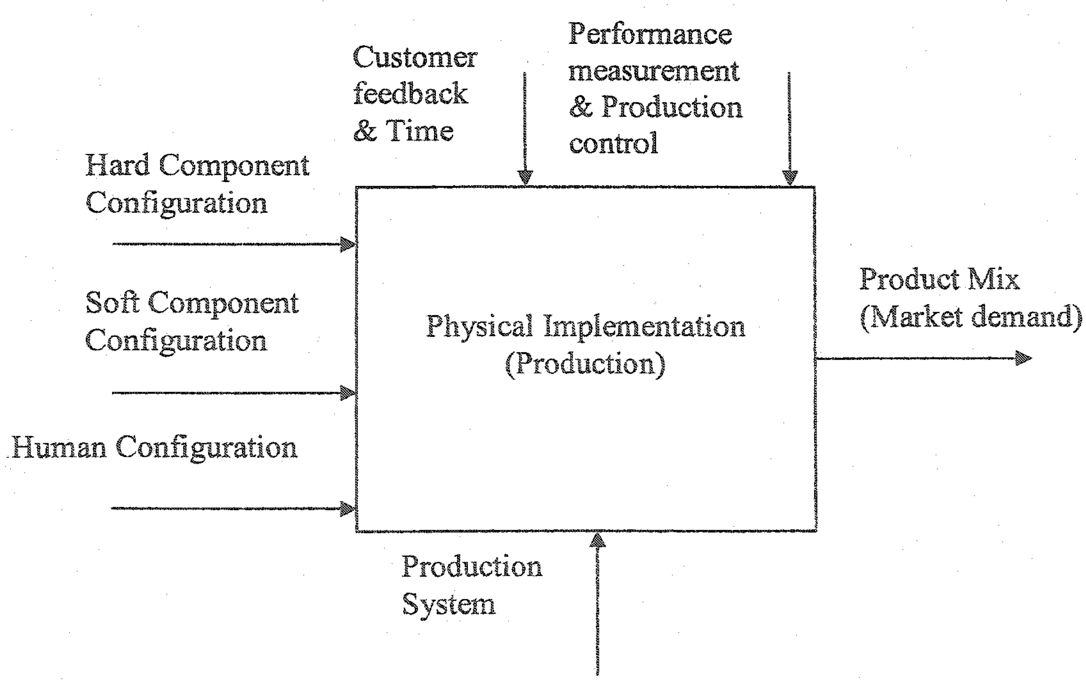


Figure 4.9 $IDEF_0$ Representation of Physical Implementation of RMS

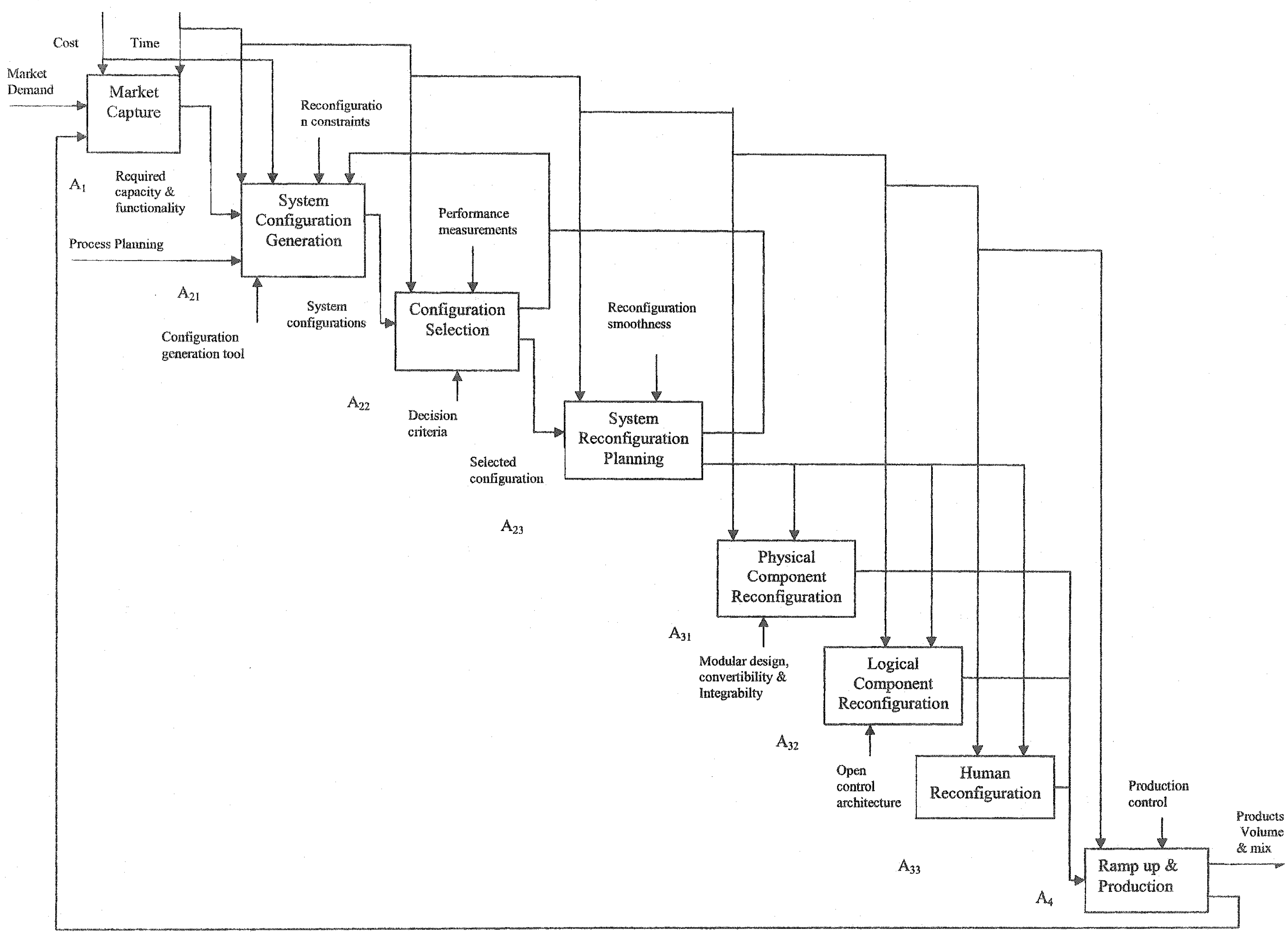


Figure 4.10 IDEF$_0$ Representation for the Design and Control of Reconfigurable Manufacturing Systems

4.4 CONTROL OF RECONFIGURABLE MANUFACTURING SYSTEMS DESIGN PROCESS

4.4.1 Introduction

What is System Control?

A system "has a complex multi-variable nature and for its effective control it is important that information flows and that set points are well defined to allow people to be effective controllers of a system" [Parnapy, 1979].

The control of the reconfigurable manufacturing systems is carried out through controlling the design process described in the previous design module with its different layers. The control of any system is done to maintain the system within a desired state or to achieve a certain objective. In manufacturing systems the control of the system is carried out to guarantee that the manufacturing system, whatever its type, achieves its required goals. These goals are the strategic objectives decided by the high level of the corporation.

The successful design of the manufacturing systems is the design that accomplishes the required strategic objectives through each design level of the system. This is achieved by having the suitable performance measurements that reflect the strategic goals. Each design level or process has its specific performance measurements that are used for the control of that level or process.

Since the control process of reconfigurable manufacturing systems is based on the strategic goals of these systems and the required performance measurement, the next sections will discuss the manufacturing strategy and the performance measurements of manufacturing systems before explaining the control method that will be applied for the reconfigurable manufacturing systems control presented in the proposed architecture.

4.4.2 Manufacturing System Strategy

4.4.2.1 Definition

Strategy is the development and securing of a long-term, sustainable competitive advantage [Porter 1996]

4.4.2.2 Levels of Strategy

Figure 4.11 shows the different levels of strategy.

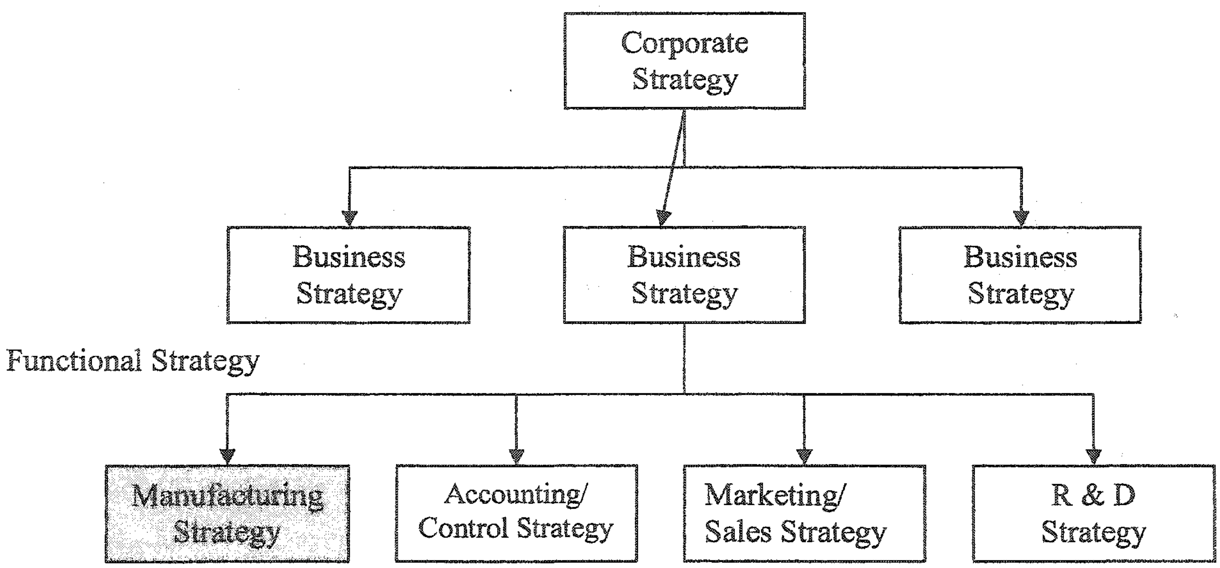


Figure 4.11 Levels of Strategy [Hayes and Wheelwright, 1984]

Corporate Strategy

It is the pattern of decision in a company that determines and reveals its objectives, purposes or goals. It defines the business in which a company will compete, preferably in a way that focuses resources to convey distinctive competencies into competitive advantage [Andrews 1980].

Business Strategy:

It defines the scope of business or its market segment targeted and the basis on which the business will reach the its competitive advantages aspects [Duda 2000]. It also involves setting priorities of these competitive aspects which include cost, quality, delivery performance, flexibility and innovations.

Functional Strategy (Manufacturing Strategy):

It is the step of defining manufacturing task where doing so involves describing what must be accomplished by the manufacturing system in order to compete [Skinner 1996]

4.4.2.3 Manufacturing Strategy Frameworks:

Abernathy et al. [1981] developed the key elements of manufacturing competitiveness strategies in on the macro and micro levels as illustrated in Table 4.1.

Table 4.1 The Key Elements of Manufacturing Competitiveness Strategies [Abernathy et al., 1981]

	Structure (Hardware)	Infrastructure (Software)
Macro (Country)	Fiscal/Tax Policies Monetary Policies Trade Policies Industrial Policies Capital Markets Political Structure Organizational Labor	Culture Tradition Religion Values Social Behavior
Micro (Company)	Business Market Selection Plant and Equipment decisions: Capacity Facility Process Tech. Vertical Integration	Measurements & Control Systems Workforce Policies Vendor Relationship Management selection and development policies Capital Budgeting System Organizational Structure

Hayes and Wheelwright [1984] developed manufacturing strategy decision categories described in Table 4.2.

Table 4.2 Manufacturing Strategy Decision Categories [Hayes and Wheelwright, 1984]

Decision Category	**Decision Variables**
Structural	
Capacity	Amount, Timing, Type
Facilities	Size, Location, Focus
Process Technology	Equipment, automation, Linkages
Vertical Integration	Direction, Extent, Balance
Infrastructural:	
Manufacturing Planning & Control	Computerization, Centralization, Sourcing
Quality	Defect prevention, Monitoring, Intervention
Organization	Structure, Reporting levels, Control.
Workforce	Skill level, Wage policies, Employment security

Applying Hayes and Wheelwright framework to the reconfigurable manufacturing systems will lead to the results shown in Table 4.3.

Table 4.3 Reconfigurable Manufacturing Strategy Decision Categories

Decision Category	**Decision Variables**
Structural	
Capacity	Scalability increments and time.
Functionality	Adaptability to various products
Enabling Technology	Modularity, Convertibility and Customization
Vertical Integration	Integrabilty to new technologies
Infrastructural:	
Manufacturing Planning & Control	Computerization & Reconfigurable Planning
Quality	Defect prevention and Diagnosability
Organization	Dynamic Reconfiguration.
Workforce	Multi Skill level

Duda et al. [2000] suggests that the strategy development should be carried out in an iterative fashion. He extended the hierarchal strategic framework of Hayes and Wheelwright and developed what he called a unified framework for strategy. The framework shows the feedback necessary for the iterative nature of the strategy development process. It also emphasizes the importance of achieving what is called the strategic fit across various functional areas. The details of the framework are shown in Figure 4.12.

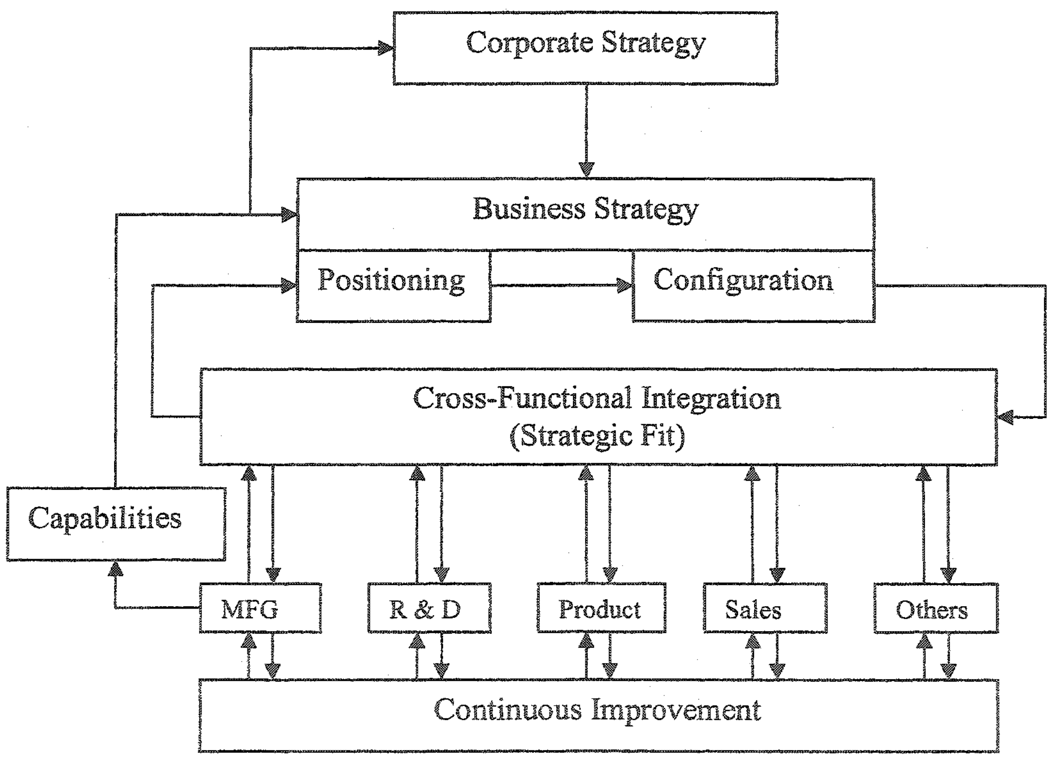


Figure 4.12 Unified Framework for Strategy [Duda et al, 2000]

The manufacturing strategy of the reconfigurable manufacturing systems can be viewed as achieving three main goals; rapid responsiveness, low cost and high quality. These strategic objectives of such systems reflect the nature of the new enterprises, like agile enterprises, that are adopting the reconfigurable manufacturing technology.

4.4.3 Performance Measurements

4.4.3.1 Introduction

The new dynamic market not only increased the level of competition, but it also changed the nature of that competition. Corporations became interested in differentiating themselves not only based on cost as it used to be, but also with respect to other performance measurements such as quality and responsiveness.

There are extensive researches about how to design an effective performance measurement system and what are the qualities of an effective set of measures [Neely et al, 1995; Maskell, 1991; Kaplan and Norton, 1992; Wisner and Fawsett, 1991].

Another major issue concerning the performance measurements and the design of manufacturing systems is related to the consistency of these measurements to the strategic objectives of the manufacturing system at every level of the design. This is why the proposed architecture in this thesis integrated both the design module with the control module and the later is stemmed out of the strategic objectives of the reconfigurable manufacturing system.

It is clear that during the design process there is always a need to balance between different performance measures that could seem to be conflicting between each other like cost of scalability and the degree of responsiveness in terms of the reconfigurable manufacturing systems. Duda [2000] developed a model for the trade off analysis between different performance measures and integrated it to the core manufacturing system design process.

In this section classical performance measures used in the control process of the reconfigurable manufacturing systems are presented followed by some new suggested performance measures that are revealed from the reconfiguration environment of this manufacturing system and still need a lot of enhancement.

4.4.3.2 Definition of Performance Measurement

Neely et al [1995] put several definitions for the performance measurements:

- Performance measurement can be defined as the process of quantifying the efficiency and effectiveness of action.
- A performance measure can be defined as a metric used to quantify the efficiency and/or effectiveness of an action.
- A performance measurement system can be defined as the set of metrics used to quantify both the efficiency and effectiveness of actions.

4.4.3.3 Classical Performance Measurements Used in RMS Design

Classical performance measurements used to control the design process of the reconfigurable manufacturing systems include [Koren et al, 1998; Urban et al, 2001; Zhong et al, 2000; Maier-Speredelozzi and Hu, 2002 and Yang and Hu, 2000]:

1) Throughput time:

Time has been described as both a source of competitive advantage and the fundamental measure of manufacturing performance. Under the just-in time (JIT) manufacturing philosophy the production or delivery of goods just too early or just too late is seen as waste. Similarly, one of the objectives of optimized production technology (OPT) is the minimization of throughput times.

In reconfigurable manufacturing systems, the throughput time plays a major role in evaluating the responsiveness of the system. Time in general is one of the most crucial control parameters in the design process of reconfigurable manufacturing systems.

2) Quality:

Traditionally quality has been defined in terms of conformance to specification with high performance and hence quality-based measures of performance have focused on issues such as the number of defects produced and the cost of quality. The true cost of quality is a function of the prevention, appraisal and failure costs.

In reconfigurable manufacturing system, since it is a very dynamic system, the impact of different configurations on the quality of the production should be considered as key factor for both the selection efficiency of the configuration change of these systems.

3) Complexity:

Reconfigurable manufacturing systems are considered complex systems. Qualitatively, to understand the behavior of a complex system we must understand not only the behavior of the parts or modules but also how they act together to form the behavior of the whole. Complexity of a manufacturing system is defined as a measure of uncertainty in achieving the specified functional requirement of the system.

Therefore, in reconfigurable manufacturing systems, complexity is related to information content needed to maintain the reconfiguration of the system in a feasible manner while satisfying the customer needs. The easier the system is configured to meet market demand at low cost the less complex the system is and the more reconfigurable the system is.

4.4.3.4 New Performance Measurement Suggested in RMS Designs

In this section a group of performance measurements that can be said that they are specific for the reconfigurable manufacturing systems is introduced. Since reconfigurable manufacturing systems are considered relatively new, almost no one developed a complete idea about what specific performance measurements should be devoted for these systems.

Zhong et al. [2000] talked about convertibility as one of the performance measurements for system configuration evaluation Convertibility is the capability of a system to adjust production functionality, or change from one product to another, with consideration of costs and time. This metric was presented in terms of time required to convert the system to the new configuration.

Urban [2001] tackled this issue in a considerable way when he introduced and modeled the effort and efficiency measurements in reconfigurable manufacturing systems. He described them as follows:

- The Effort: The efforts to modify the system's and the system's components structure can generally be measured by the ratio:

  Effort = Number of modules to be modified / Number of total modules

- The Efficiency: Efficiency in the implementation of functionalities must depend on the mix to be worked. It can be calculated as

  Efficiency = NF / AF

Where NF = No. of needed functionalities and AF = No. of available functionalities

In this thesis three performance measurements are suggested that are totally devoted for reconfigurable manufacturing systems reflecting its strategic objectives and are used for the control of the reconfigurable manufacturing systems design process in the proposed architecture. All of these measurements are still in the theoretical phase and needs a lot development and validation. These measurements are as follows:

1) Capacity Scalability Index (S):

Capacity Scalability by definition is the ability to easily change existing production capacity by rearranging an existing production system and/or changing the production capacity of reconfigurable components (e.g. machines) within that system [Koren et al 1998]. Based on that definition the performance measurement required would be a metric that measures the degree of scalability of a system. In other words there is a need to develop a metric that helps to judge whether this system is more scalable than the other or not. For now, the only metric that can help in such a problem is the effort metric stated previously which was presented by Urban and measures the efforts to modify the system's and the system's components structure.

In this thesis an index is suggested to approach the same problem from a different perspective. The capacity scalability index is used to measure the degree of capacity utilization of the system at any time instance. The basic assumption of the reconfigurable manufacturing systems is that the exact capacity needed is supplied when needed. This implies that the capacity should be equal to the required demand and thus reconfigurable manufacturing systems are much more cost effective than the flexible manufacturing systems as the later is characterized by high cost due to the underutilization of its capacity.

- S = [Demand] / [Scaled Capacity]
- S should approach 1 to indicate for a good RMS scalability performance (less than 1 means lost market opportunity and more than 1 means unutilized capacity like in FMS)

It is clear that this metric is not an indication of the degree of scalability of the overall system but can be used to measure the capacity scalability from the utilization point of view at any point in time. More investigation is needed to develop this index which will be carried out in future work.

2) Reconfiguration Time (RT):

Responsiveness is the key element of the reconfigurable manufacturing systems where time plays the major role. The reconfiguration time for the whole design process is considered an indicative for the responsiveness of the system. In the proposed architecture, the time for each activity in each layer is considered in the control module in order to control the responsiveness of the whole design process. Therefore the reconfiguration time is the sum of the different design and implementation process time. In real practice the time units will range from days to weeks.

The reconfiguration time is expressed as follows:

- $RT = T_m + T_s + T_c + T_p$

  T_m: The sum of time consumed during each design activity in the market capturing layer

  T_s: The sum of time consumed during each design activity in the System Reconfiguration layer

T_C: The sum of time consumed during each design activity in the Component Configuration layer + Ramp up Time

T_P: Time for production

- RT^* = Required Reconfiguration Time (Responsiveness Level strategically indicated by the high level management)

To measure the responsiveness of the system RT is compared to RT*. Thus, this metric does not measure general responsiveness of a system; however it measures the responsiveness relative to a previous strategic responsiveness level indicated by each corporation. The responsiveness time is just a suggestion to maintain the importance of the time while designing the reconfigurable manufacturing systems; however more work is required to generalize and validate this metric to measure the real responsiveness of reconfigurable manufacturing systems.

3) *Reconfiguration Cost (CR):*

Cost modeling of manufacturing systems is very important in the control of the design process. Traditional cost modeling of manufacturing systems included the cost of direct labor, operational cost and capital cost [Cram 1997]. Some approaches to model the cost manufacturing systems was through activity based costing to overcome the limitations of the traditional cost modeling techniques [Glancy 1992]. In reconfigurable manufacturing systems the cost modeling still needs to be more investigated to accommodate for the new technologies involved in such systems.

The cost effectiveness of the reconfigurable manufacturing systems is achieved through its adjustable resources that enable system scalability in response to changing customer needs. Resources include the hard, soft, and human components of the system. Resources could be adjusted at the system level or at the machine level. The cost of such resource adjustment could be calculated through calculating each of components involved in the reconfiguration design process like cost of adding machines, tools, reprogramming, adjusting the control system, human resource allocation…etc.

A very preliminary description for of CR equation could be:

$CR = C_{RT} + C_{HR} + C_{SR} + C_{MR} + C_O$

C_{RT} is the Reconfiguration Time cost (includes downtimes for scalability and delay, decision time, & ramp up time)

C_{HR} is the cost of Hard Reconfiguration (the sum of each physical element cost described in the architecture)

C_{SR} is the cost of Soft Reconfiguration (the sum of each logical element cost described in the architecture)

C_{MR} is the cost of Human Reconfiguration (the sum of each human element cost described in the architecture)

C_O is the cost of additional parameters that should be further included in the component level (installation, maintenance…etc.)

Two important points should be mentioned while talking about the cost of reconfiguration. The first point is that in this research the system is assumed to be reconfigurable which means that adopting the RMS technology has been economically justified and all associated costs of early construction of these systems is not included in the term CR. The second point is that the cost of reconfiguration should always be compared with the profit or benefit associated with capturing the market demand and being competitive in the market. However, such benefit is very intangible and very hard to be estimated before it happens.

The values of the cost parameters in CR are to be input to the control module of the architecture to maintain the design process of the system within the feasible limit as indicated in the strategic objective of the corporation. The problem in such a metric is in obtaining the real value of all these cost parameters as some of these parameters can be easily indicated while other parameters, especially those dealing with soft and human configuration, are difficult to evaluate. One way of overcoming this problem is to roughly estimate these cost values based on experience or similar deterministic cost values. However, working on the cost values of the reconfiguration is still a wide area of research that has a significant importance in the decision making within this new technology and need to be more studied. The cost of reconfiguration CR will be used in the next chapter while modeling the capacity scalability in the first layer of the architecture.

4.5 APPLICATION OF THE DESIGN AND CONTROL ARCHITECTURE FOR THE RECONFIGURABLE MANUFACTURING SYSTEMS

4.5.1 Printed Circuit Board (PCB) Automatic Assembly Industry

In Traditional PCB automatic assembly line (sometimes called surface mount technology SMT), it consists of a loader/unloader magazine for loading the PCB into and from the line, a screen printing machine for printing the solder paste over the PCB to hold the electronic components, automatic pick and place machines to place or assemble the components over the PCB (this is the heart of the line) through different types and sizes of feeders and nozzles, reflow oven for solidifying the solder paste to maintain robust connectivity for the components over the PCB (this is achieved through providing a pre-designed thermal profile) and finally some inspection devices like the ICT (in-circuit tester) inline or at the end of the line.

The automatic assembly process simply starts by printing the solder paste (highly conductive martial) over the PCB in the designated solder pads for the of the components, then followed by placing the different components over these pads through the automatic pick and place machined and finally solidifying the viscous paste under the components through the oven to firmly fix the components over the PCB. Inspection and quality checks are carried out in the line and after the assembly process through microscopic or any visional tool to check for the shape and quality of the paste and an in-circuit tester ICT is also used to check for the electronic circuit functionality (open and closed circuits) and the conditions of the assembled components of the assembled PCB. Figure 4.13 is a typical PCB assembly line.

In a reconfigurable PCB automatic assembly line, the previous components of the line are designed to be reconfigurable. PCB automatic assembly line has great potential for modular design especially for some of its critical parts that will enable the scalability of the line's capacity and functionality.

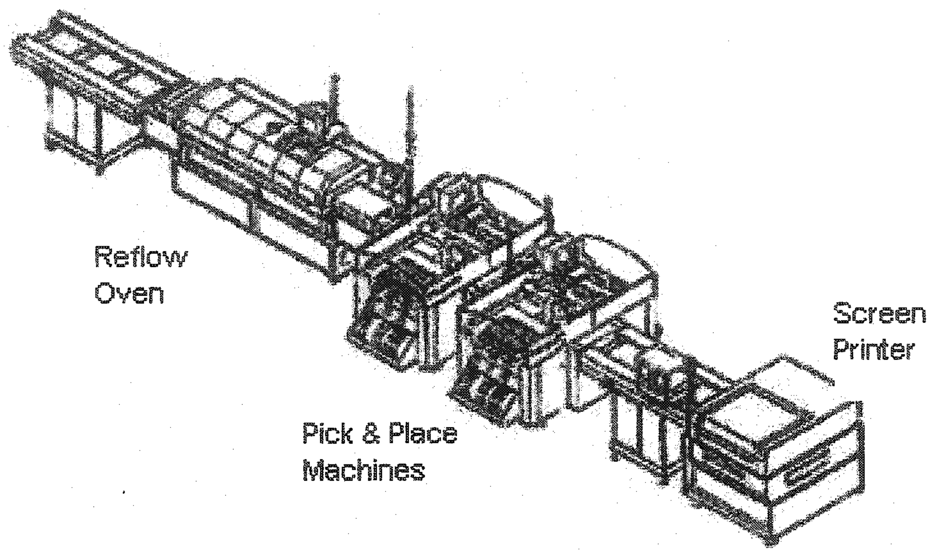


Figure 4.13 PCB automatic assembly line [17]

On the system level, the reconfiguration of these assembly systems would be through the addition or removal of machines. Practically speaking the machines that are added or removed are the automatic pick and place machines as they are the bottle neck of any automatic PCB assembly line. Other types of machines could be added based on the capacity needed. To have a smooth reconfiguration of these lines on the system level, the infra structure of the line should be also designed to accommodate for these changes in terms of the pneumatic and electrical facilities. The ramp up time of the changes of these assembly systems is mainly consumed in aligning the conveyors and the cameras of the installed machines.

On the machine level, the automatic pick and place machines are designed to assemble different types of electronic components and IC chips by its modular design that can accommodate different types of cameras, according to the size of the components and chips and different types and sizes of nozzles to pick these components and chips. Also these machines are designed to assemble different volumes of PCB through adding and removing different numbers and kinds of components feeders. This is assisted by a reconfigurable open control system of those machines that can compensate for these different parts.

The printing machine is also modularly designed to be reconfigured to act as screen printing machine for the solder paste or as a glue dispenser (in case of double PCB side assembly) according to the application by just adding the required dispensing modules.

The reconfiguration of the reflow oven is done through reprogramming the settings of the thermal profile according to the type of the paste and product (logic or soft reconfiguration). For the ICT machine it is reconfigured through modular design of the jigs and testing probes. Finally the material handling devices (loaders, unloaders and conveyors) are sizeable according to the product in the line.

Figure 4.14 shows the possible system-level reconfiguration changes that could occur to the reconfigurable automatic PCB assembly line where one (or more) machine is added to the line in series or in parallel depending on the capacity required. These machines could have different configurations on the machine level, Figure 4.15, which leaves the designer of the system with multiple options between the number and the configuration of the required machines for the PCB assembly line.

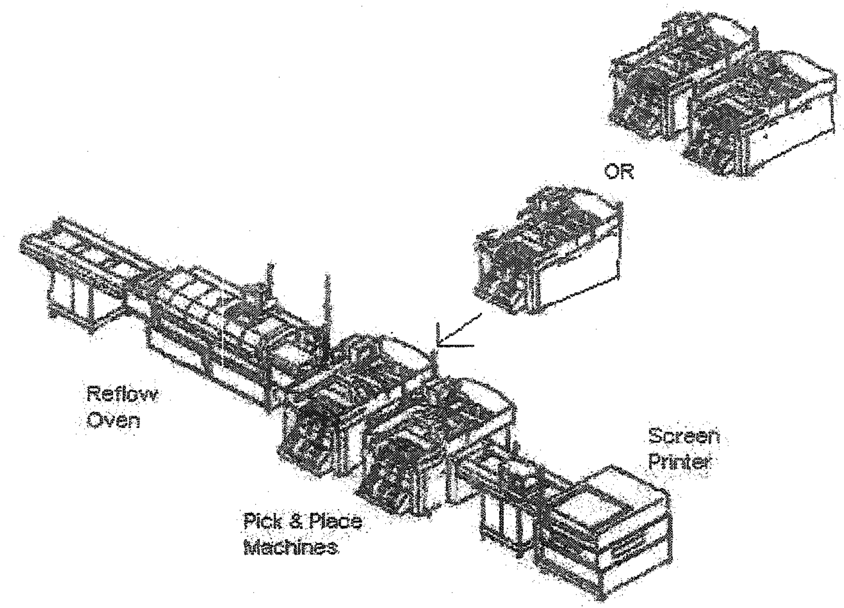


Figure 4.14 System-Level Reconfiguration for PCB Assembly Line

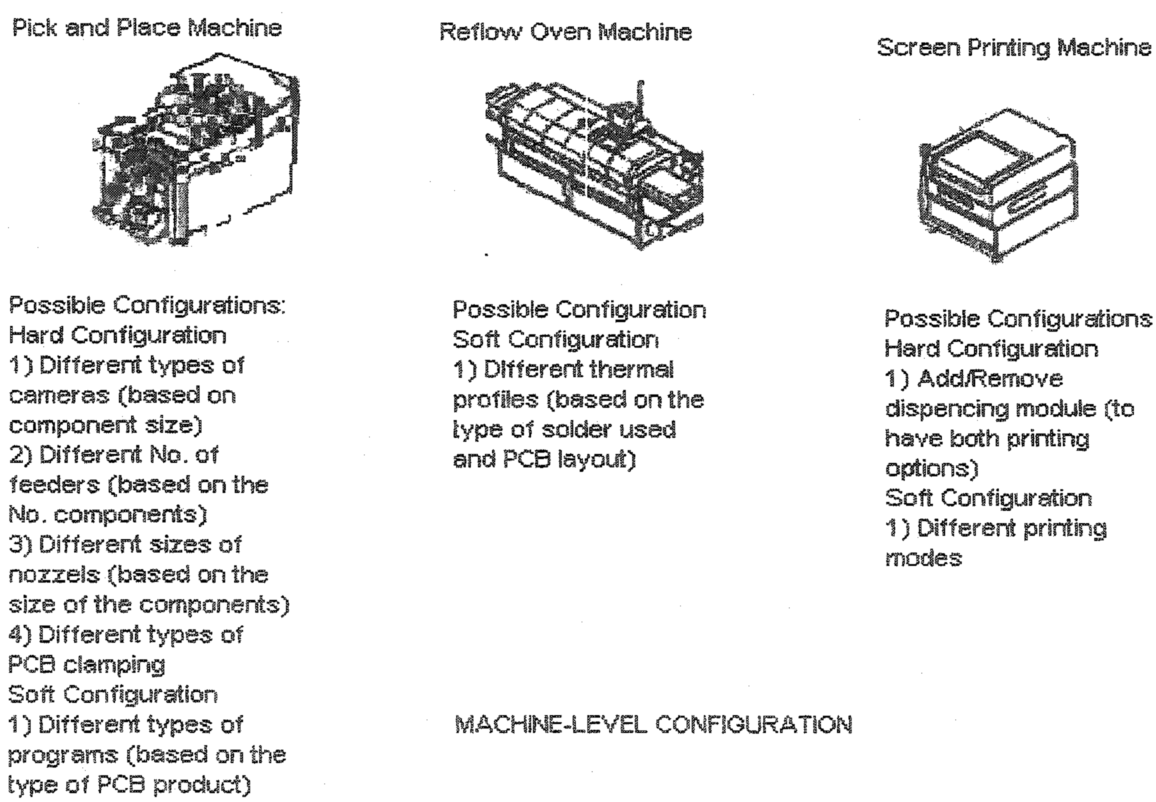


Figure 4.15 Machine-Level Reconfiguration for PCB Assembly Line

4.5.2 Applying the RMS Design and Control Architecture to a Reconfigurable Computer Peripherals PCB Automatic Assembly Industry

The application in this thesis is the computer peripherals automatic assembly. These peripherals include main boards, VGA cards, sound cards, memory cards and fax modem cards and thus the assembly line should be able to assemble a great mix of products. In addition, this type of market is characterized by being very turbulent due to the short life cycle of the products and the high need for mass customization of the products. In this environment the need to apply the reconfigurable manufacturing technology is highly recognized. In the following sections the different layers of the proposed architecture will be applied to this industry.

4.5.2.1 Market Capture Layer in reconfigurable PCB assembly Line

As previously discussed, this layer is responsible for capturing the market demand, which in this case will be the required mix of computer peripherals. After determining the capacity scalability plan for time horizon T, the capacity scalability policy or schedule is generated and delivered to the system configuration layer in the shape of required production levels. Also based on the kind of the peripherals (like PC motherboards, VGA cards, Fax modems...etc.) and the electronic components to be mounted (like the size of the IC chips, diameter of the BGA chips, size of the passive components, number of PCB sides to be assembled...etc.) the functionality required is determined and also delivered as input to the system configuration tool.

The control module will act in this layer to control the development of the scalability policy at the minimum time with the minimum cost.

Figure 4.16 shows the previous design and control processes of the first layer of the architecture.

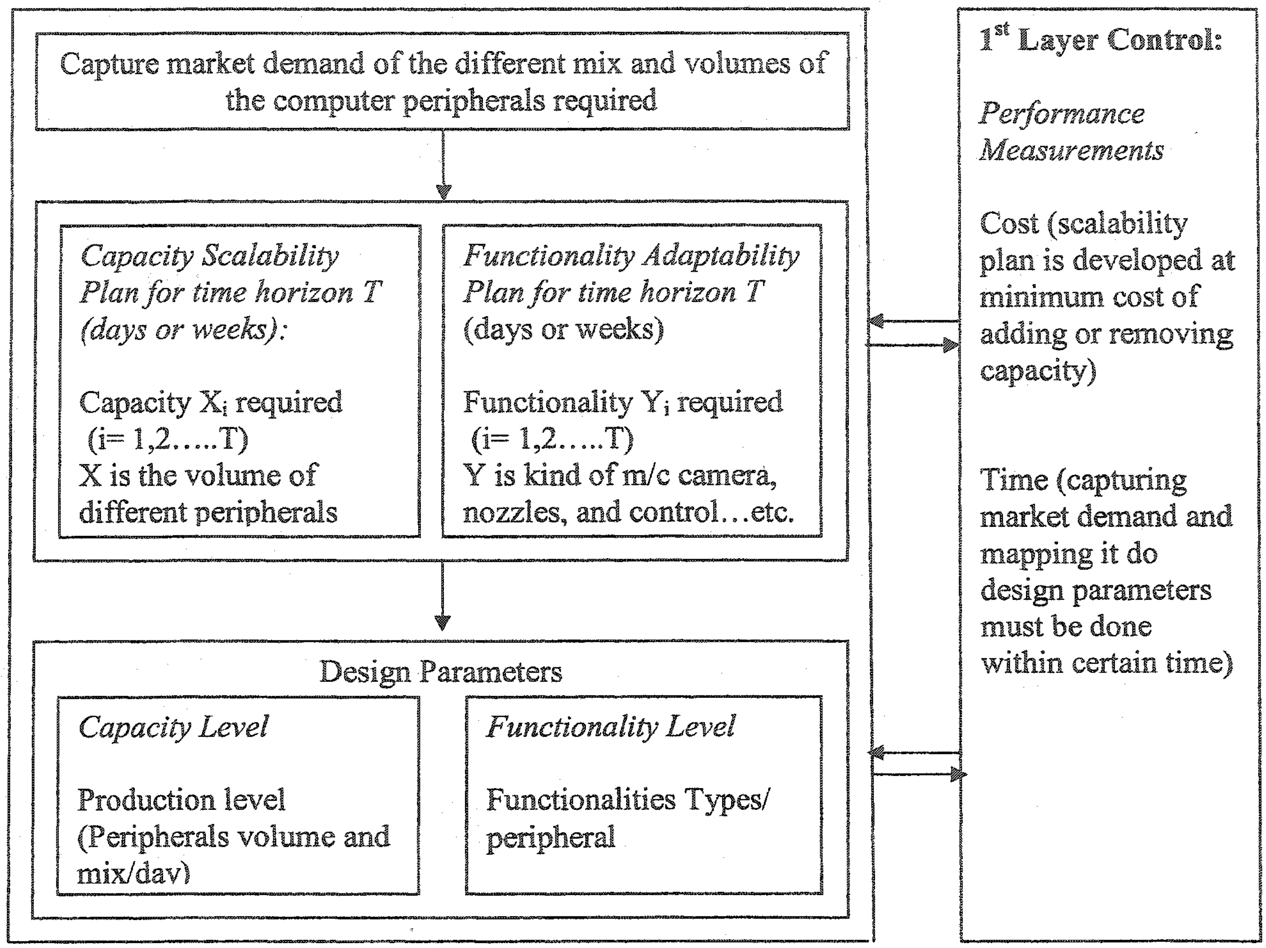


Figure 4.16 Market Capture Layer in Reconfigurable PCB Assembly Line

4.5.2.2 System Configuration Layer in reconfigurable PCB assembly Line

After determining the capacity and functionalities policies needed, they are delivered to the system configurator tool of the line to prescribe the physical, logical and human (re)configuration of the system.

The physical or hard configuration of the automatic PCB assembly line will include; the number and arrangement of the required pick and place machines to be added/removed, the required feeders, cameras and nozzles for each machine to be added/removed, the required module for the printing machine (screen printing or glue dispensing), the design of the ICT machine and finally the adjustment required for the material handling. equipments (PCB magazines, loaders/unloaders and conveyors).

The logical configuration of that system includes the change, retrieval or generation of the pick and place software required for the assembled peripherals types, the retrieval or generation of the required thermal profile for the used paste in the reflow oven machine and adjusting or re-planning the existing assembly routes.

For the human configuration, in this case it will only include some adding or removing of labors depending on the number of inspection locations and required material handling equipments.

The generation of the configuration(s) of this kind of lines is usually constrained by the space of the factory, the capabilities of the existing machines modules and the cost of line reconfiguration indicated by the high-level of the corporation as a strategic limit.

If there were multiple line configurations generated in the previous step, a selection process is carried out and controlled by the performance measurements used for the automatic PCB assembly lines, which are usually the throughput of the line and the quality (especially the solder joints). Optimization of the selected line configuration is used to fine tune the line.

Planning for system reconfiguration follows the configuration selection to ensure the smoothness of the system reconfiguration process. The whole system configuration process is controlled also by the required time T_s to maintain the strategic level of responsiveness. The system configuration layer is shown in Figure 4.17.

4.5.2.3 Component Configuration Layer in reconfigurable PCB assembly Line

Since this layer deals with the operational and floor-level implementation of the system configuration, for the computer peripherals automatic assembly case this

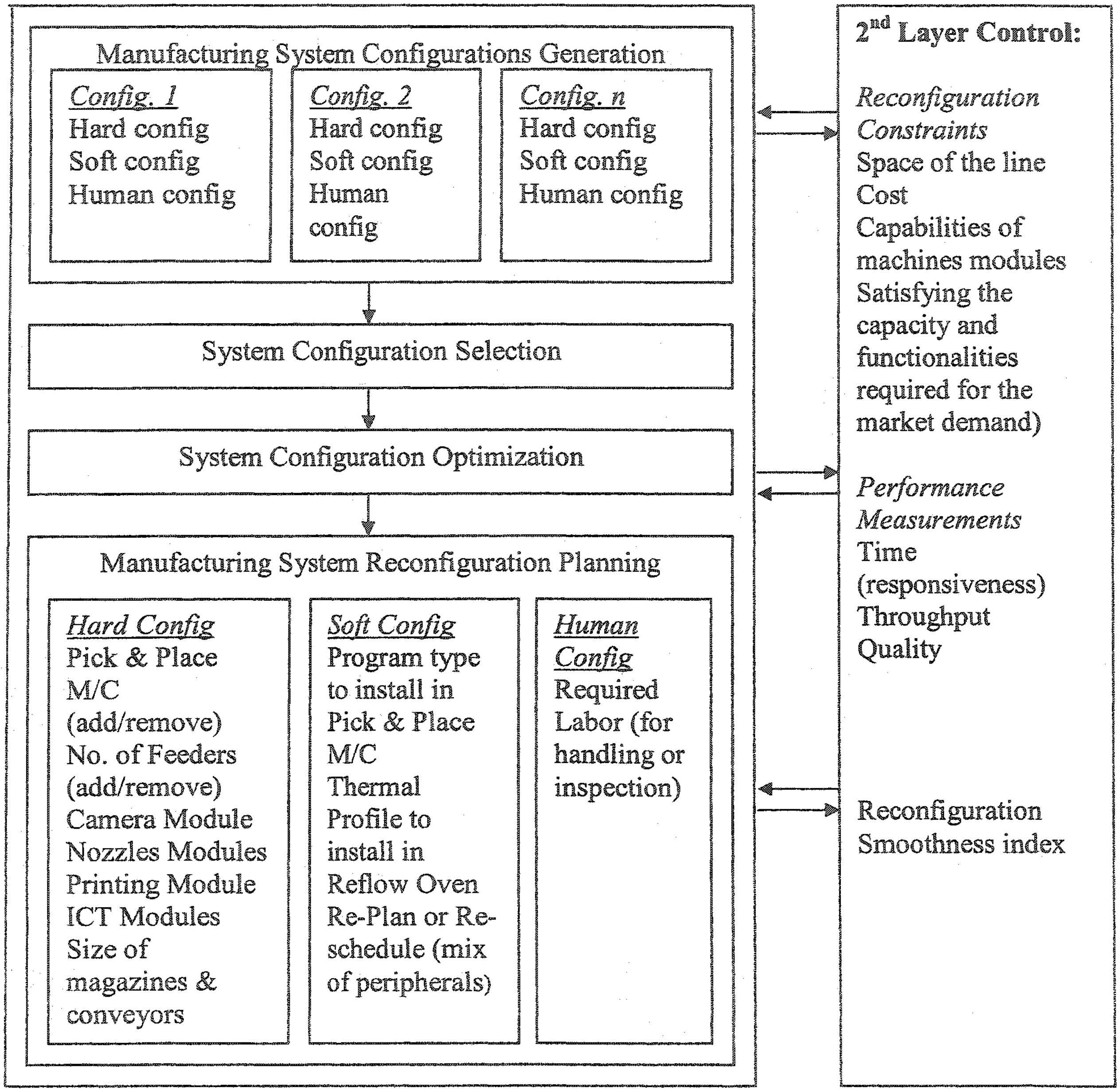


Figure 4.17 System Configuration Layer in Reconfigurable PCB Assembly Line

layer will deal with physical or hard configuration implementation including the required adding or removing of pick and place machine(s) or any of its parts (cameras, nozzles and feeders). It also deals with construction of the newly reconfigures ICT machines, and fixing or sizing the material handling equipments (conveyors, loader/unloader machines, tray and PCB holders…etc.) according to the required computer peripheral application.

As for the soft component-level configuration it includes installation of the required pick and place program and the associated control changes in the architecture of the machines to accommodate for the new features installed or removed. Also adjusting the thermal profile according to any new paste types used and executing the new reconfigured production routes, scheduling and plans are all considered within the soft component-level reconfiguration.

The human configuration in that level is just done through the physical task allocation, distributing work sheets for the new configuration design and finally if any training needed for the labor staff for any new model, it is carried out.

The new assembly configuration is then ready for the production by first ramping up (in a minimum time) and the main time consumer at that phase is for the aligning and calibration of new cameras and conveyors installed. The production is then carried out to produce the required computer peripherals mix.

The control module of the component-level layer is responsible to maintain the physical reconfiguration at the minimum time T_c* with the minimum cost. As for the real production it is controlled by the normal production control techniques (statistical, inspection…etc.). The feedback from the customer and the maintenance centers are very important for the control of the computer peripherals industry. Figure 4.18 shows the previous reconfiguration and control processes of the third layer of the architecture.

4.6 CHAPTER SUMMARY

The chapter presented integrated multi layer architecture for the design of reconfigurable manufacturing systems. The methodology used for developing the architecture was based on the software system design methodology. The proposed architecture is an open and

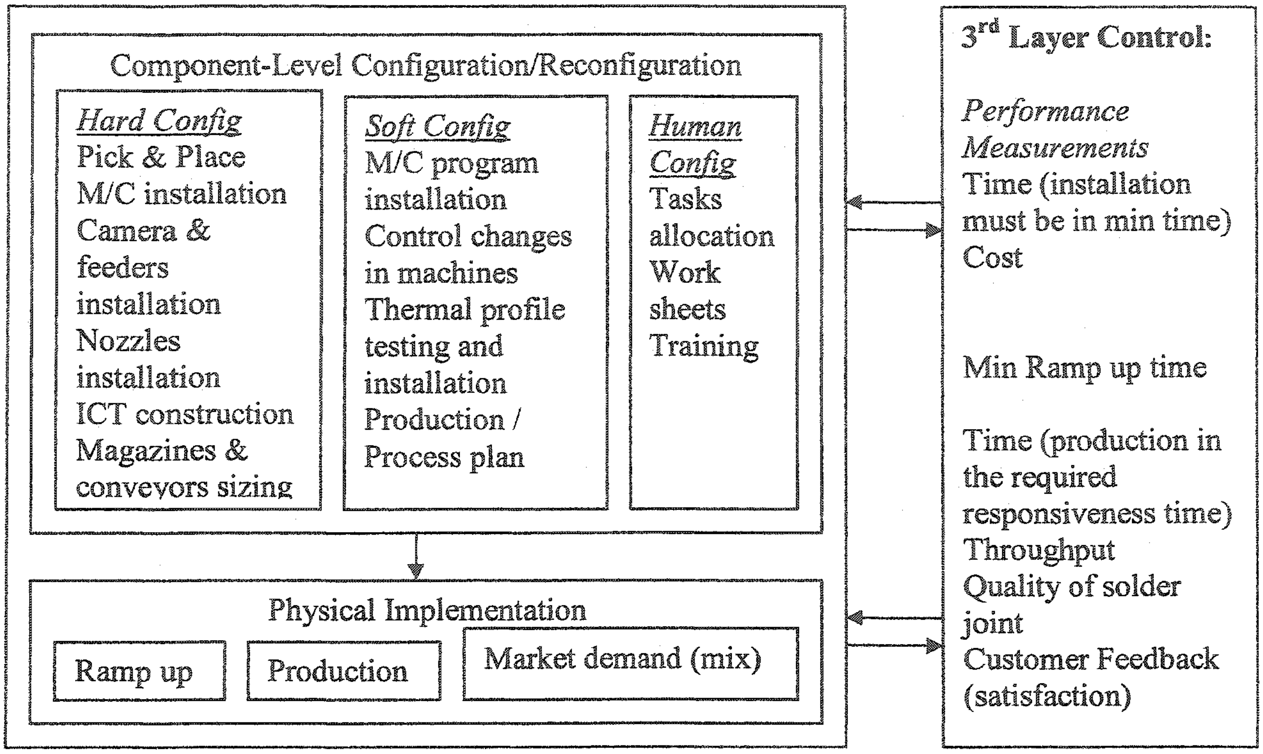


Figure 4.18 Component-Level Configuration Layer in Reconfigurable PCB Assembly Line

mixed one that contains two main modules; the design module and the control module.

The design module describes the full design processes on the macro level starting from capturing the market demand to generating and selecting the best configuration to satisfy this demand to the final physical implementation of that system configuration. Each of these design layers was described using $IDEF_0$ models to give a better explanation of the activities involved.

The architecture showed how each design layer is controlled through the control module presented. In this chapter different performance measurements that reflect the strategic objectives of the reconfigurable manufacturing system. The performance measurements were both classical and new which are developed only for the reconfigurable manufacturing systems.

The architecture could be considered a comprehensive explanation of the reconfigurable manufacturing systems as it captures the full reconfiguration process in the reconfigurable manufacturing systems. It opens the door for researchers to visualize the different areas that need to be developed in such systems.

This architecture is considered the first architecture to tie different aspects of the design of reconfigurable manufacturing systems and how to control these activities. The Application of the automatic printed circuit board (PCB) assembly industry discussed in this chapter aimed to illustrate how such architecture can be applied in real reconfigurable industrial environment.

Further work is needed to model each of the layers or even each activity in each layer. These models or tools, like capacity scalability model or system configuration tool, should be integrated together to develop a generic framework for the design and control of the reconfigurable manufacturing systems.

In the rest of the thesis an approach for modeling one of the layers of the architecture is presented. The layer selected to be modeled is the first layer of the market capture module and this will be done by presenting a tool for generating optimal capacity scalability policy to be delivered for the system configuration layer of the architecture.

CHAPTER 5

CAPACITY SCALABILITY MODELING IN THE PROPOSED RECONFIGURABLE MANUFACTURING SYSTEMS ARCHITECTURE

5.1 INTRODUCTION

As stated in the objectives of the proposed architecture, the development of that general design architecture should be extended from the qualitative level to the quantification level so it would increase its practicality in terms of real world application. The quantification or modeling of the whole architecture layers is a huge task that is beyond the scope of this thesis but considered is in the future research work. However, in this chapter a capacity scalability model for the first design layer (market capture layer) of the proposed reconfigurable manufacturing systems design architecture is presented. The model is used to develop a computer tool that generates an optimal capacity scalability schedule or plan for reconfigurable manufacturing systems. The model is based on the optimal plant size with arbitrary increasing time paths of demand approach presented by Manne and Veinott [1967].

A review on the capacity scalability problem is first conducted to show how such problem was first addressed in the classical manufacturing systems followed by the approaches done to solve this problem in reconfigurable manufacturing systems.

A theoretical background about convex sets and concave functions is presented to pave the road for the modeling process. The properties of theses sets and functions will be the mathematical base of the formulated capacity scalability model. Also a detailed explanation of the regeneration point theorem will be introduced before the formulation of the model. The regeneration point is mapped to the reconfigurable manufacturing paradigm as the scalability point of that system.

Following the theoretical background is the development of the model. The development starts by some assumptions concerning the inputs and the outputs parameters of the model. Also the cost function for capacity scalability that fits the reconfigurable manufacturing systems is also presented.

The model is then formulated based on dynamic programming and a computer tool is developed using MATLAB to generate optimal capacity scalability schedule or plan for reconfigurable manufacturing systems. Finally some numerical examples are used to illustrate the use of the formulated model and the developed tool and to show the relation between the capacity scalability planning horizon and the cost of capacity scalability policy which will lead to modifying the adopted model. Also comparing different capacity scalability plans and testing the effect of decreasing demand over the generated optimal capacity schedule are carried out.

5.2 GENERAL REVIEW FOR CAPACITY SCALABILITY PROBLEM

Capacity is defined as the maximum rate of production and the ability to yield production [Farshid et al., 2002]. The capacity scalability problems were classically addressed as the problem of capacity expansion. The difference between the two approaches is that scalability also addresses the reduction of the capacity besides the expansion. Another major difference is the enabling technologies for both problems. As it will be discussed most of the techniques used for capacity expansion problem are classical techniques, whereas for capacity scalability problem the modern technologies such as modular design and open control architectures are used to implement successful capacity scalability policies.

Reconfigurable manufacturing systems are assumed to have their capacity scalable in a cost effective manner. This assumption is one of the major principles that are the base of every design activity in these systems. The proposed architecture in this thesis is also based on the assumption that the system is scalable and presents in this chapter an approach to capacity scalability policy modeling in a realistic practical way.

5.2.1 About the Capacity Scalability Problem

The major decisions in any capacity scalability problem or planning are:

- What is best the expansion/reduction capacity size?
- When is best the expansion/reduction time?
- Where is the best expansion/reduction location?

The word "best" (sometimes called optimal), in the previous questions means satisfying the market demand at a minimum cost. A capacity scalability policy is supposed to answer the previous questions. However, in real practice it is difficult to have a capacity scalability policy that satisfies all questions in an optimal way. The proposed capacity scalability model (and tool) in this thesis generates a policy that answers the size question at a minimum cost. The time for scalability is also indicated through a strategic decision that should be taken by the high-level of the corporation to indicate the time horizon available for reconfiguration.

The cost of capacity expansion is traditionally justified by the economy of scale of the expanded capacity. In reconfigurable manufacturing systems it is assumed that capacity scalability is justified by shortage cost as responsiveness is considered a cost advantage in today's dynamic market and thus capacity is supplied *when* needed and it is also justified by cost of the underutilized capacity as the *exact* capacity is supplied *where* needed and the later gives the reconfigurable manufacturing system a merit over the flexible manufacturing systems. The cost effectiveness of the capacity scalability together with the functionality scalability in the reconfigurable manufacturing systems are also achieved through the economy of scope.

The demand pattern is a very important parameter in developing any capacity scalability policy or plan. The pattern describes the demand over a certain time horizon and this time horizon is usually the planning period that is indicated by the corporation. The demand patterns can take different forms; it could be linear or exponential and deterministic or stochastic. In a typical reconfigurable manufacturing environment, the demand is usually unpredictable and thus a stochastic pattern is the best form for capturing such demand.

However, in the proposed model, the demand is assumed to be deterministic for simplicity and applying stochastic demand for the model will be done in future work.
In the next section a general review about models and approaches developed to solve the capacity scalability problem in classical manufacturing systems, flexible manufacturing systems and reconfigurable manufacturing systems is conducted to compare the way of solving the capacity scalability problem in different types of manufacturing systems.

5.2.2 Capacity Scalability in Classical Manufacturing Systems

The classical manufacturing systems like dedicated lines and other mass production manufacturing systems encountered the capacity scalability issue through many approaches for what was known as capacity expansion problem. The capacity expansion problem in classical manufacturing included expanding the existing lines through duplication of the line or of certain machines in the line and was even extended to include the expansion of the whole facility to multiple facilities. Thus it can be said that capacity scalability in these systems was done on a very macro scale over the system level and without including the reduction of the capacity (except in very few cases). This can be understood since these classical systems were economically justified and designed for production of a specific part at high volume without dealing with variety or mix of products.

The most popular study for capacity expansion problem in classical manufacturing systems is that done by Manne [1967] for heavy industries in India. He proposed a model for a deterministic demand that grows linearly with time that balances between the cost of installing capacity before it is needed and the economies of scale savings of large size of capacity expansion. The model determined the sizes of facilities to be added and the associated times to be added so that the present worth of all expansions is minimized.

Sinden [1960] developed another model for certain conditions under which the optimal policy will consist of equal time intervals between successive expansions. Wagner and

Whitin [1958] introduced the famous dynamic lot size problem that was applied for the capacity expansion problem for finite planning horizon and discrete time scale.

In solving the capacity expansion problem for classical manufacturing systems, solutions such as accumulating inventory and importing products were proposed. Erlenkotter [1977] examined expansion policies in which shortages and inventory accumulation are allowed. His model shown in Figure 5.1 is composed of four phases for each capacity cycle.

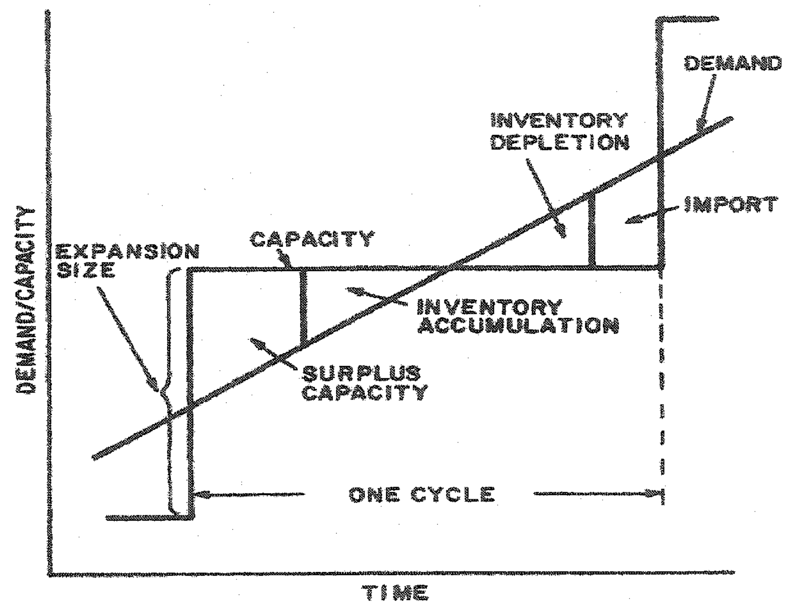


Figure 5.1 Capacity Expansion with Inventory Accumulation and Shortage

The phases are: surplus capacity phase in which capacity exceeds demand but no inventory is built up, an inventory accumulation phase, an inventory depletion phase in which the shortage is satisfied solely by the inventory, and the import phase in which capacity shortages are satisfied by import capacity. The optimal capacity expansion policy consists of expansion sizes and times interval, which allow for inventory accumulation and capacity shortage.

Freidenfields [1981] examined the linear demand with capacity shortages satisfied only by imports and he proposed a dynamic programming algorithm that uses policy iteration or a value iteration scheme to find optimal policy. He also extended this algorithm to a more general model that includes congestion costs.

Also for solving the capacity expansion problem in classical manufacturing systems, multi facility solution was proposed. It should be distinguished between the multi location problems (multi facility) and multi type problems in capacity expansion. The former deals with the case in which facilities may be installed in various locations. Products can be shipped from any production facility to various demand locations at specified cost. Obviously, the optimal shipment plan may change over time. On the other hand, multi type problems deal with the case in which several capacity types (e.g. different types of machines) are being used to satisfy a given type of demand but it can be converted (perhaps at some cost) to satisfy a different type of demand.

Luss [1982] stated that in some applications of the classical industries, the converted capacity mentioned can be rearranged to its original type at any time and at no cost. In other applications converted capacity becomes an integral undistinguishable part of the new capacity type so that free rearrangements of converted capacity are not possible. Within this context it can be said that reconfigurable manufacturing systems are concerned with the multi type capacity that can be freely changed and rearranged through its modular design as discussed earlier.

Dealing with stochastic demand patterns in classical manufacturing systems was very well addressed by Freidenfields [1980] when he modeled demand as a birth-death process. He suggested that when capacity shortages are not allowed, the stochastic model can be reformulated as an equivalent deterministic model. The assumption of not allowing capacity shortages fits into the reconfigurable manufacturing systems capacity scalability principle and thus this model could be applicable to modeling capacity in reconfigurable systems.

In general, a lot of simple and complex mathematical models including; linear, non linear, dynamic and integer programming together with other optimization techniques were applied to the different capacity expansion problem dimensions (single or multiple facilities, imports, inventory accumulation…etc) of the classical manufacturing systems. These models can guide the solution of the capacity scalability problem in reconfigurable manufacturing systems; however, extensive effort should be made to adjust these models to the capacity scalability scope and objective of the reconfigurable manufacturing systems.

5.2.3 Capacity Scalability in Flexible Manufacturing Systems

The capacity scalability management in flexible manufacturing systems is considered a complicated task. Functionality scalability is usually much used in FMS than capacity scalability and it is mainly achieved through the existence of multipurpose programmable machines. The problem of modeling capacity scalability problem in FMS arises from the great alternatives of identical and non-identical machines available in the system with multiple functionalities. Capacity scalability is very expensive in flexible manufacturing systems and thus it is usually dedicated to mid-volume production with high variety.

Leachman and Carnon [1992] proposed a procedure to generate the capacity set of alternative machine types assuming that processing time among alternative machine types are identical or proportional across the operation that they can perform.

Roundy et al. [2000], considered a discrete-time capacity expansion problem in flexible manufacturing environments that can deal with multiple product families with multiple machine types and non-stationary stochastic demand. Capacity expansion decisions are made to strike an optimal balance between investment costs and lost sales costs.

Liberopoulos, G. [2002] expressed the capacity of the flexible manufacturing system in terms of the total production rates of all part types over all machines. The capacity set is expressed as convex hull of a set of points corresponding to all possible assignment of machines to part types where in each assignment each machine allocates all its capacity to only one part type.

The capacity scalability in flexible manufacturing systems is viewed as how can the system satisfy the demand within the existing capacities alternatives in an optimal way due to the existence of fixed but programmable machines. In other words the flexible manufacturing systems are not designed for adding or removing any capacity units but there are multiple functional alternatives. Thus most of the capacity scalability approaches in flexible manufacturing systems handle this problem as a problem of finding the optimal control of production flow (alternatives) of the systems [Kimemia and Gershwin, 1983].

5.2.4 Capacity Scalability in Reconfigurable Manufacturing Systems

Although it has been suggested that capacity scalability should be considered in reconfigurable manufacturing systems there has been very little research on how to actually achieve it. As mentioned before, capacity scalability in reconfigurable manufacturing systems is the ability to smoothly change the existing system capacity through rearranging or changing (adding or removing) the system components.

Son et al. [2001] suggested station paralleling within a stage as a possible approach to scale the capacity of the system. He developed design criteria to model the required parallel machines and its location in this homogeneous paralleling flow lines HPFL. To prove the potential of his approach he compared the life cycle of his HPFL scalable system with the traditional transfer line systems and found that if the traditional transfer lines are not totally balanced (which is almost always the case), then HPFL are more cost effective when it comes to capacity scalability. This is because the HPFL has smaller steps for capacity scalability than the transfer lines. Although this approach for justifying the capacity scalability is fine, however the scalability was only viewed as adding one or more machine in parallel to the system which is considered a very narrow view for capacity scalability in reconfigurable systems that needs a lot of enhancement.

Asl and Ulsoy [2002] presented an approach to capacity scalability in reconfigurable manufacturing systems based on the use of feedback control theory to manage the capacity scalability problem. They showed that feedback provides suboptimal solutions for the capacity management problem which are more robust under system uncertainties and disturbances in the forecasts of market demand relative to the existing capacity management methods. In their approach they assumed that the capacity change in the reconfigurable manufacturing system is quantized, and the possible values for X_i are members of a set X called the Scalability Set, $X = \{X^1, X^2, ..., X^N\}$. The quantized values for X_i can be shown as $[Xi]_X$ which indicates that X_i can only take values in X. This was followed by developing a deterministic continuous time model based on the quantized capacity scalability to generate a capacity policy in reconfigurable manufacturing system at minimum cost.

Another approach for capacity management in reconfigurable manufacturing systems with stochastic market demand was presented by Asl and Ulsoy [2002] also where an optimal solution for the capacity scalability management based on Markov decision theory. Also they considered the time delay between the time the capacity is ordered and the time it is delivered. The optimal policy in their work is presented as optimal boundaries representing the optimal capacity expansion and reduction levels. The effects of change in the cost function parameters and the delay time on the optimal boundaries were presented for a capacity management scenario. Their work is considered as an extension to Rocklin and Kashper [1984] method where they integrated to it their previous dynamic model for capacity scalability.

The work of Asl and Ulsoy in general is considered the first and the only approach to model the capacity scalability for reconfigurable manufacturing systems. However, their quantification of the capacity scalability needs to be more validated in terms of some assumptions. The capacity scalability notion should also be expanded beyond the machine context (hard configuration) to include other capacity parameters in reconfigurable manufacturing systems like soft configuration and human configuration.

It is clear that there is a very wide area of research to model and investigate the capacity scalability principles in the reconfigurable manufacturing systems. Most of the work concentrated on time of capacity scalability; however, more work is required to also include the size of capacity scalability. There is a need for more approaches to model the capacity scalability of these systems in terms of size and time at minimum cost to maintain the cost-effectiveness as well as the responsiveness of reconfigurable manufacturing systems and to prove the practicality of such systems. This need is addressed in the model presented in this chapter of the thesis.

5.3 THEORETICAL BACKGROUND

5.3.1 Convex Set

A set S is convex if $\forall\, x, y \in S$, and for any $c \in [0, 1]$, then the linear combination:

$$cx + (1-c)y \in S \tag{5.1}$$

In other words, the line segment joining any two endpoints in the set also lies completely in the set Figure 5.2 demonstrates the definition of a convex set.

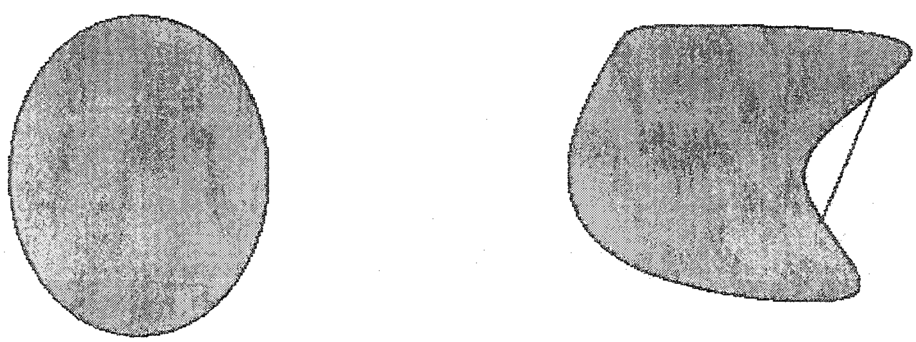


Figure 5.2 Convex Set (Left Side) and Non-Convex Set (Right Side)

A point s in a convex set S is called an extreme point of S if there do not exist two distinct points x and y such that:

$$s = (1/2)\, x + (1/2)\, y \tag{5.2}$$

5.3.2 Concave and Convex Functions

The functions are normally concave, convex or neither one of them as shown in Figure 5.3. A function is said to be concave if for any pair of points, x_1 and x_2, and a given lambda, λ, such that $0 \leq \lambda \leq 1$, the following holds:

$$f[\lambda x_1 + (1-\lambda) x_2] \geq \lambda f(x_1) + (1-\lambda) f(x_2) . \qquad (5.3)$$

To be strictly concave, the inequality must be strictly satisfied. For convex functions, the inequality is reversed.

It can be also said that a twice differentiable function (i.e. a function that is differentiable and for which its derivative is differentiable) is concave if its second derivative is non-positive and is convex if its second derivative is non-negative:

A function is Concave on the interval I if $f''(x) \leq 0$ for all x in the interior of I

A function is Convex on the interval I if $f''(x) \geq 0$ for all x in the interior of I.

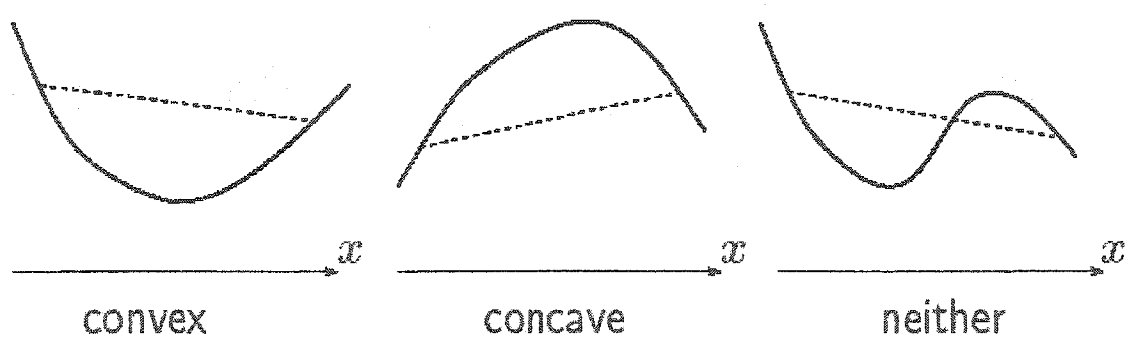


Figure 5.3 Types of Functions

The importance of concave and convex functions in optimization theory comes from the fact that for a concave function every stationary point is a global maximizer, and for a convex function every stationary point is a global minimizer.

Note that a function is both concave and convex if and only if it takes the form $f(x) = ax + b$ (that is, is "affine").

5.3.3 Important Properties

5.3.3.1 Property 1 (P1):

If $C(.)$ is a concave function on a closed bounded convex set V having finitely many extreme points, then $C(.)$ achieves its minimum on V at an extreme point of V.

This can be proved as follows. Let $e_1 \ldots e_m$ denote the extreme points of V. The extreme points are labeled so that

$$C(e_1) = \min_{1 \le i \le m} C(e_i) \qquad (5.4)$$

It is known that each v in V can be expressed in the form

$$v = \sum_{i=1}^{m} \alpha_i e_i \qquad \text{where } \alpha \ge 0,\ i = 1,2,\ \ldots,\ m \text{ and } \sum_{i=1}^{m} \alpha_i = 1 \qquad (5.5)$$

Then from the definition of a concave function it follows that

$$C(v) \ge \sum_{i=1}^{m} \alpha\, C(e_i) \ge C(e_1) \qquad (5.6)$$

Thus e_1 minimizes $C(.)$ over V. In addition, in searching for the minimum of $C(.)$ over V, this property implies that no loss of optimality occurs if we confine our search to the extreme points of V. This property will play a major role in the developing of the capacity scalability model presented in this thesis.

5.3.3.2 Property 2 (P2):

Sums of concave functions are concave.

5.3.3.3 Property 3 (P3):

The set of solutions to a finite system of linear equalities and inequalities is a convex set and has finitely many extreme points

5.3.3.4 Property 4 (P4):

A concave function of a linear function is concave.

These were some properties that will be used in the development of the proposed model.

5.4 ASSUMPTIONS FOR THE MODEL

The modeling of the reconfigurable capacity scalability layer of the proposed design architecture is based on the following assumptions:

1) Time (or capacity planning horizon) is idealized to be consisted of discrete periods 1, 2.......*T*.
2) Demand in period t (the difference between demands in periods t and t-1) is known D_t where $D_t \geq 0$ and

$$\sum_{t=1}^{T} D_t > 0. \tag{5.7}$$

3) Capacity scalability decision is a set of variables v_t where $t = 1, 2.....T$.
4) Z_t denotes the end of period excess capacity. In reconfigurable manufacturing system Z_t tends to be zero (scalability index).

$$Z_t = \sum_{j=1}^{t} (v_j - D_t) \quad (t = 1, 2,.......T) \tag{5.8}$$

A feasible capacity scalability plan or schedule is where:

$$v_t \geq 0, \tag{5.9}$$

$$Z_0 = 0 \text{ and } Z_T = 0 \tag{5.10}$$

Let V denote the set of feasible capacity schedules of the reconfigurable manufacturing system. From Equations (5.8)-(510) and the third stated property, P3, it could be said that V is a closed, bounded convex set. This conclusion is very important as it will be used to develop the optimal capacity scalability schedule or plan as will be shown in the next sections.

5.5 THE COST FUNCTION

Let $C(v)$ represent the cost associated with the capacity scalability v. The function $C(v)$ is expressed in terms of the present value of costs as of time 1. The cost for each period t is mainly the cost of adding or removing capacity like adding another spindle to a machine, or adding a machine, or even adding a line or group of machines. In the example of the automatic printed circuit board PCB assembly the cost function will reflect the cost of adding or removing pick and place machine(s) or another feeders inside the machine to increase or decrease capacity. Thus we can say that the model is really concerned with physical or hard capacity reconfiguration of the manufacturing system.

$$C(v) = \sum_{t=1}^{T} C_t(v_t) \tag{5.11}$$

Manne [1961] studied several types of industries and showed that the cost function of capacity addition for these industries is expressed as a power function (Figure 5.4) or as a power function pieced together with a linear segment (Figure 5.5). Also Luss [1982] stated that most of the capacity expansion (scalability) functions are concave representing the economies of scale of the expansion sizes.

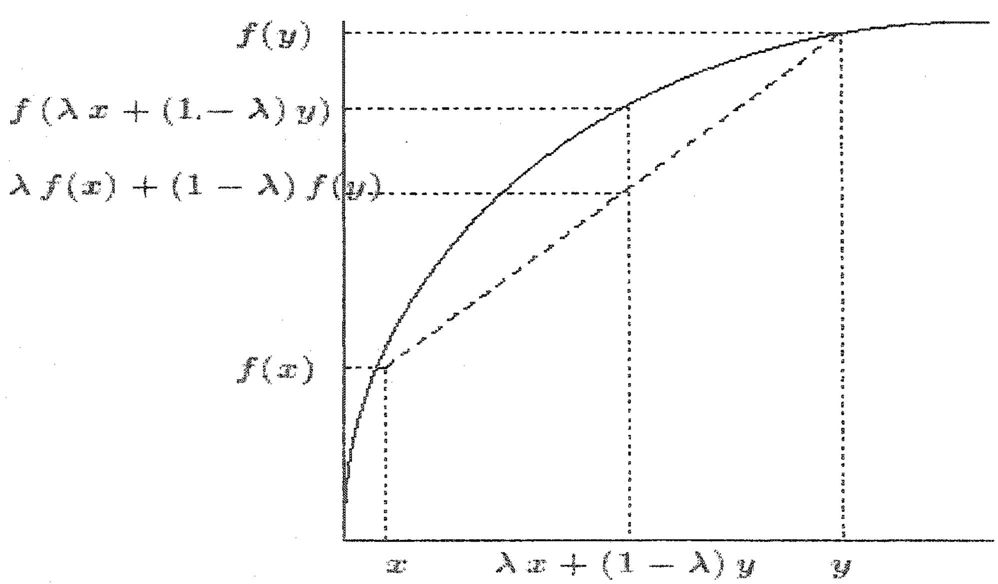


Figure 5.4 Cost Function as Power Function [Manne 1967]

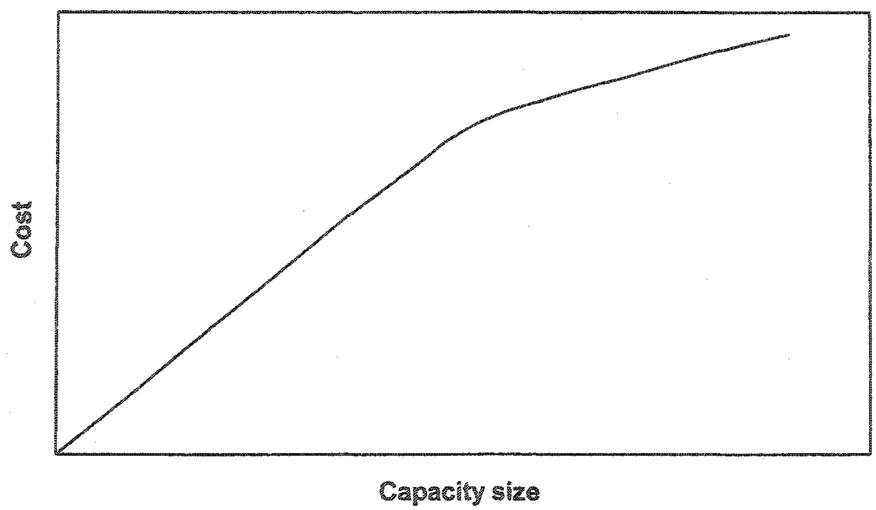


Figure 5.5 Cost Function as Power Function Pieced Together with a Linear Segment

Previous research in capacity scalability cost function in reconfigurable manufacturing systems expressed it as a staircase structure, Figure 5.6, as they assumed that capacity can only be scaled as integral multiples of the capacity scalability set, Asl, F. et al [2002]. However, we can claim that such assumption is not very practical in the reconfigurable manufacturing environment because the capacity scalability decision involves different items (tools, machines ….etc) that indeed differ in their cost due to the difference in their size, installation cost, running cost, maintenance cost and overhead cost.

Although the cost function of capacity scalability is usually concave representing the economies of scale as stated before, sometimes it is not a concave function especially if different technologies are used in capacity scalability process. In that case, the cost function is piecewise concave i.e., it is concave in the range covered by any single technology. This case could be considerable for reconfigurable manufacturing systems; however, in this model we assume that the cost function will be concave and the piecewise cost function case will be considered in further research. Figure 5.7 shows the different types of cost functions.

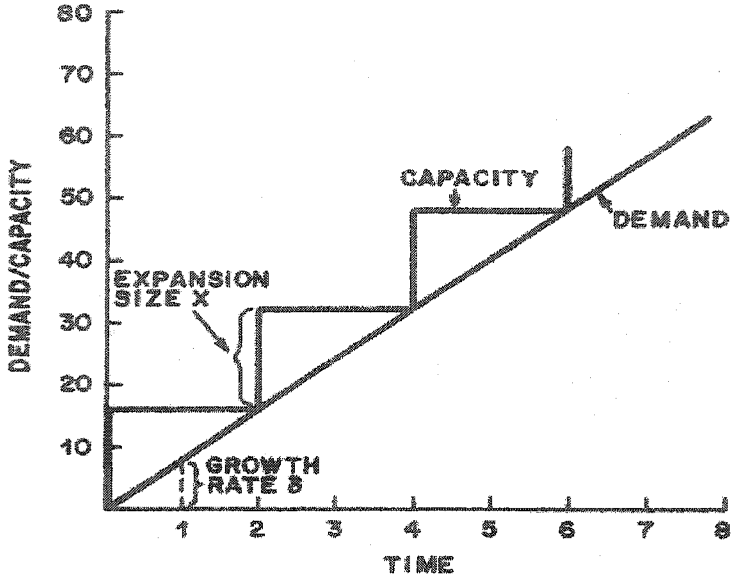


Figure 5.6 Capacity Expansion as a Staircase Function [Asl 2001]

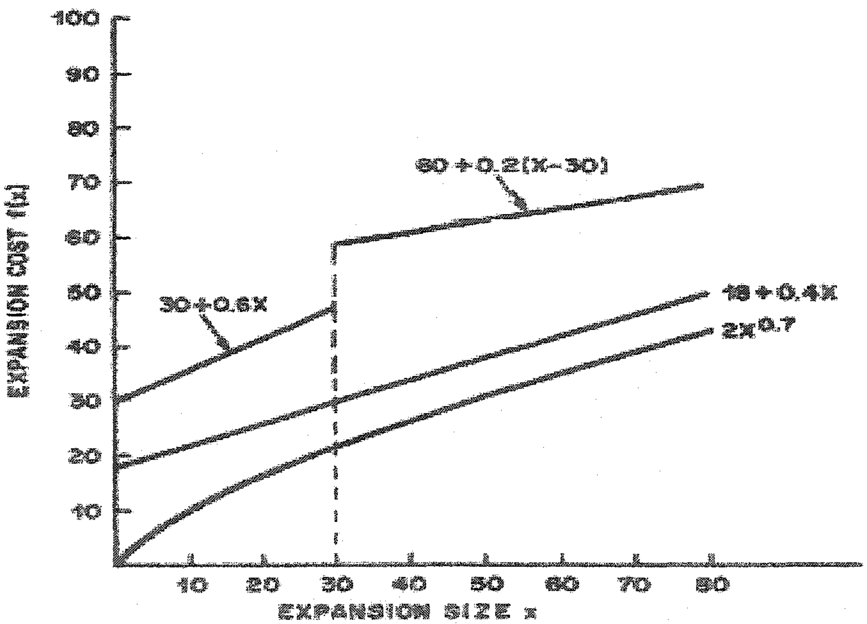


Figure 5.7 Typical Capacity Scalability Cost Functions (Top is a Piecewise Cost Function, Middle is a Linear Cost Function and Bottom is a Power Cost Function) [Luss1982]

In developing the model it is assumed that the cost function of capacity scalability takes the form of power functions. These types of cost functions are considered concave functions. This leads to a very important fact that is based on the previous mentioned properties of convex sets and concave functions, P1, and can be stated as follows: A feasible capacity scalability schedule or plan is considered an *optimal* plan if it minimizes the concave cost function $C(.)$ over the convex set of capacity scalability V.

Based on the previous fact, a capacity scalability tool is developed to decide for the optimal capacity scalability schedule that will be delivered to the manufacturing system configurator to reconfigure the system as been illustrated in the design architecture presented in this thesis.

5.6 REGENERATION POINT THEOREM

5.6.1 Point of Regeneration (Scalability Point)

A point of regeneration of a scalability schedule or plan v is said to occur in period t if Z_t (the end of period excess capacity) = 0, [Manne, 1967]. For a feasible capacity schedule v, such a point necessarily occurs in period 0 and T (the beginning and the end of the capacity planning horizon capacity planning horizon). A feasible capacity schedule is considered to have the regeneration point property if between any two periods in which the capacity is added there is a regeneration point. Thus v has the regeneration point property if whenever:

$$i < k \text{ and}$$

$$v_i > 0;\ v_{i+1} = v_{i+2} = \ldots = v_{k-1} = 0;\ \text{and } v_k > 0 \qquad (5.12)$$

there exist a period t, $i \leq t \leq k\text{-}1$, in which there exist a regeneration point.

Thinking about this property from a reconfigurable manufacturing systems perspective where the definition of these systems entitles that the exact capacity is added to the system when needed and where needed will imply that the reconfigurable manufacturing system is targeting to have $Z = 0$ at most of the times. Thus it can be said that the capacity scalability of reconfigurable manufacturing systems, which is considered to be one of the major characteristics of these systems, matches with regeneration point property stated above. In other words, reconfigurable manufacturing systems are systems that scale their capacity through multiple regeneration points.

In reconfigurable manufacturing systems the regeneration point would be called the scalability point. The importance of the regeneration or scalability point property for the development of the capacity scalability model lies in the following theorem.

5.6.2 Regeneration Point Theorem

The theorem states that "there is an optimal capacity schedule which has the regeneration point property" [Manne, A. and Veinott, A. 1967].

This means that the search for an optimal capacity schedule or plan, which is the target of our model, can be confined to those schedules with the regeneration point property. The proof of the theorem consists of some preliminary definitions and lemmas.

Although *C(.)* need not to be concave on *V*, it is concave on the following subset of *V*, called basic set,

$$V_{i_1 \ldots i_{T-1}} = \{v \mid v \varepsilon V \text{ and } (-1)^{i_t}(Z_t) \geq 0 \text{ for } t = 1, \ldots. T-1\} \qquad (5.13)$$

where each subscript i_t is 0 or 1.

The 2^{T-1} such sets are identified by the T - 1 subscripts i_t is 0 or 1. As a specific illustration, let $T = 3$, then the four basic sets are:

$V_{00} = \{v \mid v \varepsilon V, Z_1 \geq 0, Z_2 \geq 0\}$,

$V_{01} = \{v \mid v \varepsilon V, Z_1 \geq 0, Z_2 \leq 0\}$,

$V_{10} = \{v \mid v \varepsilon V, Z_1 \leq 0, Z_2 \geq 0\}$,

$V_{11} = \{v \mid v \varepsilon V, Z_1 \leq 0, Z_2 \leq 0\}$.

The basic set $V_{00 \ldots 0}$ is of special interest because it contains *Zs* that are not negative which means that the feasible capacity scalability schedule has no unsatisfied market demand.

Lemma 1:

There is an optimal capacity schedule, which is an extreme point of some basic set.

Proof:

V is the union of 2^{T-1} basic sets. Referring to P3 in the convex sets properties, the basic sets are closed, bounded convex sets having finitely many extreme points. Also using P2, P4 and Equation (5.9), it is clear that *C(.)* is concave on each basic set (although not necessary on V). By P1, *C(.)* achieves its minimum on each basic set at an extreme point of that set. Thus, *C(.)* achieves its minimum on V at an extreme point of some basic set, which proves the lemma.

Lemma 2:

Each extreme point of each basic set has the regeneration point property.

Proof:

The proof is by contraposition. Suppose there is a feasible v that does not have the regeneration point property. Then there is a time periods i and k such that Equation (5.10) holds and $Z_t \neq 0$ for all periods t, with $i \leq t \leq k\text{-}1$. It will be shown that v cannot be an extreme point of any basic set by generating two distinct alternative vectors v_x and v_y within the same basic set v and showing that v may be formed by taking one-half the sum of these two. Thus v cannot be an extreme point.

Let $$€ = \min\,[v_i, v_k, \min_{i<t<k-1} \leq |Z_t|\,]. \qquad (5.14)$$

By Equation (5.6) and the assumption $Z_t \neq 0$ for all t over the interval $i \leq t \leq k\text{-}1$, it follows that $€ > 0$. Let u_l be a T-component vector having the element +1 in the t^{th} position and zeros elsewhere. Define two distinct alternative schedules to v and denote v_x and v_y by:

$$v_x = v + € (u_I - u_k) \quad and \quad v_y = v - € (u_I - u_k) \tag{5.15}$$

Let the vectors (Z_x) and (Z_y) denote the excess capacities associated with the alternative schedules v_x and v_y respectively. From the definition of €, it follows that v_x and v_y are feasible. Also for $t < i$ and for $t \geq k$, $Z_t = Z_x = Z_y$.

For $i \leq t \leq k\text{-}1$, $Z_x = Z_t + €$ and $Z_y = Z_t - €$. Consequently, if Z_t is non-positive or non-negative, then both (Z_x) and (Z_y) are also non-positive or non-negative. Therefore, if v lies in a specified basic set then v_x and v_y also lie that set. But $v_x \neq v_y$ and $v = (1/2)\ v_x + (1/2)\ v_y$. Therefore v cannot be an extreme point of the specified set. This completes the proof.

Note: The converse of lemma 2 is also true, i.e. any feasible schedule having the regeneration (scalability) point property must also be an extreme point of some basic set.

The regeneration point theorem follows from the previous two lemmas.

5.7 FORMULATION OF THE CAPACITY SCALABILITY SCHEDULING MODEL

Based on the fact that reconfigurable manufacturing systems are designed to have (as much as possible) no excess capacity and that Z = 0, therefore the model will focus on the basic set $V_{00...0}$ because it contains *Zs* that are not negative which means that the feasible capacity scalability schedule has no unsatisfied market demand. The regeneration point theorem will be applied in the model formulation as follows:

Assume we have a feasible capacity schedule v with the scalability point property. Let one scalability point occur at period i and the next scalability point occur at period k (with $i < k$). Then necessarily there is an integer j, $i+1 \leq j \leq k$, such that:

$$v_j = \sum_{t=i+1}^{k} D_t \tag{5.16}$$

$$v_t = 0 \quad (t \neq j \text{ and } i+1 \leq t \leq k)$$

Since Z = 0 therefore, j must be equal i + 1. Other wise if $j > i + 1$ then Z_{i+1} will not be equal 0 and thus will not belong to the basic set $V_{00...0}$ and will violate the scalability requirements of reconfigurable manufacturing systems and thus:

$$v_{i+1} = \sum_{t=i+1}^{k} D_t \qquad (5.17)$$

From the previous results, it follows that in scalable reconfigurable manufacturing systems the feasible capacity scalability schedule or plan is *uniquely* determined by its scalability (regeneration) points.

The present worth (sometimes called discounted cost) c_{ik} of all costs for scaling the capacity during the planning period $i + 1,\ldots, k$ may be computed from:

$$c_{ik} = \sum_{t=i+1}^{k} C_t(v_t) \qquad (5.18)$$

Where v_t is determined using Equation (5.17). It was previously said that period 0 and T are scalability points. Hence in order to calculate the total cost of a feasible capacity scalability schedule with the capacity scalability property we sum up the costs c_{ik} associated with each of its successive pairs of scalability points.

The optimum capacity scalability schedule may be found using a dynamic programming approach with backward recursive methodology in the following form:

Let f_t be the minimum discounted cost of satisfying the demand increments $D_{i+1}, \ldots, D_t$, given that a scalability point occurs at period i and that an optimal schedule is followed in periods $i + 1,\ldots, T$. Using the regeneration point theorem, f_i may be computed from:

$$f_T = 0$$

$$f_i = \min_{i<k<T} \ (c_{ik} + f_k) \qquad (5.19)$$

5.8 DEVELOPMENT OF THE CAPACITY SCALABILITY TOOL

The formulated model is used to develop a computer tool that computes the optimal capacity scalability policy. The tool takes the following inputs:

- Planning time horizon T which depends on strategic decision of how frequent, in terms of years or months, can the corporation afford to scale its capacity in response to the changes of the demand profile.
- Single period demand during this time D_t ($t = 1,2 \ldots T$) it assumed to be deterministic for simplicity (applying the model for stochastic demand will a future research objective).
- Cost for scaling (add or remove) a capacity unit. In general the cost function would take a power form as Equation (5.20). This form maintains concavity and at the same time satisfies the economy of scale benefit of the capacity scaling.

$$A^t * (B * v) \qquad (5.20)$$

where t is the time increment over the horizon T, v is the size of capacity scalability and A and B are constants based on the application.

The output of the tool is the optimal (minimum cost) capacity scalability schedule indicating the periods of time where the facility should rescale its capacity and the sizes for these scalability intervals. The tool also calculates the minimum cost of that capacity policy. The software used for developing this tool was MATLAB which is a powerful programming tool for problems requiring optimization techniques like the dynamic programming adopted in this thesis. The flowchart of the developed tool is shown in Appendix A and the code is shown in Appendix B. Figure 5.8 is an $IDEF_0$ representation for the developed capacity scalability tool.

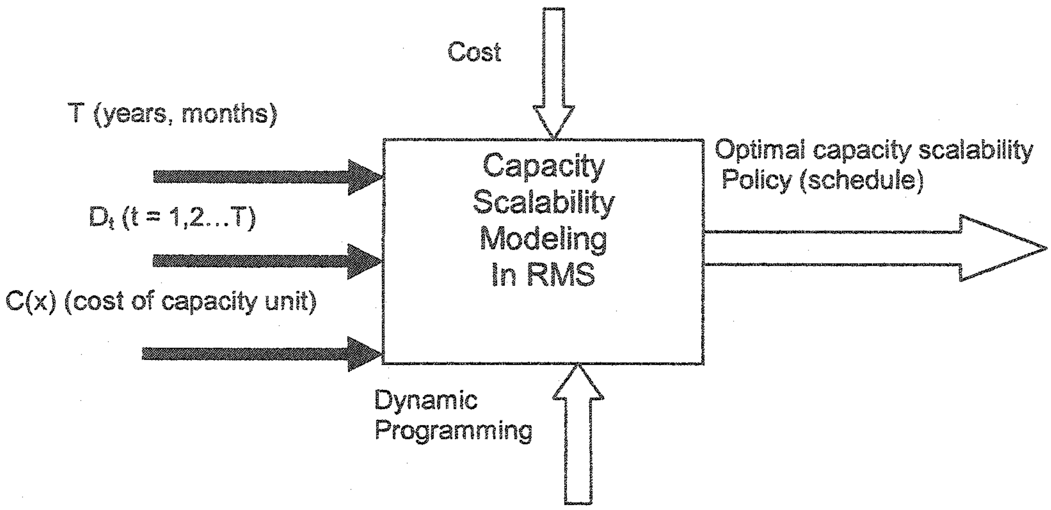


Figure 5.8 IDEF$_0$ Representation for the Developed Capacity Scalability Tool

5.9 NUMERICAL EXAMPLE

To validate the model and the developed tool a numerical example from the Indian industry was adopted [Manne, A. and Veinott, A. 1967]. The data used were as follows:

The time horizon over which the capacity will be scaled, T, is 6 intervals where the interval could be years or months.

The demand profile over this period is as follows: $D_1 = 0.5$, $D_2 = 1.0$, $D_3 = 1.5$, $D_4 = 1.5$, $D_5 = 1$ and $D_6 = 0.5$ units (the demand is deterministic as a simple case to illustrate the model). This demand profile is shown in Figure 5.9.

The cost function for capacity expansion or reduction (scalability) of capacity unit v is similar to Equation (5.20) and it is shown in Equation (5.21).

$$C(v) = 0.8^{(t-1)} * (5+(10*v_t)) \qquad \text{where } t = 1,2,\ldots T \tag{5.21}$$

The previous data were plugged into the capacity scalability tool developed and the resulted optimal capacity scalability schedule is shown in Table 5.1 and Figure 5.10.

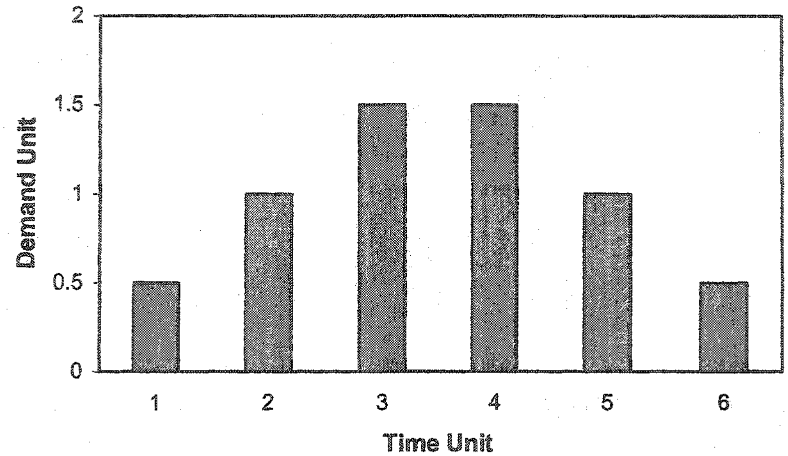


Figure 5.9 Demand Profile For Manne, A. and Veinott, A. [1967] Case Study

Table 5.1 Capacity Scalability Schedule at T= 6

	When to scale the capacity	Value of the scaled capacity
T = 6	1 (time unit)	1.5
	3 (time unit)	3
	5 (time unit)	1.5

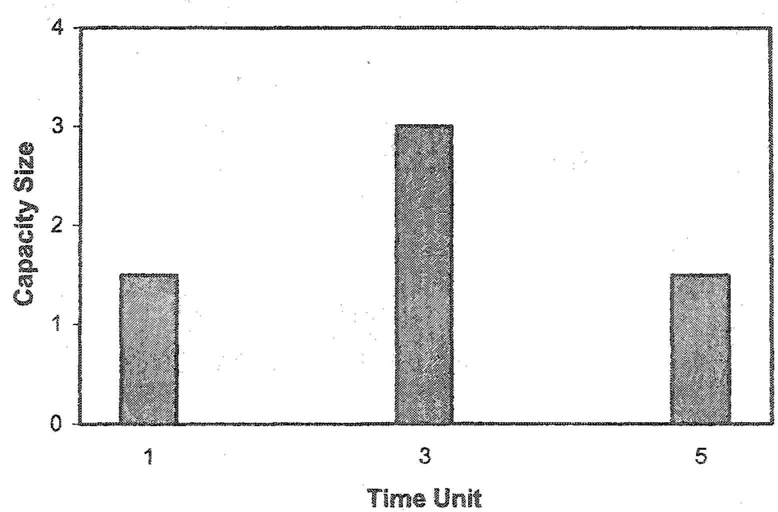


Figure 5.10 Optimal Capacity Scalability Schedule For Manne, A. and Veinott, A. [1967] Case Study

The cost of the optimal capacity scalability was calculated to be 50.6 cost units. The capacity scalability schedule and the cost for capacity scalability were equal to the values obtained by Manne, A. and Veinott, A. calculated which validates the developed tool calculations.

5.10 INVESTIGATING THE OPTIMAL CAPACITY SCALABILITY SCHEDULING COST

Using the same data from the previous section, the capacity scalability tool will be used to examine the effect of changing the period within which the capacity is to be scaled over the cost. The sum of the demand profile will be kept constant while the value of the planning horizon T will change. The high value of T for the same demand profile indicates that the corporation is offering the capacity scalability planner more opportunity to change the capacity with response to demand. In other words this approach investigates the effect of relaxing the demand over longer planning time T over the cost of the capacity scalability schedule. It can be also said that the capacity planning horizon, T, reflects the level of sensitivity to changes to demand that the corporation would like to have. The higher the value of T the less sensitive the corporation is to the demand change and vise versa.

Table 5.2 shows the results of the schedules and costs for capacity scalability at different values of capacity planning horizons T. In Figure 5.11 the cost of capacity scalability schedule versus the different values of T are plotted.

Table 5.2 Capacity Scalability Schedules for Different Values of Planning Horizons

Capacity Planning Time Horizon	**Capacity Scalability Intervals**	**Capacity Scalability Values**	**Cost of Capacity Scalability**
T = 4	1	3	57.4
	3	3	
T = 6	1	1.5	50.6
	3	3	
	5	1.5	
T=8	1	1.1	44.2
	3	1.55	
	5	2	
	7	1.35	
T=10	1	0.75	41.94
	3	1.75	
	5	1.7	
	7	1.8	
T = 12	1	0.9	35.74
	4	1.3	
	6	2.3	
	9	1.5	
T = 14	1	0.8	33.47
	4	1	
	6	1.6	
	8	1.5	
	11	1,1	
T=16	1	0.8	32.08
	4	1.5	
	7	1.7	
	10	1.05	
	13	0.95	

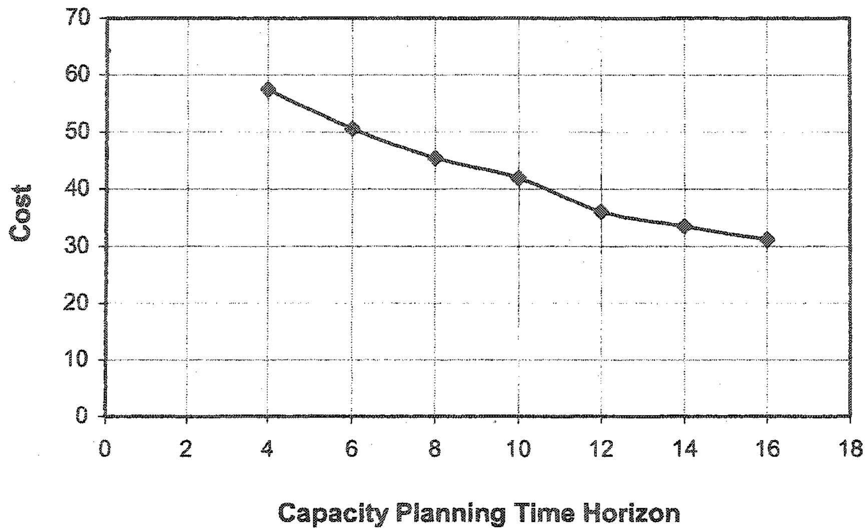


Figure 5.11 The Cost of the Capacity Scalability Schedules Versus Capacity Planning Time Horizon

The figure shows that as planning time horizon increases the cost of capacity scalability decreases. The analysis of this result can be stated as follows:

- Examining the cost function, which the model was based on, reveals that the cost was calculated as a function of the size of the capacity unit only.
- The previous point leads to a logic explanation for why the cost decreases as the T increases. The wider the planning horizon is the more scalability intervals one can have in the capacity schedule and thus the less capacity size is required at each interval leading to less cost.
- However, this is not the real practical case. One of the arguments in the practical implementation of the reconfigurable manufacturing systems is the cost of reconfiguration of the system. In other words, the cost of changing the production systems to scale the capacity at each scalability interval. The cost function of the model does not include the cost of reconfiguration and thus needs to be modified. Also the cost of delaying the demand should be recognized when increasing the capacity planning horizon. However, the delay cost will not be included in the

modification of the cost function as it is an intangible cost and varies from application to another.

The costs associated with reconfigurable manufacturing systems in general can be divided into the cost for establishing such systems from the beginning and the cost incurred while running the system and interacting with the market demand. The cost for constructing the reconfigurable manufacturing systems is not included in any of the analysis in this thesis as we are assuming that we are working in a reconfigurable manufacturing system already. The cost associated with operating the reconfigurable manufacturing system is what we called the cost of reconfiguration CR.

The cost of reconfiguration includes many parameters such as the cost of downtime to rescale the system or to ramp up the new configuration with the new capacity. This is added to other associated costs related to physical, logical and human reconfiguration required for system's capacity scalability (the components of CR have been discussed in section 4.4.4.4). All these costs are added together to form the cost of reconfiguration CR.

Based on the previous analysis the cost function of the proposed capacity scalability model must be modified to include the cost of reconfiguration. This can be achieved through adding the cost of reconfiguration of the system to the cost function. Thus the capacity scalability policy cost will be the cost of the capacity unit added (which is function of its production size) plus the cost of reconfiguration multiplied by the number of reconfiguration times in that optimal policy (which is equal to the number of scalability points).

The cost of reconfiguration of a system is difficult to calculate and varies from system to system (as mentioned in section 4.4.4.4). Specific calculation of that cost is a wide research area and beyond the scope of this thesis. However to illustrate the modification introduced to the model the cost of reconfiguration will be estimated. In the numerical example used in this section CR will be estimated to take different values to illustrate its effect on the capacity scalability schedules.

The new cost function that will be introduced to the capacity scalability model will be:

$$C(v) = \sum_{t=1}^{T} C_t(v_t) + CR*n \tag{5.22}$$

(where n is the number of capacity scalability points)

The new cost function that will be introduced to the capacity scalability tool for the previous example is:

$$C(v) = 0.8^{(t-1)} * (5+(10*v_t)) + CR*n \tag{5.23}$$

Table 5.3 shows the previous results after adding the modification to the model and tool.

Table 5.3 Capacity Scalability Schedules with the Modified Cost Function

Capacity Planning Time Horizon	Capacity Scalability Intervals	Capacity Scalability Values	Cost of Capacity Scalability	Cost of Capacity Scalability with CR=20
T = 4	1	3	57.4	97.4
	3	3		
T = 6	1	1.5	50.6	110.6
	3	3		
	5	1.5		
T=8	1	1.1	44.2	124.2
	3	1.55		
	5	2		
	7	1.35		
T=10	1	0.75	41.94	121.94
	3	1.75		
	5	1.7		
	7	1.8		

Table 5.3 Capacity Scalability Schedules with the Modified Cost Function (cont.)

Capacity Planning Time Horizon	Capacity Scalability Intervals	Capacity Scalability Values	Cost of Capacity Scalability	Cost of Capacity Scalability with CR=20
T = 12	1	0.9	35.74	115.74
	4	1.3		
	6	2.3		
	9	1.5		
T = 14	1	0.8	33.47	133.47
	4	1		
	6	1.6		
	8	1.5		
	11	1,1		
T=16	1	0.8	32.08	132.08
	4	1.5		
	7	1.7		
	10	1.05		
	13	0.95		

Figure 5.12 shows the new relation between the capacity planning horizon T and the cost of capacity scalability. The general trend indicates that as T increases the cost of capacity scalability increases.

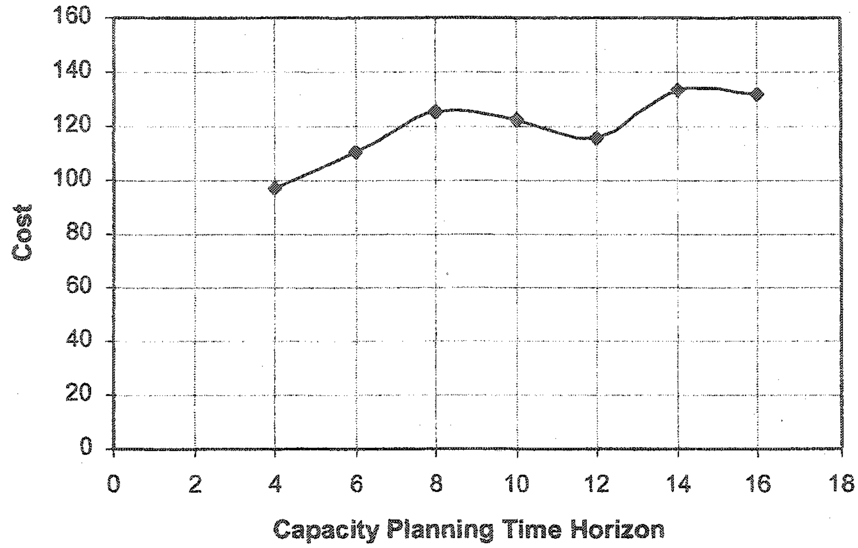


Figure 5.12 The Cost of the Capacity Scalability Schedules (with New Cost Function) Versus Capacity Planning Time Horizon

To combine the previous two results one can claim that among the challenges for the success of the reconfigurable manufacturing systems is to decrease the reconfiguration cost of the system. Research must be conducted to approach this problem. The less the reconfiguration cost is the closer the system is to Figure 5.11 i.e. cost decreases with the increase of the capacity planning horizon. To illustrate this conclusion various values for CR were considered in Table 5.4.

Table 5.4 The Capacity Scalability Schedules' Costs for Different Values of CR

Capacity Planning Time Horizon	Capacity Scalability Intervals	Capacity Scalability Values	Cost of Capacity Scalability	Cost of Capacity Scalability with CR=20	Cost of Capacity Scalability with CR=10	Cost of Capacity Scalability with CR=5
T = 4	1	3	57.4	97.4	77.4	67.4
	3	3				

Table 5.4 The Capacity Scalability Schedules' Costs for Different Values of CR (cont.)

Capacity Planning Time Horizon	Capacity Scalability Intervals	Capacity Scalability Values	Cost of Capacity Scalability	Cost of Capacity Scalability with CR=20	Cost of Capacity Scalability with CR=10	Cost of Capacity Scalability with CR=5
T = 6	1	1.5	50.6	110.6	80.6	65.6
	3	3				
	5	1.5				
T=8	1	1.1	44.2	124.2	84.2	64.2
	3	1.55				
	5	2				
	7	1.35				
T=10	1	0.75	41.94	121.94	81.94	61.94
	3	1.75				
	5	1.7				
	7	1.8				
T = 12	1	0.9	35.74	115.74	75.74	55.74
	4	1.3				
	6	2.3				
	9	1.5				
T = 14	1	0.8	33.47	133.47	83.47	58.47
	4	1				
	6	1.6				
	8	1.5				
	11	1,1				
T=16	1	0.8	32.08	132.08	82.08	57.08
	4	1.5				
	7	1.7				
	10	1.05				
	13	0.95				

Figure 5.13 shows the different capacity scalability schedules' costs versus different values of T. The curves in the figure show that as the cost of reconfiguration decreases the cost of the capacity scalability schedule decreases. This result emphasizes the importance of having more focus and more research on how to decrease the reconfiguration cost of reconfigurable manufacturing systems.

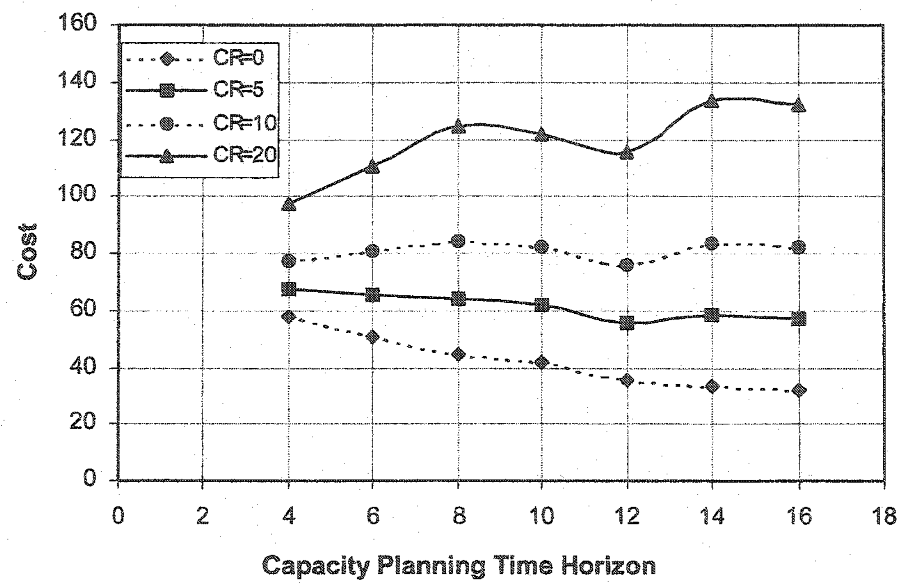


Figure 5.13 The Different Capacity Scalability Schedules' Costs Versus Different Values of T

This section highlighted the fact that minimizing the cost of capacity scalability scheduling in reconfigurable manufacturing systems is a trade-off problem. The demand relaxation that leads to less capacity scalability cost should be balanced with the cost of demand delay. Also the analysis highlighted that the cost effectiveness of reconfigurable manufacturing systems is highly related with decreasing the cost of reconfiguration of the system.

5.11 OPTIMAL CAPACITY SCALABITY APPROACH COMPARED TO OTHER CAPACITY PLANNING APPROACHES

In planning for the capacity of any manufacturing system there are three approaches. The first approach is to construct a capacity at the beginning of the planning period (t_1) which is equal to all anticipated demand over the planning period. This is the case in flexible manufacturing systems. The second approach is that at each point over the planning period you supply a capacity that is equal to the demand at that point (i.e. instantaneous capacity scalability with each demand change). The third approach is to have an optimal capacity schedule that balance between the previous two approaches in satisfying the market demand at a minimum cost.

The capacity scalability activity in the proposed architecture of this thesis is of the third approach. The developed capacity scalability tool is used with the same data to illustrate this approach and was modified to calculate also the cost associated with implementing the first two approaches at different capacity planning horizons and compares between the three of them. This will be achieved through keeping the sum of all the required demands over different values of T constant.

The demand profiles will also take three shapes. The first shape is a fluctuating demand profile that reflects the random nature of demand for a reconfigurable systems environment. The second shape is an increasing demand profile where the corporation is facing an increase in their sales. The third shape is the opposite of the previous profile i.e. a decreasing demand profile where the sales are decreasing. The cost of reconfiguration will be assumed to be equal to 5.

Figures 5.14 to 5.18 show the fluctuating demand profiles cases that were delivered to the capacity scalability tool with different values of T.

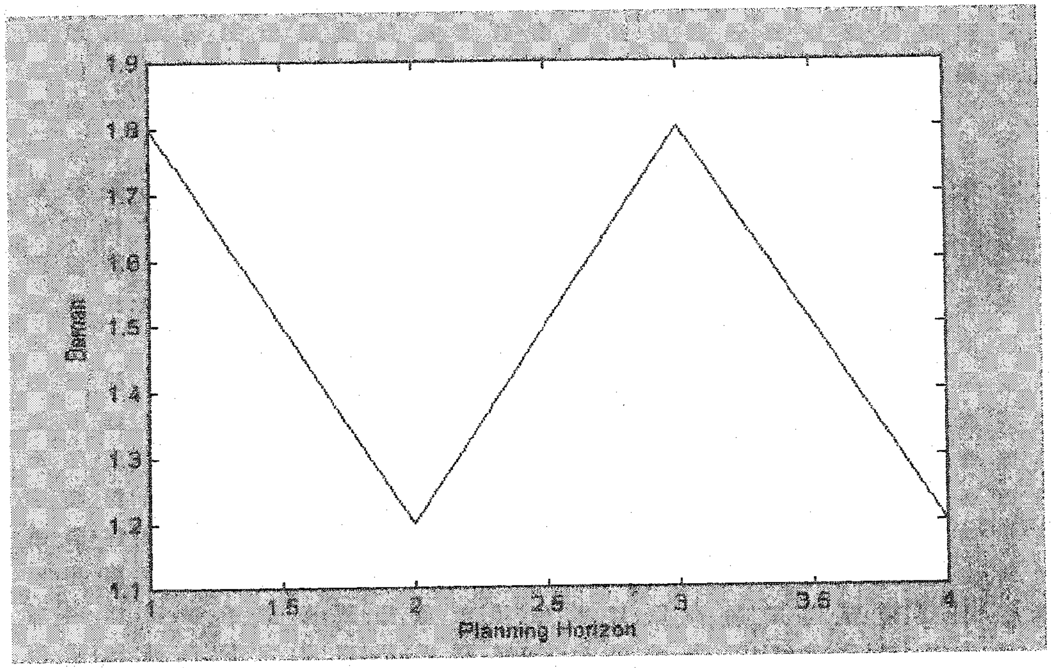


Figure 5.14 Fluctuating Demand Profile at Planning Horizon = 4

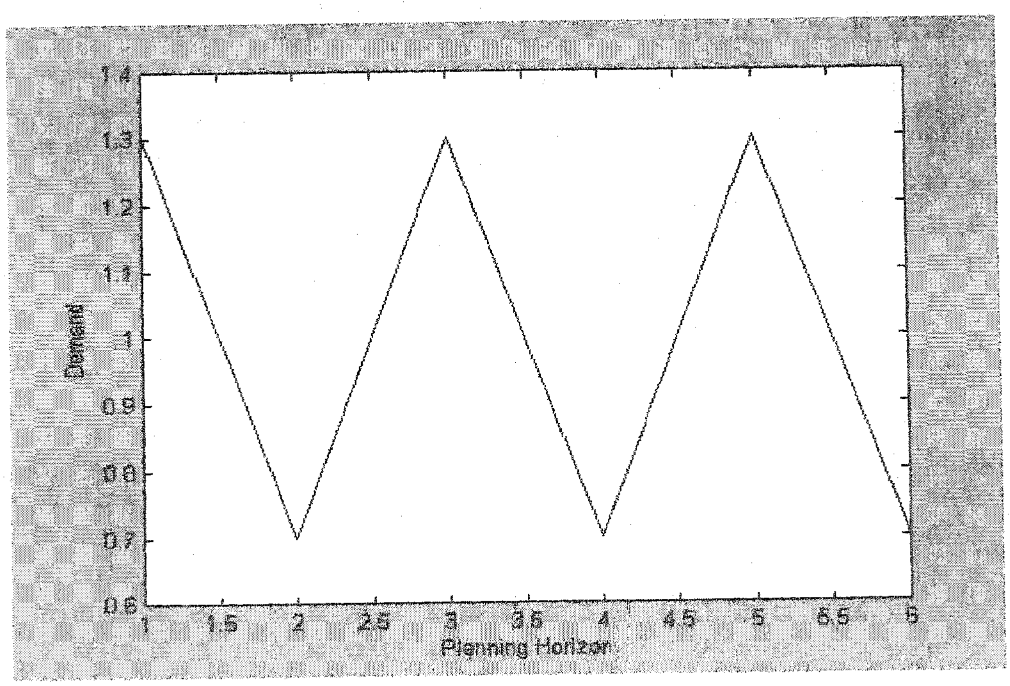


Figure 5.15 Fluctuating Demand Profile at Planning Horizon = 6

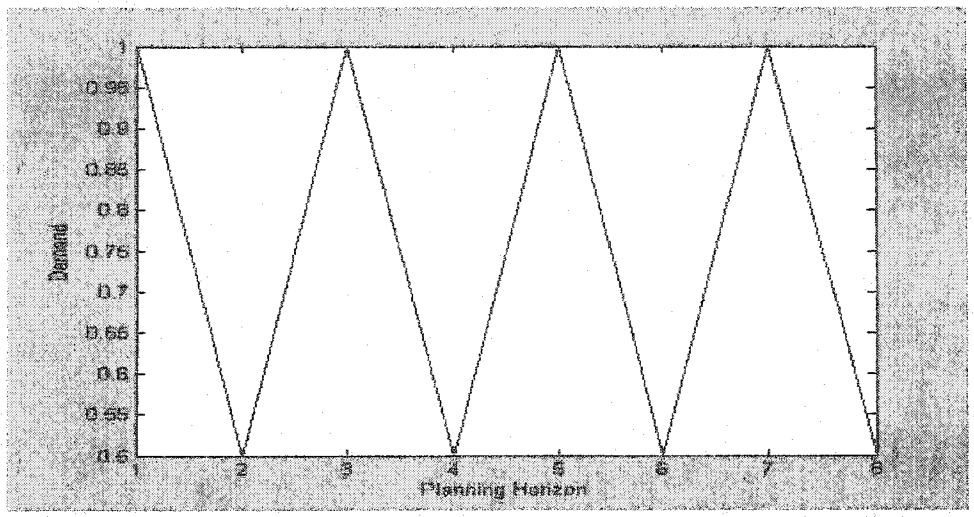


Figure 5.16 Fluctuating Demand Profile at Planning Horizon = 8

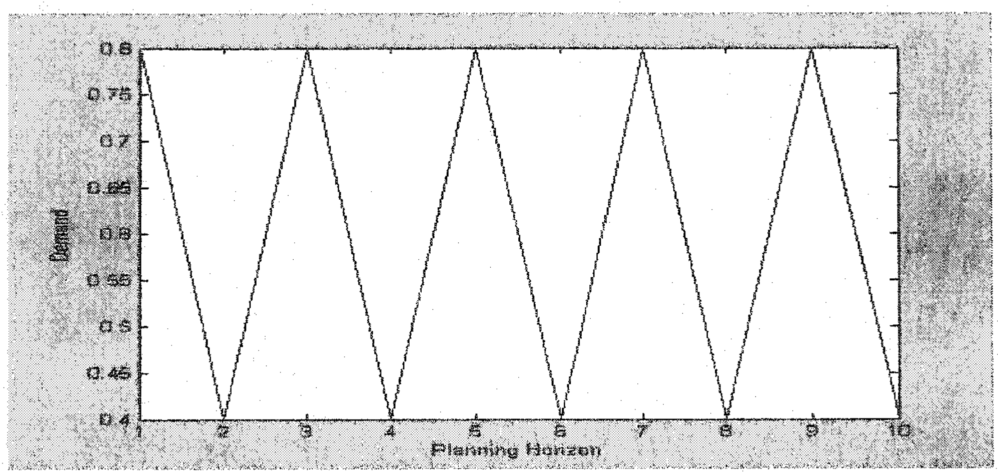


Figure 5.17 Fluctuating Demand Profile at Planning Horizon = 10

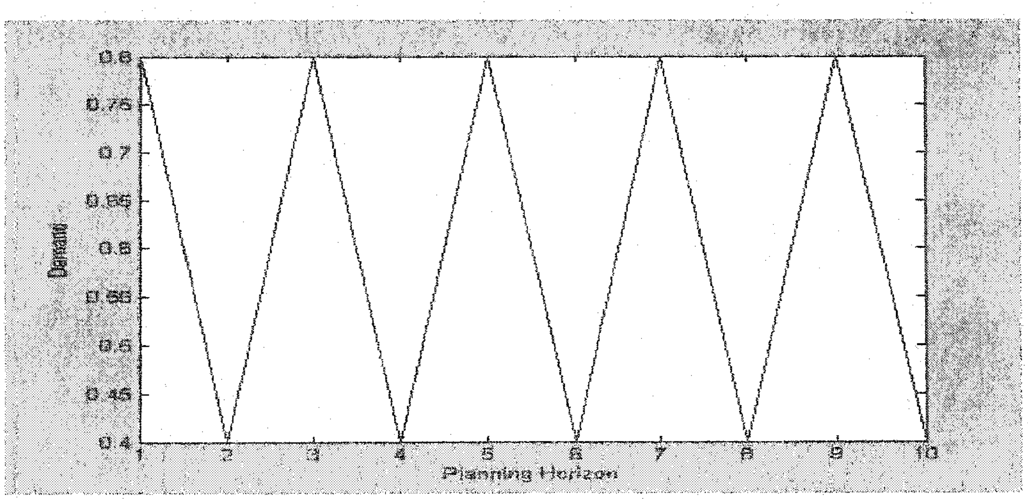


Figure 5.18 Fluctuating Demand Profile at Planning Horizon = 12

Table 5.5 displays the cost of each of the previous capacity scalability approaches without considering the cost of reconfiguration. Table 5.6 displays the same cost results but considering the cost of reconfiguration.

Table 5.5 The Cost of Capacity Scalability Approaches with Different Values of T without Considering the CR at Fluctuating Demand Profiles

Capacity Planning Time Horizon	Cost of Supplying All Capacity at the Beginning	Cost of Capacity Scalability with Each Demand	Cost of Optimal Capacity Scalability
4	65	60.024	57.4
6	65	56.57	51.24
8	65	53.17	46.23
9	65	50.08	42.15
12	65	47.6	38.8

Table 5.6 The Cost of Capacity Scalability Approaches with Different Values of T Considering the CR at Fluctuating Demand Profiles

Capacity Planning Time Horizon	Cost of Supplying All Capacity at the Beginning	Cost of Capacity Scalability with Each Demand	Cost of Optimal Capacity Scalability
4	70	80.024	67.4
6	70	86.57	66.25
8	70	93.17	66.23
9	70	100.08	67.15
12	70	107.6	68.8

Figures 5.19 and 5.20 compares the cost curves of each of the capacity scalability approaches without considering the cost of reconfiguration and with considering that cost respectively.

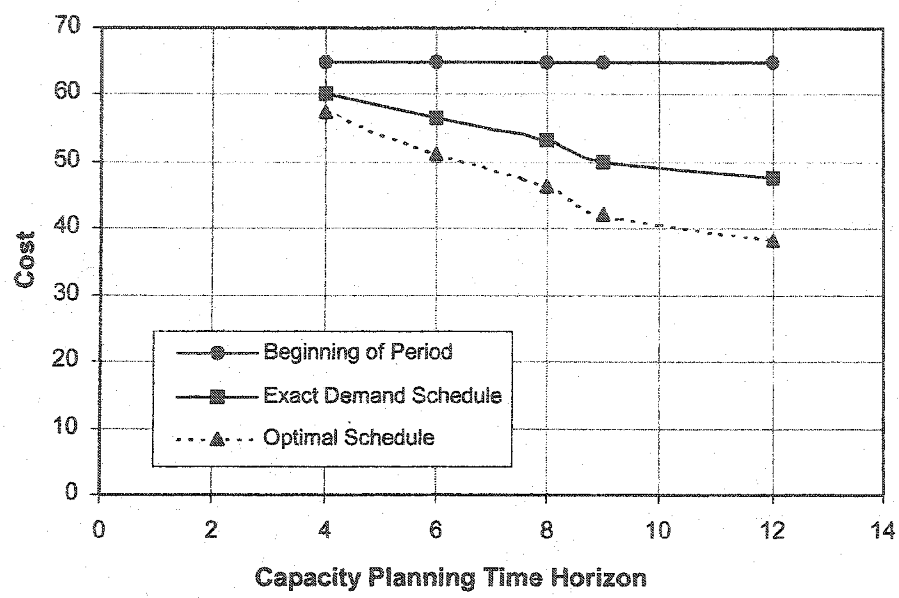


Figure 5.19 The Cost of Capacity Scalability Approaches with Different Values of T without Considering the CR at Fluctuating Demand Profiles

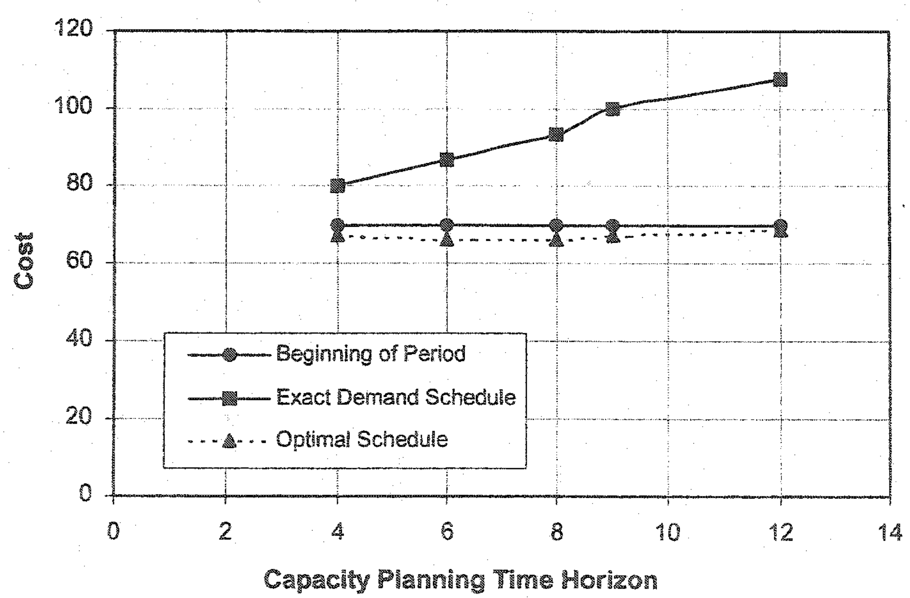


Figure 5.20 The Cost of Capacity Scalability Approaches with Different Values of T Considering the CR at Fluctuating Demand Profiles

Figures 5.21 to 5.25 show the increasing demand profiles cases that were delivered to the capacity scalability tool with different values of T.

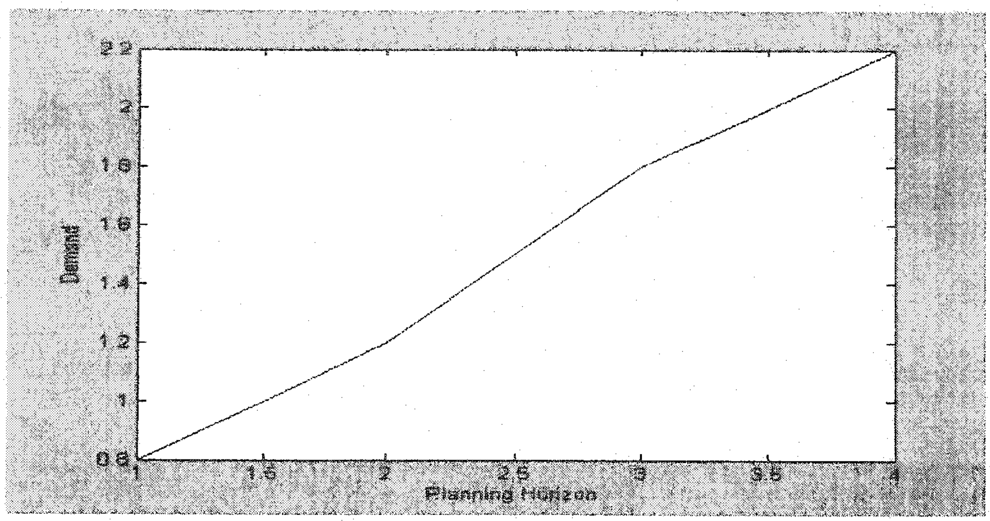


Figure 5.21 Increasing Demand Profile at Planning Horizon = 4

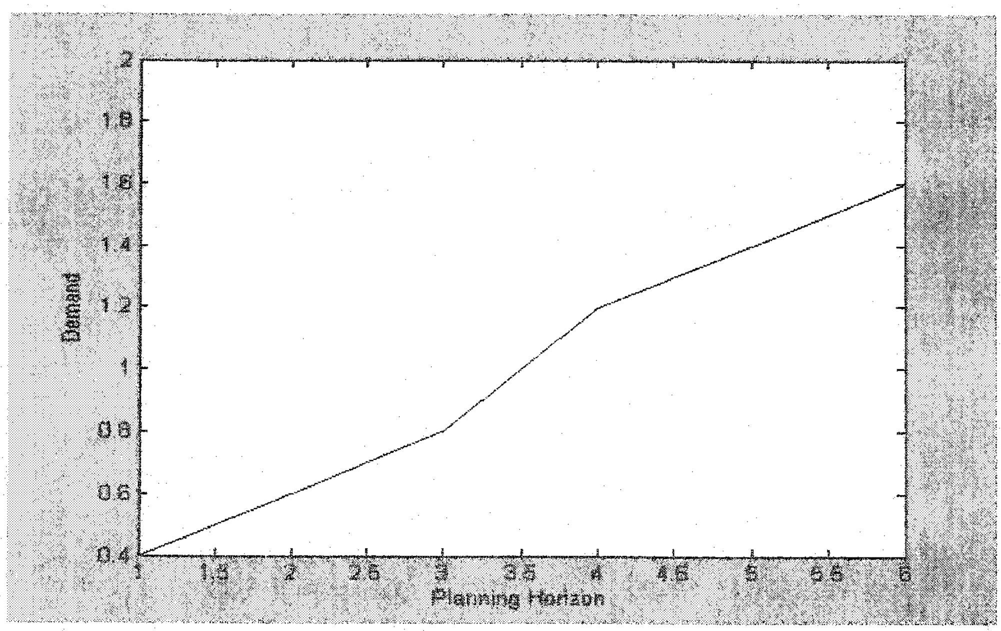


Figure 5.22 Increasing Demand Profile at Planning Horizon = 6

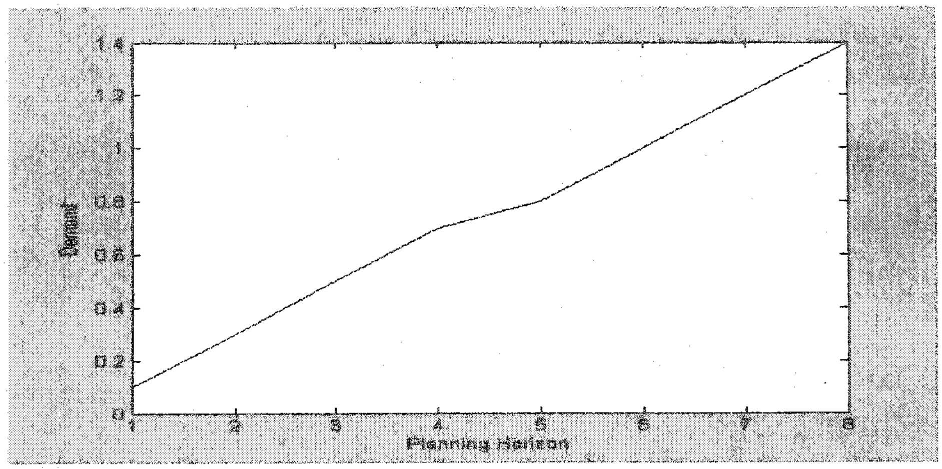


Figure 5.23 Increasing Demand Profile at Planning Horizon = 8

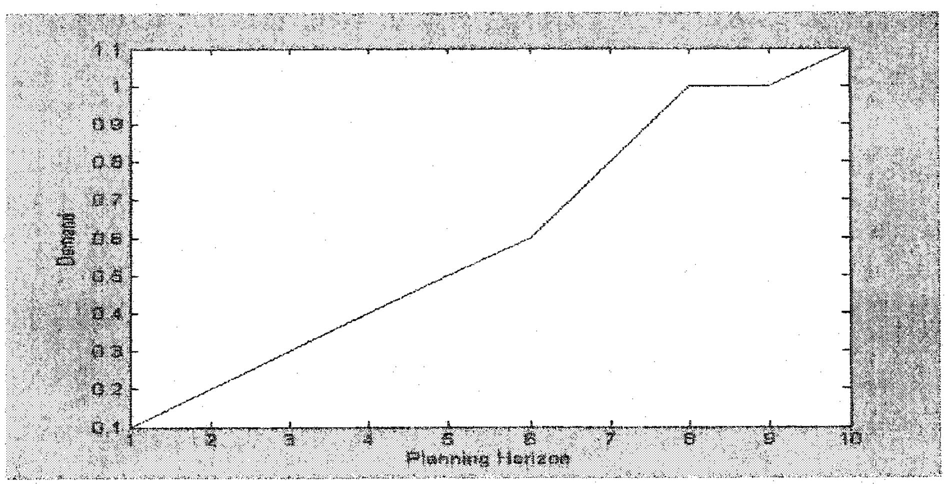


Figure 5.24 Increasing Demand Profile at Planning Horizon = 10

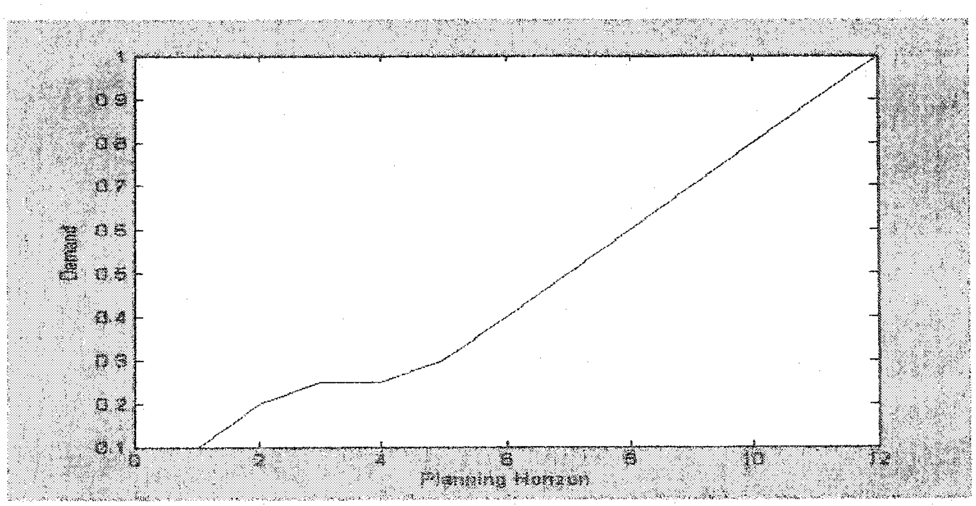


Figure 5.25 Increasing Demand Profile at Planning Horizon = 12

Table 5.7 displays the cost of each of the previous capacity scalability approaches without considering the cost of reconfiguration. Table 5.8 displays the same cost results but considering the cost of reconfiguration.

Table 5.7 The Cost of Capacity Scalability Approaches with Different Values of T without Considering the CR at Increasing Demand Profiles

Capacity Planning Time Horizon	Cost of Supplying All Capacity at the Beginning	Cost of Capacity Scalability with Each Demand	Cost of Optimal Capacity Scalability
4	65	55.14	53.54
6	65	49.48	45.33
8	65	43.62	37.07
9	65	40.24	31.63
12	65	37.94	27.97

Table 5.8 The Cost of Capacity Scalability Approaches with Different Values of T Considering the CR at Increasing Demand Profiles

Capacity Planning Time Horizon	Cost of Supplying All Capacity at the Beginning	Cost of Capacity Scalability with Each Demand	Cost of Optimal Capacity Scalability
4	70	75.14	68.54
6	70	79.48	60.33
8	70	83.62	57.07
9	70	90.24	51.63
12	70	97.94	52.94

Figures 5.26 and 5.27 compares the cost curves of each of the capacity scalability approaches without considering the cost of reconfiguration and with considering that cost respectively.

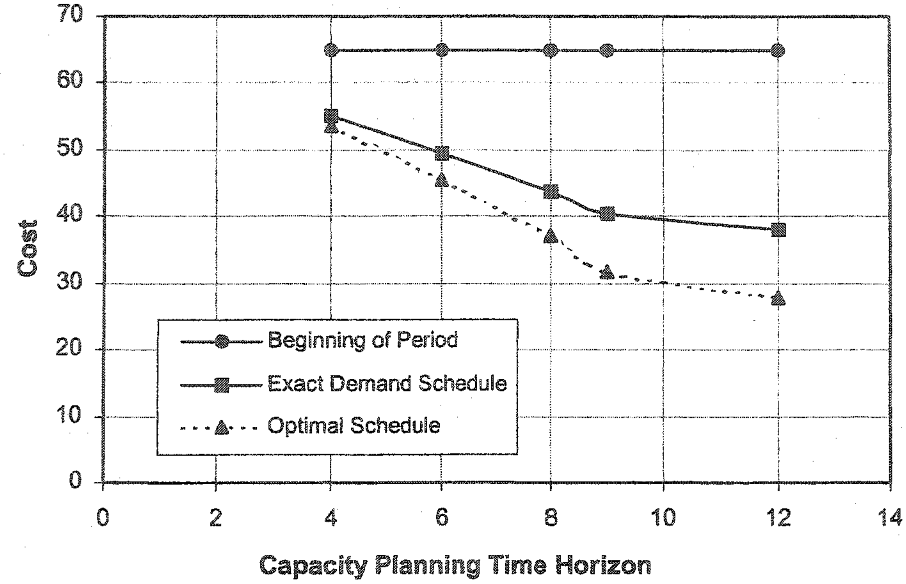


Figure 5.26 The Cost of Capacity Scalability Approaches with Different Values of T without Considering the CR at Increasing Demand Profiles

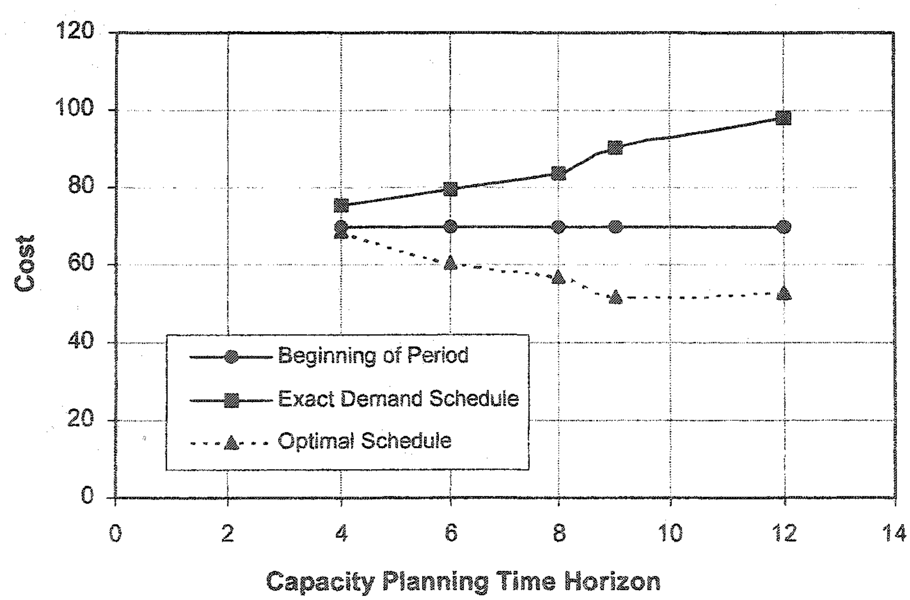


Figure 5.27 The Cost of Capacity Scalability Approaches with Different Values of T Considering the CR at Increasing Demand Profiles

Figures 5.28 to 5.32 show the decreasing demand profiles cases that were delivered to the capacity scalability tool with different values of T.

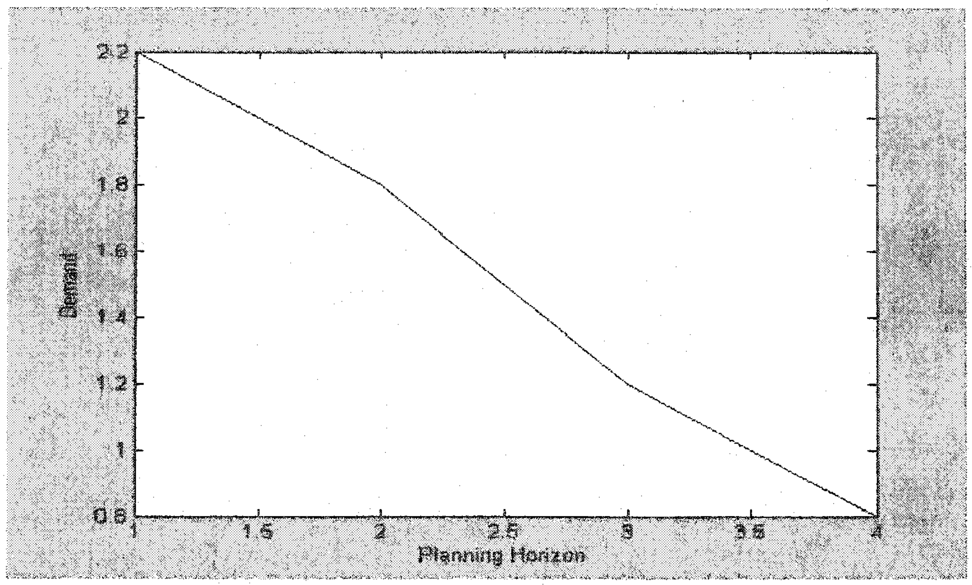


Figure 5.28 Decreasing Demand Profile at Planning Horizon = 4

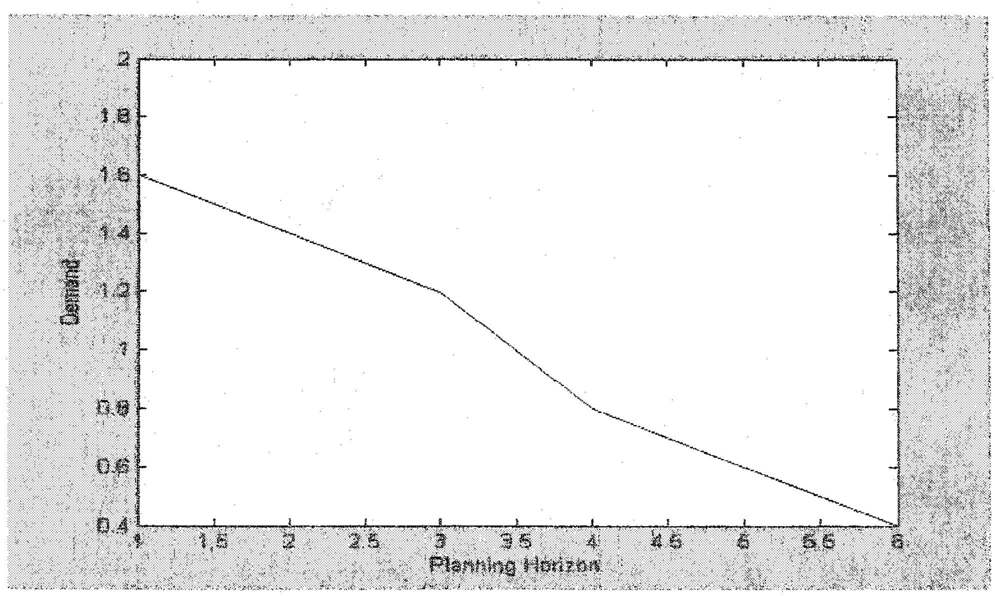


Figure 5.29 Decreasing Demand Profile at Planning Horizon = 6

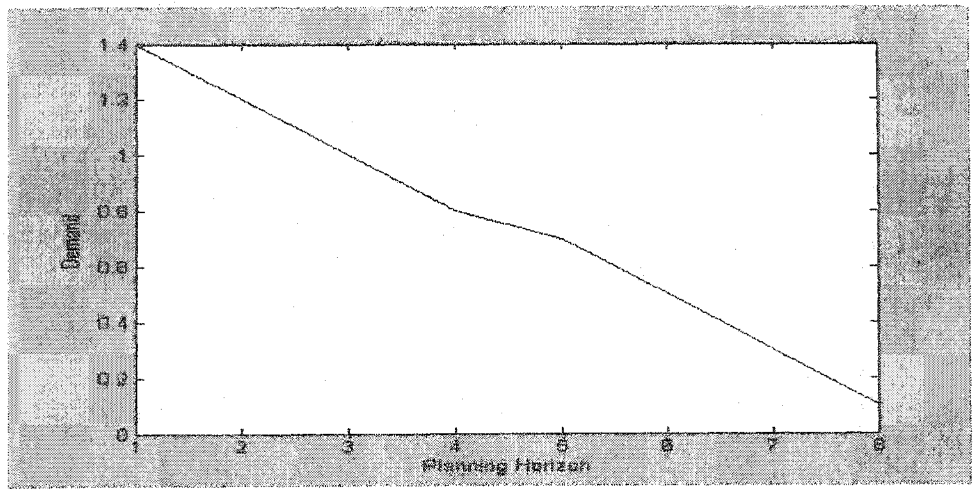


Figure 5.30 Decreasing Demand Profile at Planning Horizon = 8

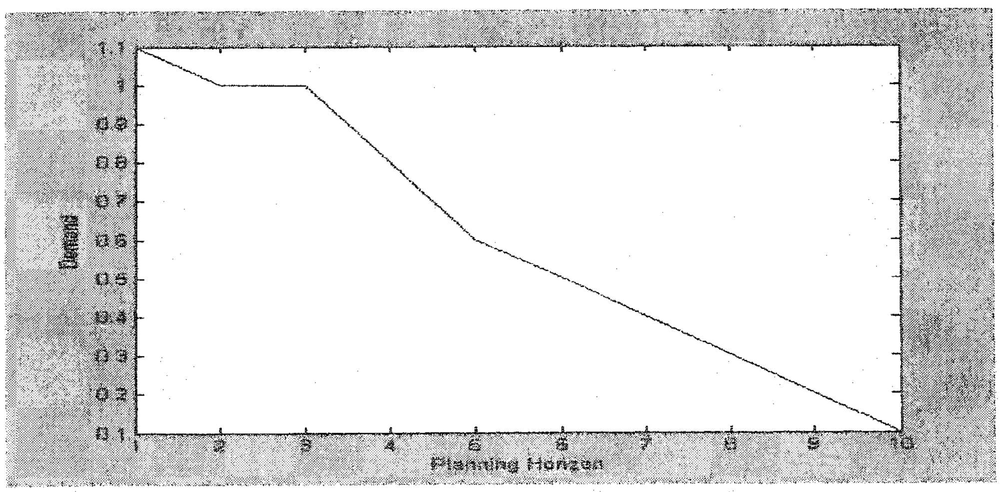


Figure 5.31 Decreasing Demand Profile at Planning Horizon = 10

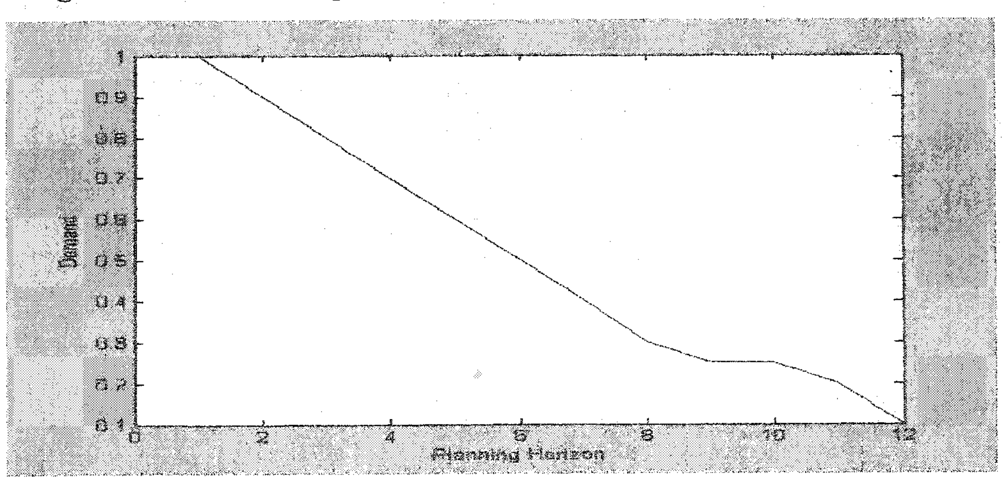


Figure 5.32 Decreasing Demand Profile at Planning Horizon = 12

Table 5.9 displays the cost of each of the previous capacity scalability approaches without considering the cost of reconfiguration. Table 5.10 displays the same cost results but considering the cost of reconfiguration.

Table 5.9 The Cost of Capacity Scalability Approaches with Different Values of T without Considering the CR at Decreasing Demand Profiles

Capacity Planning Time Horizon	Cost of Supplying All Capacity at the Beginning	Cost of Capacity Scalability with Each Demand	Cost of Optimal Capacity Scalability
4	65	62.93	61
6	65	61.2	57.14
8	65	60.4	54.3
9	65	58	51.11
12	65	56.1	48.34

Table 5.10 The Cost of Capacity Scalability Approaches with Different Values of T Considering the CR at Decreasing Demand Profiles

Capacity Planning Time Horizon	Cost of Supplying All Capacity at the Beginning	Cost of Capacity Scalability with Each Demand	Cost of Optimal Capacity Scalability
4	70	82.93	71
6	70	91.2	72.14
8	70	100.4	69.3
9	70	108	66.11
12	70	116.1	68.34

Figures 5.33 and 5.34 compares the cost curves of each of the capacity scalability approaches without considering the cost of reconfiguration and with considering that cost respectively.

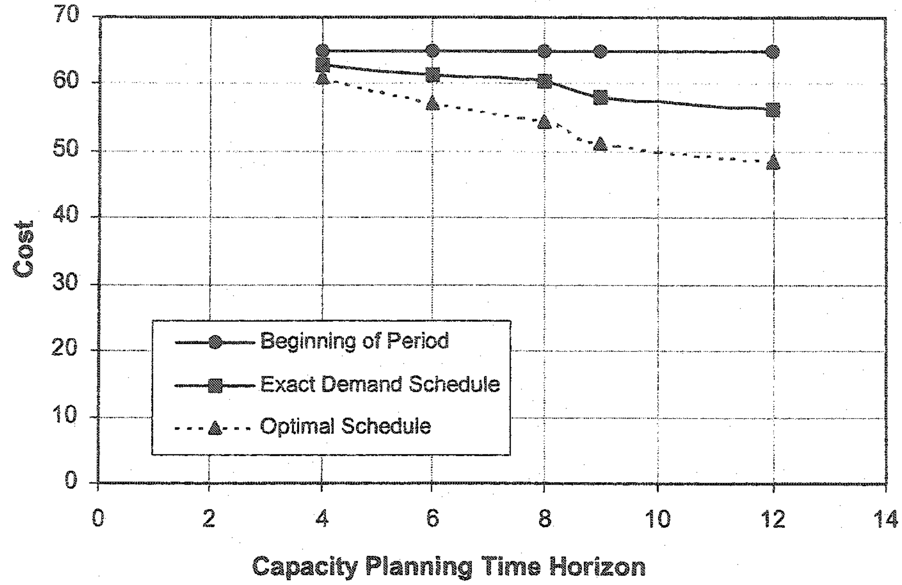


Figure 5.33 The Cost of Capacity Scalability Approaches with Different Values of T without Considering the CR at Decreasing Demand Profiles

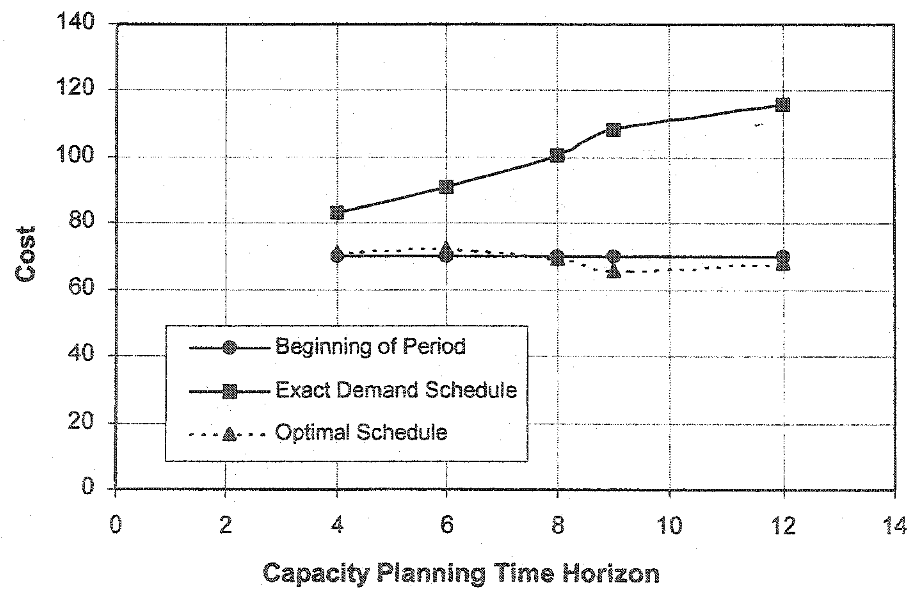


Figure 5.34 The Cost of Capacity Scalability Approaches with Different Values of T Considering the CR at Decreasing Demand Profiles

Analysis of the previous figure leads to the following conclusions:

- The optimal capacity scalability schedules generated by the developed tool showed better performance in terms of cost in all demand scenarios. This indicates the superiority of the considered capacity scalability approach in this thesis under different demand profiles.
- When the cost of configuration is considered, the exact chasing of the demand or the approach of changing the capacity with each demand change exhibit very high cost. This is significant when T increases as the number of capacity changes will increase leading to higher cost of reconfiguration and thus a higher cost of capacity scalability. Such an approach in reconfigurable manufacturing systems with high cost of reconfiguration is not recommended at all. The exact chase of the demand is considerable if the profit of capturing each demand at each period of time is very high. This depends on the nature of the market and the customer segment that the corporation adopting such capacity scalability approach is targeting.
- The first approach of supplying all the capacity required for the anticipated demand at the beginning of the planning period is in general of high cost. Such a policy is typically found in flexible manufacturing systems FMS.
- The graphs emphasize on the previously mentioned conclusion that indicated the importance of working on decreasing the cost of reconfiguration, CR.
- In general the approach for optimal capacity scalability schedule suggested in this thesis balances between being responsive to market changes and being cost effective which matches the objective of the reconfigurable manufacturing systems. This is why such approach was used to model the capacity scalability layer in the proposed architecture of the reconfigurable manufacturing systems.

5.12 EXAMINING THE OPTIMAL CAPACITY SCALABILITY APPROACH IN "0" DEMAND PROFILES

The last scenario discussed in this thesis is the one reflecting the case where the corporation is facing a decreasing demand to the extent that it can zero demand for a certain period t (i.e. $D_t = 0$). In order to compare this case with previous demand profile case the sum of demands over both periods will be the same, the cost of reconfiguration will be the same and same cost function will be used. The shape of the demand profile will change having periods equal to zero. Figures 5.35 to 5.40 illustrate these demand profiles with different values of T that will be delivered to the capacity scalability tool.

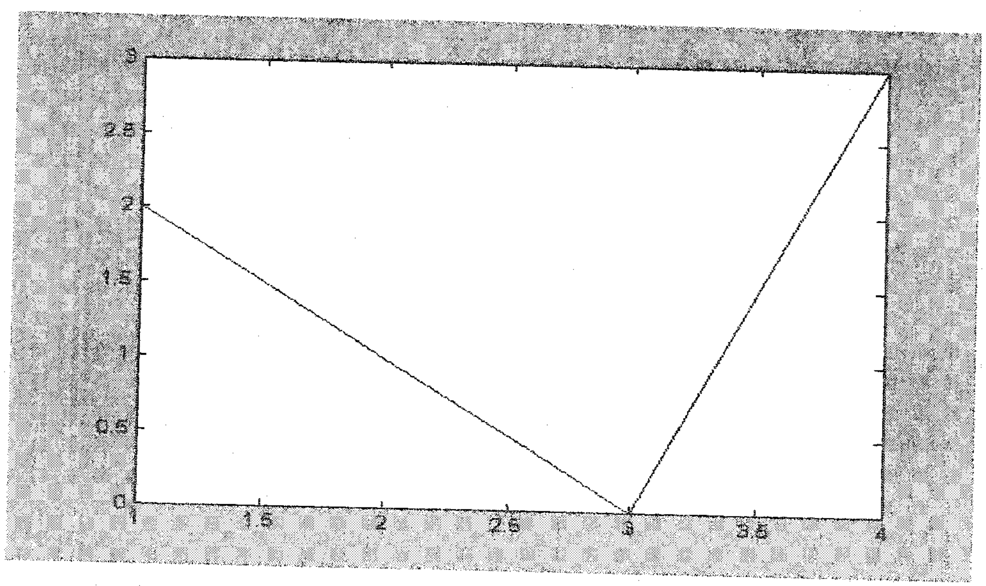


Figure 5.35 Temporary "0" Demand Profile at Planning Horizon = 4

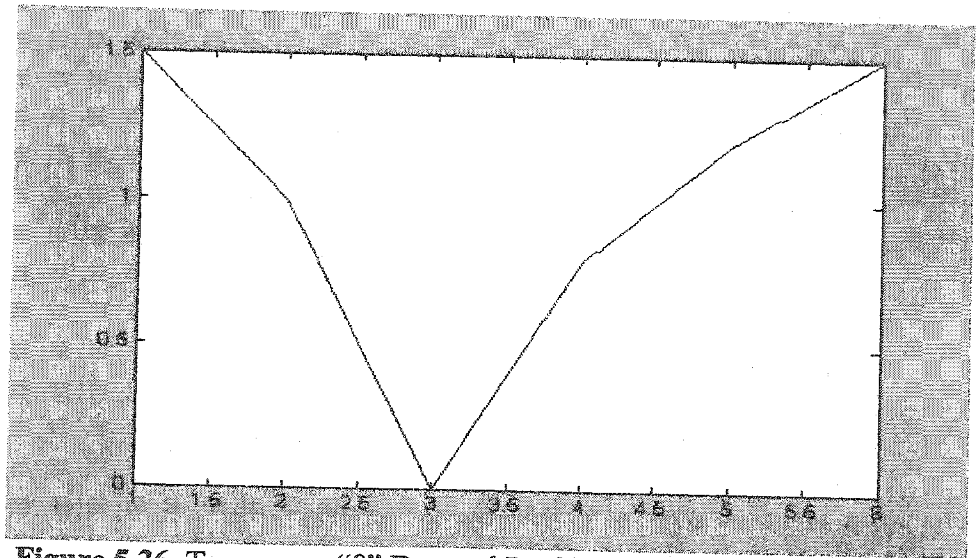


Figure 5.36 Temporary "0" Demand Profile at Planning Horizon = 6

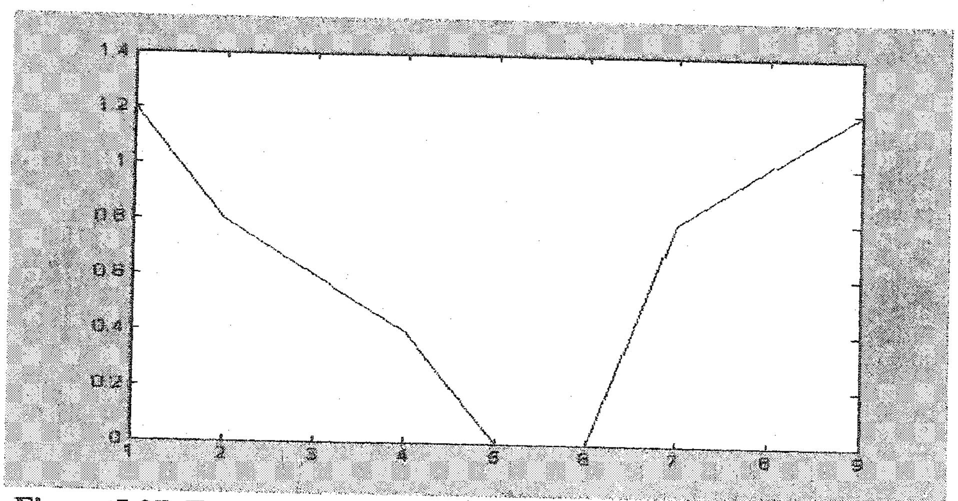


Figure 5.37 Temporary "0" Demand Profile at Planning Horizon = 9

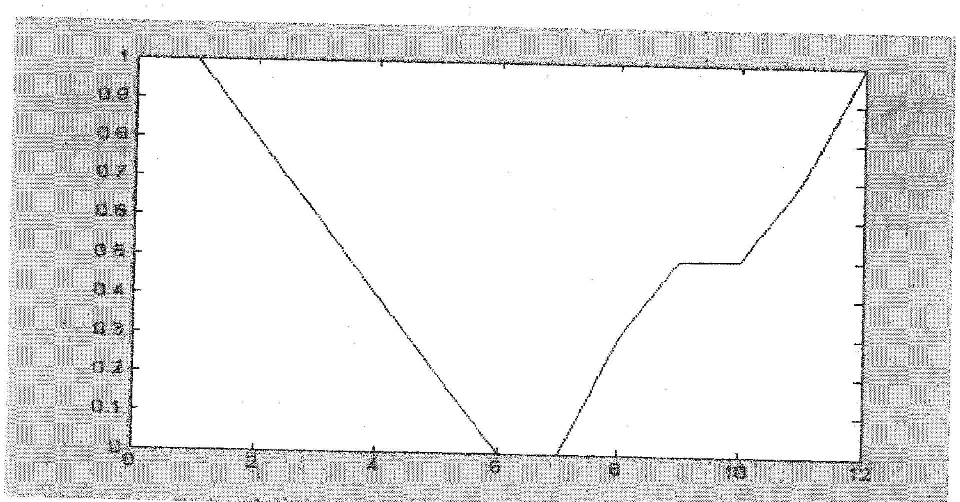


Figure 5.38 Temporary "0" Demand Profile at Planning Horizon = 12

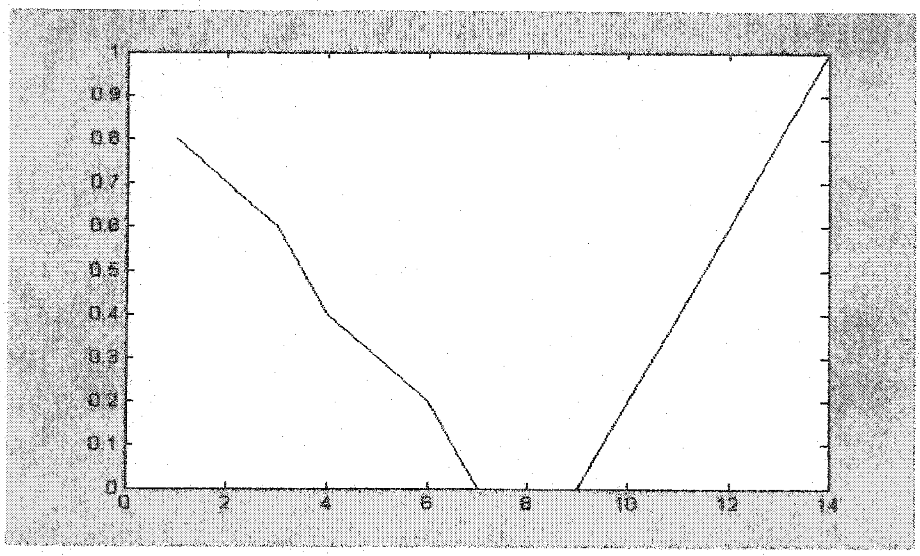


Figure 5.39 Temporary "0" Demand Profile at Planning Horizon = 14

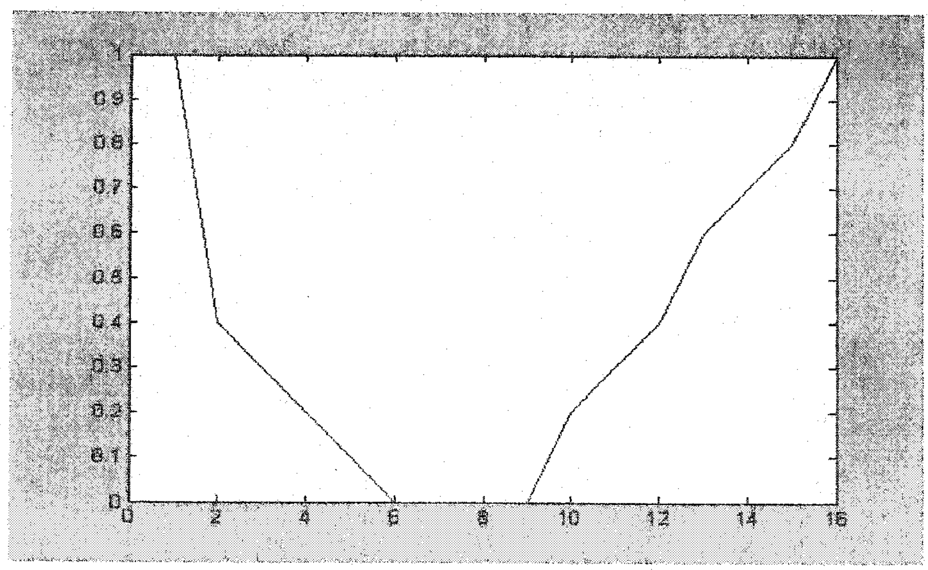


Figure 5.40 Temporary "0" Demand Profile at Planning Horizon = 16

The results of the costs of the optimal capacity scalability in the random demand profile and the temporary zero demand profile are shown in Table 5.11 and plotted in Figure 5.41.

Table 5.11 The Capacity Scalability Schedules' Cost for a Temporary "0" Demand Profile

T	Capacity Schedule Cost in Random Demand Profile	Capacity Schedule Cost with "0" Demand Profile
4	67.4	62.92
6	65.6	64.3
8	60.39	60.74
9	60.39	63.4
12	61	60.01
14	60.87	56.66
16	51.04	49.1

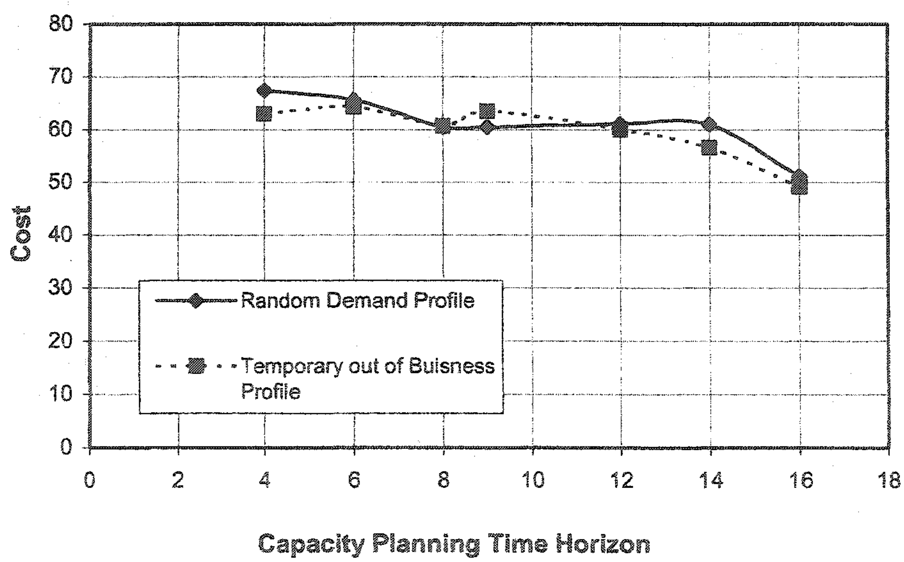


Figure 5.41 Optimal Capacity Scalability Cost with Random and "0" Demand Profiles

In the analysis of the Figure 5.41, it is shown that the change in the cost of the optimal capacity scalability schedules with the temporary zero demand profile compared to that of the random demand profile is very small. This shows the ability of the proposed tool to deal with various demand scenarios in an optimal way.

5.13 CHAPTER SUMMARY

The chapter represented an approach to model the first layer of the proposed architecture of the design of reconfigurable manufacturing systems that deals with capturing the market demand and mapping it to capacity requirements. The approach for that target was through adopting a model that is based on the optimal plant size with arbitrary increasing time paths of demand presented by Manne, A. and Veinott, A., [1967]. The selection of that model was based on the similarity between the regeneration point theorem, which is the core of the model, and the concept of capacity scalability in reconfigurable manufacturing systems.

Based on that model, a computer tool for generating optimal capacity scalability schedule was developed to be integrated to the proposed architecture. The schedule indicates the points of capacity scalability over time with the required size to be scaled with minimum cost. However, validating the new model revealed the need to modify the cost function of the model to reflect the real reconfigurable manufacturing systems environment. This was achieved through considering the cost of reconfiguration of the system in the cost of capacity scalability. Evaluating the cost of reconfiguration is a wide area of research and was not included in this thesis, however, the various constitutes of that cost element were recognized

Assuming different values for the cost of reconfiguration with different capacity scalability planning horizons, the results of the developed tool showed that a cost effective capacity scalability schedules in reconfigurable manufacturing systems could be realized through decreasing the cost of the reconfiguration of the manufacturing system.

The developed tool was used to explore different capacity scalability approaches with three demand profiles. The profiles considered were the fluctuating demand profile, increasing demand profile and decreasing demand profile. The results showed the superiority of the optimal capacity scalability schedule generated by the proposed tool over both the exact demand capacity scalability approach and the approach of supplying all required capacity at the beginning of the planning period in terms of cost in all the demand profiles considered.

Examining the effect of temporary out of business demand profile over the cost of the optimal capacity scalability schedule showed negligible change compared to that with random demand profile. This result illustrates the ability of the proposed model to deal with different demand profiles in an optimal way.

CHAPTER 6
CONCLUSIONS

6.1 SUMMARY AND CONCLUSIONS

The manufacturing system design approaches reported in the published literature are characterized by having wide diversity. Some of these approaches are used for selecting the appropriate system for a certain market environment, others are used for the physical design of manufacturing systems and third groups are dedicated to control the design process of manufacturing systems. They also vary between general manufacturing systems approaches to dedicated approaches for a certain kind of manufacturing systems.

However, few approaches combined the design and control of manufacturing systems and much fewer extended the approach from the qualitative dimension to the quantitative (analytical) one in order to be applied to real world application. None of the developed design approaches were applied to the reconfigurable manufacturing systems.

This thesis presented an integrated multi layer architecture for the design of reconfigurable manufacturing systems and how to control the design process. The methodology used for developing the architecture was based on a system analysis and design methodology. The proposed architecture is an open and mixed one that contains two main modules; the design module and the control module.

The design module describes the full design processes on the macro level starting from capturing the market demand to generating and selecting the best configuration that satisfies this demand and up to the final physical implementation of that system configuration.

The architecture showed how each design layer is controlled through the control module presented. Different performance measurements that reflect the strategic objectives of the reconfigurable manufacturing system were discussed. Some of these performance measurements were classical and others were newly suggested especially for the reconfigurable manufacturing systems.

The architecture could be considered the first comprehensive explanation of the reconfigurable manufacturing systems as it captures the full reconfiguration process in the reconfigurable manufacturing systems. It opens the door for researchers to visualize the different areas that need to be developed in such systems. The Application of the automatic printed circuit board (PCB) assembly industry discussed in this thesis aimed to illustrate how such architecture can be applied in real reconfigurable industrial environment.

The thesis extended the systematic approach of the design and control of reconfigurable manufacturing system to the analytical approach. This was achieved through modeling the first layer of the proposed architecture that deals with capturing the market demand and mapping it as capacity requirements to be delivered as inputs to the system configurator.

The developed model takes as an input the planning time horizon, the single period demand during this time and the cost for scaling the capacity unit. The output of the model is an optimal (at minimum cost) capacity scalability schedule that indicates the points of scalability over the planning time and the size of the capacity to be scaled with. This schedule is delivered as an input to the system configurator in the second layer of the proposed architecture.

A computer based tool for generating optimal capacity scalability policy was developed and integrated to the proposed architecture. The numerical results generated by the capacity scalability tool led to the modification of the adopted model in terms of the cost function to include the cost of reconfiguration of the reconfigurable manufacturing systems giving the model a more practicality.

The developed tool together with different demand and capacity scenarios were used to highlight some important results. One of these results is the importance of trying to decrease the cost of reconfiguration as a basis for a successful implementation of reconfigurable manufacturing systems. This was shown through assuming different values for the cost of reconfiguration and using them as input to the computer tool to see the effect of the cost of reconfiguration on the overall capacity scalability scheduling cost when relaxing the demand profile over different capacity scalability planning horizons. Also this result showed that the cost of the optimal capacity scalability schedules decreases with demand relaxation indicating that capacity scalability decision involves a trade-off analysis between the lowering the cost of capacity scalability and the cost of delaying the demand.

Another result shown was that the optimal capacity scalability schedule generated by the proposed model is more cost effective when dealing with different demand profiles than other capacity scalability approaches. The demand profiles considered were the fluctuating demand, increasing demand and decreasing demand. This result was illustrated through comparing the approach of adding all required capacity at the beginning of the capacity planning horizon as in flexible manufacturing systems (FMS) and the approach of instantaneous capacity change with each demand change with the suggested optimal capacity scalability approach at the different demand profiles considered.

A third conclusion was the ability of the developed capacity scalability tool to deal with the temporary "0" demand profile in the same cost effective way as with the random demand profile. Thus it is claimed that the developed tool can deal with the today's market with its different scenarios.

Modeling the capacity scalability in the first layer of the developed architecture is considered the second approach for modeling the capacity scalability in reconfigurable manufacturing systems and the first approach to view the quantity of the required capacity to be scaled. Previous approach considered only the optimal time to scale the capacity in these systems.

6.2 RECOMMENDATIONS FOR FUTURE WORK

6.2.1 The Architecture for the Design of Reconfigurable Manufacturing Systems

More analytical modeling is required to cover the different design and control activities prescribed in the proposed architecture layers. Succeeding in integrating the systematic approach with the quantitative analytical approach will result in a comprehensive formal design framework that can be generic for any reconfigurable manufacturing system.

More research is required to numerically develop the suggested performance measures used to control the design process of the reconfigurable manufacturing systems. There is a need to develop a metric that measures the scalability of the systems and can be used as selection criteria between different reconfigurable systems. The reconfiguration time is another performance measure that was discussed in the thesis and still needs more enhancements in terms of how it can be calculated through the different reconfiguration processes and how it can be used to evaluate and control the design process of these manufacturing systems.

The cost of reconfiguration was discussed in the thesis as a performance measure that should control the design process of the reconfigurable manufacturing systems and as an important constitute of calculating the capacity scalability cost. The discussion showed that evaluating the real cost of reconfiguration for a reconfigurable manufacturing systems is a substantial research task as it includes cost modeling for the reconfiguration activities together with new technologies that are difficult to model from a cost perspective. Also the "opportunity cost" for capturing the market demand, which should balance with the cost of reconfiguration, is another intangible cost item to model due to the unpredictable demand patterns. In general cost modeling in reconfigurable manufacturing systems is a potential for more research especially to prove the cost effectiveness of such new manufacturing systems.

6.2.2 The Capacity Scalability Model

The model for the capacity scalability schedule adopted in this thesis can be extended to deal with stochastic demand pattern. Such extension is more realistic as reconfigurable manufacturing systems deals with unpredictable demand that may be stochastic in nature.

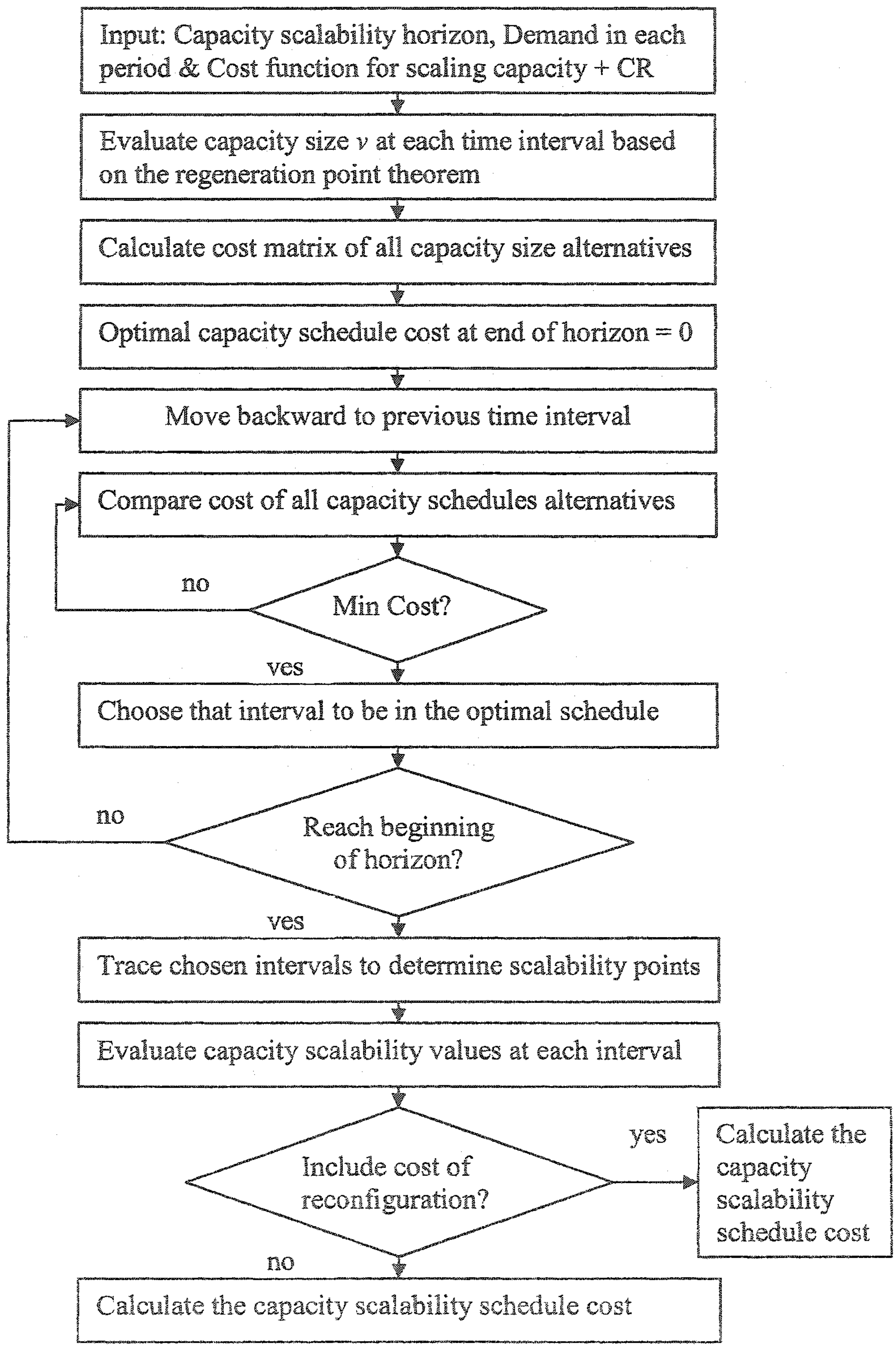
The model in this thesis dealt with scaling the capacity from a physical or a hard point of view. An extension for this capacity scalability approach would be through considering other scalability alternatives like time-related scaling of capacity (example extra shifts) and the logical capacity scalability as discussed in the developed architecture in chapter four.

It should be also pointed out that the capacity scalability model is limited to concave cost functions only. Further research is required to modify the model to deal with different types of cost functions that reflect the cost of different technologies used to scale the capacity of reconfigurable manufacturing systems.

The generated capacity scalability tool can be used to investigate different scenarios of demand as well as different types of cost functions. The thesis discussed some of these scenarios that are expected in a reconfigurable manufacturing system environment; however, other scenarios can still be researched to examine the cost of capacity scalability and how to optimally deal with dynamic demand patterns.

APPENDIX A

FLOW CHART FOR THE DEVELOPED OPTIMAL CAPACITY SCALABILITY SCHEDULING COMPUTER TOOL



APPENDIX B

THE DEVELOPED OPTIMAL CAPACITY SCALABILITY SCHEDULING COMPUTER TOOL CODE (USING MATLAB)

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Capacity Scalability Tool computes the optimal capacity schedule in
% Reconfigurable Manufacturing Systems using dynamic programming.
%
% Syntax :
%   cost_estimation = Capacity_Scalability policy and its cost
%   v = Decision variable denotes the size of capacity scalability
%       of the reconfigurable manufacturing system
%   c(i,k) = The present value of all costs incurred during periods
%            i+1,...,k
%   f(i) = The minimum discounted cost of satisfying the demand
%          increments D(i+1),...,D(T).
%   z =  The capacity scalability points.
%   vc = The capacity scalability values.
%
% Input to the function :
%   T = Scalability planning horizon
%   D = The single period demand period
%   C(v) = The cost function in terms of capacity (v)
%   CR = The cost of reconfiguration
%
% Output :
%   cost_estimation = Optimal Capacity Scalability Schedule and its cost
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [F,CR,Capacity_Scalling_Points,Capacity_Scalling_Values,c] =
cost_estimation(D,Rec_Cost)

D=D(:)';
[m,T]=size(D);

[q,r] = size(D);
if r~=T
   error('The number of the demands should be equal to the planning horizon T');
   return;
end

c=zeros(T,T);
cc=zeros(T,T);
```

```
V=zeros(T,T);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Required Capacity Evaluation (V)

for i=0:T-1
   for k=i+1:T
      V(i+1,k) = sum (D((i+1):k));
   end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Evaluation of Cost Coefficient Matrix (c)

for i=0:T-1
   for k=i+1:T
      v=V(i+1,k);
      c(i+1,k)=scalability (v,i+1);
   end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Backward Dynamic Programming

F=zeros(T+1,1);
F(T+1,1)=0;
Pos=zeros(T+1,2);

for i=T:-1:1
   F(i)=min (c(i,i:T)+F(i+1:T+1)');
   [I,J]=find ((c(i,i:T)+F(i+1:T+1)')==F(i));
   Pos(i,2)=J+(i-1);
end

%To get the position
for i=1:T
   Pos(i+1,1)=i;
end

clear Z
Z(1,1)=0;
a=1;
b=1;
while Z(b,1) < T,
   b=b+1;
   Z(b,1)=Pos(a,2) ;
```

```
   a=Pos(a,2)+1;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Calculating the optimal capacity scalability schedule without cost of reconfiguration


'Optimal Capacity Scalability policy cost is '

F=F(1,1);
[m,n]=size(Z);

vc=D';
a=1;

for i=2:m
  b=Z(i,1);
  vc(a,1)=sum(vc(a:b,1));
  vc(a+1:b,1)=0;
  a=b+1;
end

%Capacity_Scalling_Points= find(vc==0)-1;
Capacity_Scalling_Points= find(vc~=0);
Capacity_Scalling_Values =vc(Capacity_Scalling_Points);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Calculating the optimal capacity scalability cost including reconfiguration cost

 'Optimal Capacity Scalability policy cost including reconfiguration cost is'

 CR=F(1,1)+ Rec_Cost*(m-1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

The following is the module for inputting any cost function that is function in the capacity size v and tine t as explained in chapter 5 (the numbers shown here is for the numerical example used in the thesis).

```
function c = scalability (V,T)

c =0.8^(T-1)*(5+(10*V));
```

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