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Lifecycle approach to economic and strategic justification of RMS investments

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LIFECYCLE APPROACH TO ECONOMIC AND STRATEGIC JUSTIFICATION OF RMS INVESTMENTS

by

Onur Kuzgunkaya

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ABSTRACT

Global competition, increased customization of products, shorter product lifecycles and delivery times require more agility from manufacturing companies. In contrast to conventional manufacturing systems, the new paradigm of Reconfigurable Manufacturing Systems (RMS) aim to achieve agility by adapting itself to changing market conditions, using its reconfiguration capabilities. Since RMS are evolving systems, the justification techniques should include features that incorporate the aspect of reconfiguration and the strategic benefits of reconfigurability. The purpose of this thesis is to show that lifecycle evaluation of RMS that considers both economic and strategic objectives results in providing cost-effective, easy to manage and responsive manufacturing system configurations throughout the system's lifecycle.

In order to prove this thesis, a multi-criteria decision making approach has been followed. First, a lifecycle cost model has been developed representing the various activities in RMS. The cost model incorporates in-house production and outsourcing, machine acquisition and disposal costs, operational costs, and reconfiguration cost and duration. Second, a structural manufacturing system complexity metric has been developed. The complexity metric provides insight into the system components and structure, and assist in selecting a less complex system at the early design stages. Third, a manufacturing system responsiveness metric has been developed in order to assess the configurations' ability to respond to the changes in demand mix within each period of the lifecycle. These objectives are then incorporated in a fuzzy multiple objective optimization tool in order to incorporate the decision maker's preferences into the model.

The proposed methodology has been applied to a case study where various demand scenarios have been used in order to determine the suitable RMS configurations over the planning horizon. In addition, an equivalent Flexible

Manufacturing System (FMS) configuration has been generated under the same conditions in order to compare FMS and RMS investments.

The main contribution of this work is to enhance the investment evaluation of manufacturing systems by incorporating strategic along with economic objectives within a lifecycle analysis framework. A decision support tool for planning RMS configurations and their justification has been developed. It can also be used for the comparison of FMS and RMS.

DEDICATION

To my parents

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my advisor, Dr. Hoda ElMaraghy, for her contributions, guidance, and continuous support throughout my Ph.D. program. I would never be able to accomplish this task without her guidance, and I am thankful for the experience I gained in the academic research field. I would also like to thank my other committee members, Dr. Waguih ElMaraghy for contributing to the development of this research and providing invaluable comments; Dr. Mike Wang, and Dr. Robert Kent, for their helpful comments and suggestions.

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On a special note, I would like to express my sincere appreciation to my wife who has provided me the encouragement, patience and, support I needed throughout this journey. My utmost gratitude to my parents for their endless sacrifice and unconditional support for me to pursue my goals as well as to my sister who has been a source of joy during her stay.

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LIST OF ABBREVIATIONS

AGV	Automated Guided Vehicles
AHP	Analytic Hierarchy Process
AS/RS	Automated Storage and Retrieval Systems
ATCF	After tax cash flows
CASCADE	Computer Aided Scalable System Design
CNC	Computer Numerical Control
DFA	Design for Assembly
DML	Dedicated Manufacturing Line
EOQ	Economic Order Quantity
FMS	Flexible Manufacturing Systems
IFR	Increasing Failure Rate
ILP	Integer Linear Programming
IPPD	Integrated Product and Process Development
LR	Labour Rate
MHS	Material Handling Systems
NPV	Net present value
RA	Response Ability
RE	Resource Elements

RMS	Reconfigurable Manufacturing Systems
WIP	Work in Process

CHAPTER ONE

INTRODUCTION

This chapter gives a brief description of manufacturing systems and their lifecycle evaluation. This is followed by the definition of Reconfigurable Manufacturing Systems (RMS) whose characteristics provide the motivation for this work. The approach followed in this research is described and an overview of the dissertation is provided in the final section of this chapter.

1.1. Overview of manufacturing systems

The history of manufacturing systems shows that their evolution is driven by changing market conditions. Manufacturing companies were able to react to these changes using technological enablers and developing competitive edge. Mass production era was focusing on minimizing cost and achieving economies of scale by increasing the production capacity to decrease product cost and generating additional demand. As the products became widely available, the customers then started to look for quality as a deciding factor for selecting their products. This led to the focus on improvement of quality in manufacturing companies by implementing efficiency improvement techniques and lean manufacturing approach. In the 80s, companies started to increase their product variety in order to generate demand by extending their markets and achieve mass customization. Generating additional demand by increasing product variety is called economies of scope and it was achieved by using design and/or manufacturing similarity of parts (ElMaraghy, 2005). A Flexible Manufacturing System (FMS) is an integrated system of machine modules and material handling equipment under Computer Control for the automatic random processing of palletized parts. Although FMS was a promising system to meet the demand for customization and achieving product variety, its implementation in the industry was slow due to its high initial investment cost, high complexity, and need for highly skilled personnel (ElMaraghy, 2005;Mehrabi *et al.*, 2000)

Today's unpredictable market changes and decreasing product lifecycles requires an increasing level of responsiveness from manufacturing enterprises. Reconfigurable Manufacturing Systems (RMS) was proposed (Mehrabi *et al.*, 2000) to meet these requirements and provide agility.

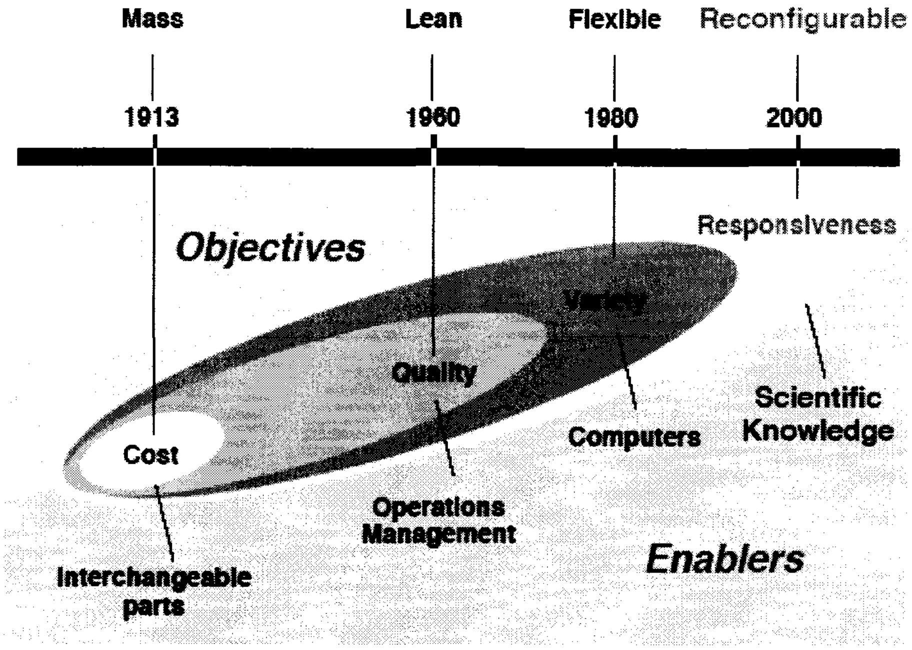


Figure 1.1 Evolution of Manufacturing Systems (Mehrabi *et al.*, 2000)

1.2. Reconfigurable manufacturing systems

Due to increased competition in today's manufacturing environment, companies are trying to survive by producing a wide range of products and by trying to adapt to changes in market in the quickest possible way. The changing manufacturing environment requires creating production systems that are themselves easily upgradeable to incorporate new technologies and new functions. Reconfigurable Manufacturing Systems (RMS) is a visionary challenge for manufacturing enterprises and is viewed as a solution to changing production environments. USA's National Research Council has identified reconfigurable manufacturing as first priority among six grand challenges for the future of manufacturing (USA NRC, 1998).

Koren et al. (1999) defined RMS as follows:

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

Unlike traditional manufacturing systems, RMS can be achieved by using reconfigurable hardware and software, such that its capacity and/or functionality can be changed over time. The reconfigurable components include machines and material handling systems, mechanisms and modules for individual machines, as well as sensors, process plans, production plans, and system control algorithms for entire production systems.

The reconfiguration of a manufacturing system is considered whenever there is a new circumstance that warrants such a change. These circumstances may be changing product demand, the introduction of new products, or the integration of new process technology into existing manufacturing systems. There might be several configuration alternatives to consider before selecting a new configuration. The objective is to adapt to new conditions without unduly increasing the system cost or complexity, or degrading the resulting product quality.

One important research area in RMS exists in system level design where there is a need to analyze the economic aspects of investing in a reconfigurable manufacturing system.

The state-of-the-art Flexible Manufacturing Systems are designed in order to provide a general flexibility a priori to deal with the anticipated variations in the products' and markets' requirements. The concept of implementing all the capability at the beginning of the FMS lifecycle results in a major initial investment. Instead of making a high capital investment up front, as in the case of FMS, RMS concept aims at providing the exact capability and capacity as needed when needed according to the market requirements. Proponents of this approach believe that this solution would be less costly over the whole lifecycle of the system. Many research efforts have focused on validating this assumption and providing suitable modeling and analysis tools.

1.3. Lifecycle modeling of manufacturing systems

Decision makers must carefully consider all economic aspects before investing in a system since they are expected to perform in competitive environments. Lifecycle cost represents all costs of resources needed to acquire and operate a facility over its expected life.

The typical lifecycle cost for a production system is usually represented by a bathtub (Figure 1.2) (Dahlen and Bolmsjo, 1996). The costs are high at the beginning of the lifecycle because of purchase, installation, and start-up costs. When the equipment is installed and working as intended, the costs decrease. In the final stage of lifecycle, the costs for repairs and disruptions increase, until they reach a no longer profitable level.

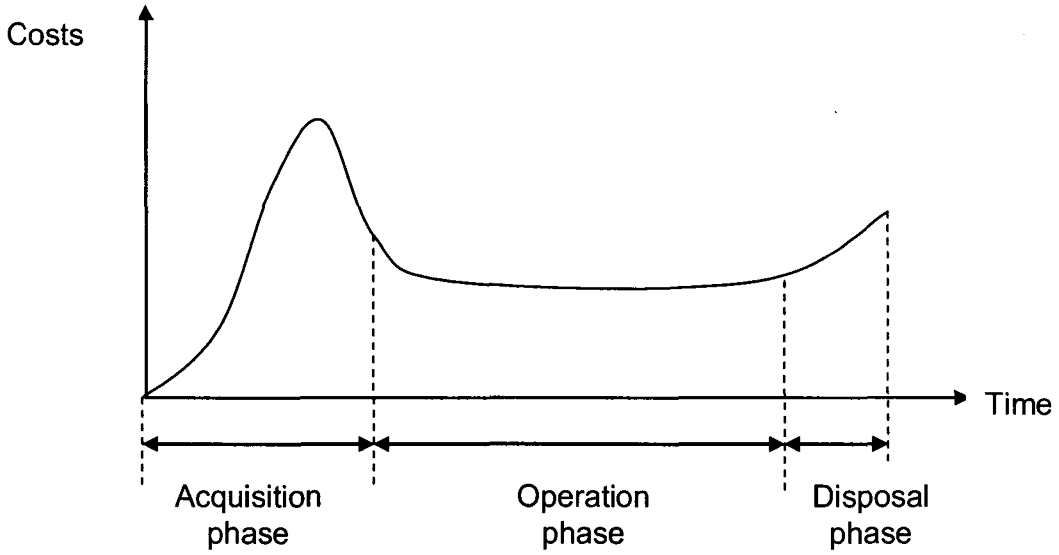


Figure 1.2 LCC graph for a conventional manufacturing system (Dahlen and Bolmsjo, 1996)

In relation to lifecycle modeling of reconfiguration in manufacturing systems, Wiendahl and Heger (2003) discuss the justification of "changeability" in manufacturing companies. In this work, the term changeability is used as a general term for transformation at all the levels of a company, including reconfigurability at the production level. The lifecycle of a factory is composed of three phases: i) planning and construction, ii) operation, and iii) dismantling. In their paper, they give a decomposition of transformation costs of a factory during its lifecycle. The transformation costs are composed of the object costs and the costs of transformation processes during the lifecycle. The transformation object costs result from the start-up and construction investments. The transformation process costs include direct and indirect implementation costs such as conversion and restoration of process capability and also indirect costs due to loss of production extra work or additional inventory costs. They state that a cost-effective manufacturing system alternative exists between a conventional inflexible system and an extremely transformable system. The authors proposed to apply a "scenario planning" methodology in order to find the most cost effective alternative.

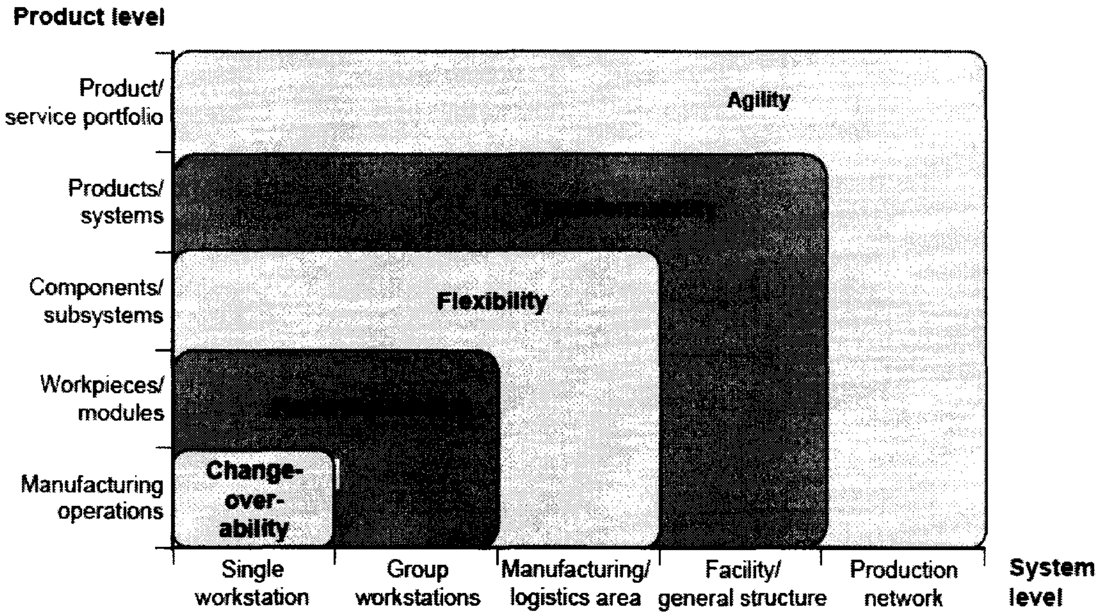


Figure 1.3 Types of changeability (Wiendahl and Heger, 2003)

1.4. Motivation of the study

The main difference between RMS and conventional manufacturing systems is the ability to evolve over time. Figure 1.4 (Kuzgunkaya and ElMaraghy, 2004) represents an example of an RMS lifecycle. At the beginning of its life, RMS is set to produce a certain capacity of product A. Based on the market requirements, product B has been introduced to the system by reconfiguring the machines. During reconfiguration, the capacity of the system decreases and a ramp-up period is needed to reach maximum capacity of the system.

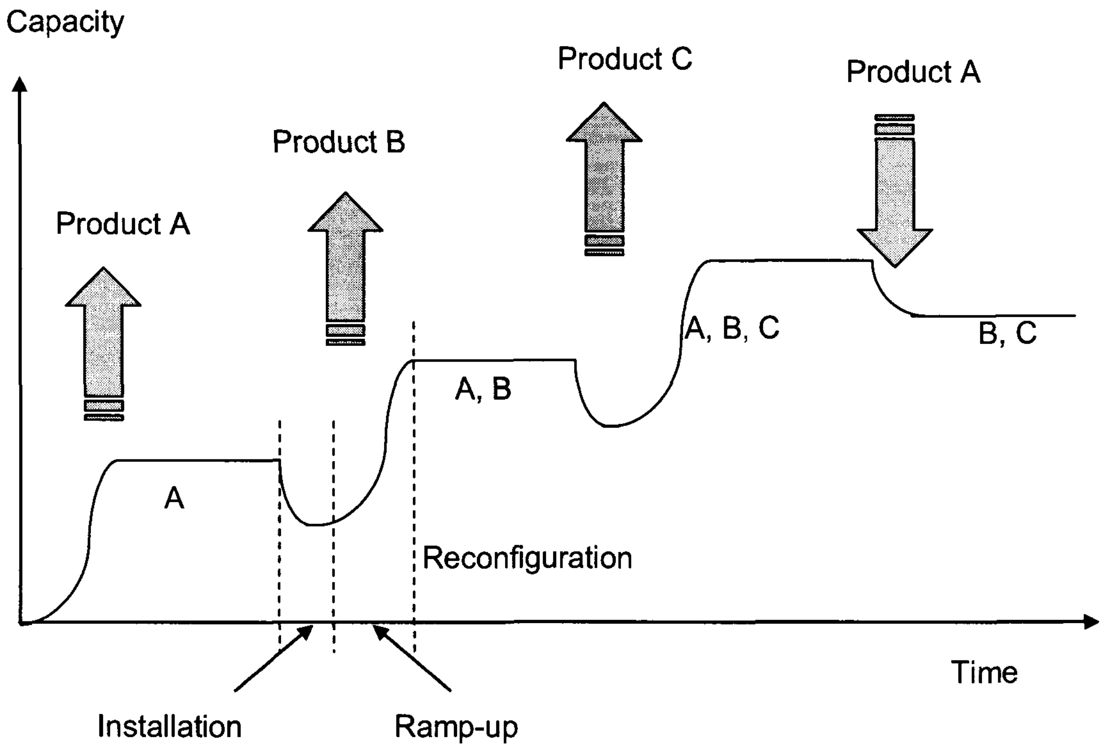


Figure 1.4 Reconfigurable manufacturing system lifecycle

The lifecycle cost graph of RMS is represented in Figure 1.5 (Kuzgunkaya and ElMaraghy, 2004). The initial installation and start-up costs are associated with the market requirements of product A. After the initial ramp-up phase is finalized, a minimum overall cost is achieved. With the introduction of product B, an increase in costs can be observed due to the purchase of new modules and equipment necessary to manufacture product B. This increase is also a result of the reconfiguration process where the throughput of the system decreases due to the modifications on the machinery. After the installation is finished and the “bugs” are fixed during the ramp-up period, the overall cost of the system achieves a lower level, thanks to its increased capacity. Removing a product from the production line will result in a decrease in overall cost as depicted in Figure 1.5. This is due to the resale of modules and components required to manufacture the product A. With two products remaining on the line, the overall cost will reach a higher level.

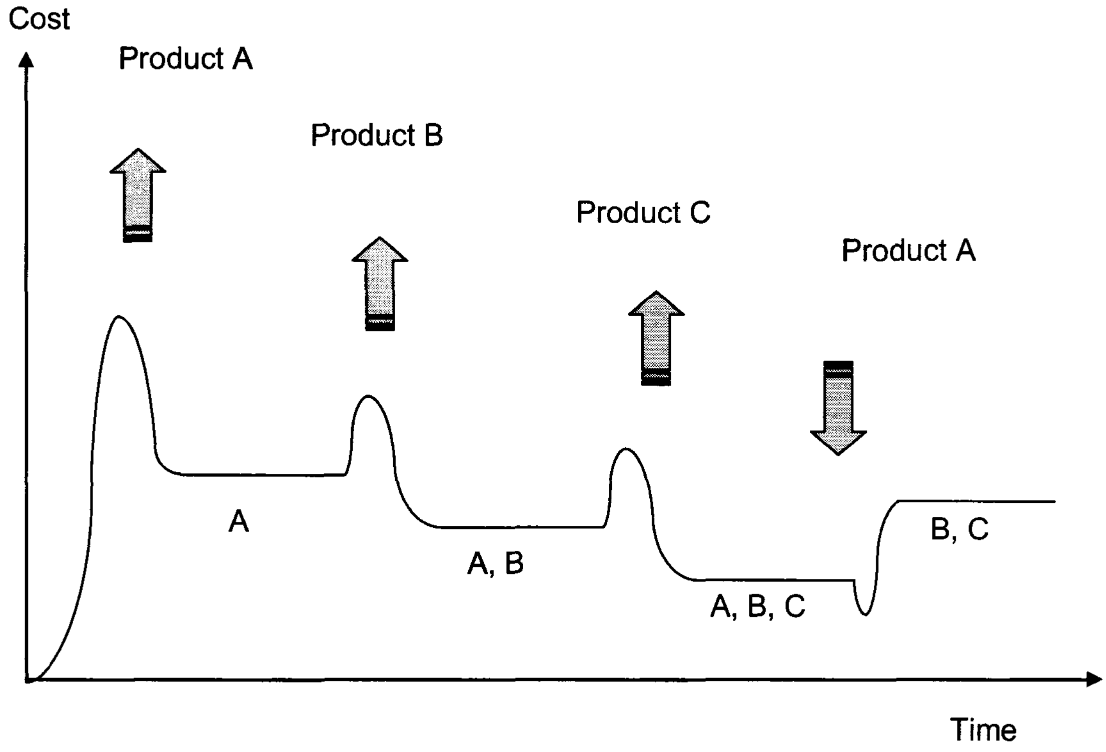


Figure 1.5 RMS lifecycle cost profile

Conventional manufacturing systems are designed to address the requirements once at the initial development phase; therefore, the effect of changes in the system configuration is not represented in lifecycle modeling of conventional manufacturing systems. Since manufacturing systems have high initial investments, it is important to select designs that will not become obsolete in a short time.

Instead of making a high capital investment up front, as in the case of FMS, the RMS concept provides the strategic benefit of providing the exact capability and capacity as needed when needed according to the market requirements. The motivation of this research work is to assess if the RMS investments can be economically justified and investigate the conditions under which RMS should be preferred to other manufacturing systems.

1.5. Objectives and approach

The objective of this research work is to develop a model that represents the lifecycle of an RMS in order to evaluate if such investments are economically justifiable.

The purpose of this thesis is

to show that lifecycle evaluation of RMS that considers both economic and strategic objectives results in providing cost-effective, easy to manage and responsive manufacturing system configurations throughout the system's lifecycle.

In order to prove this thesis, a multi-criteria decision making approach has been followed. First, a lifecycle cost model has been developed representing the various activities in RMS environment including the reconfiguration process. The cost model incorporates in-house production and outsourcing option of the demand, machine acquisition and disposal costs, operational costs, holding costs, and reconfiguration cost and duration for systems that consist of modular machines.

Second, a structural system complexity metric has been developed to ensure that the generated system configurations are easy to manage and simple. The proposed system complexity provides insight into the system components and structure, and the manageability (control and operation) of manufacturing systems configurations, as well as assisting in selecting a less complex system at the early design stages.

Third, a manufacturing system responsiveness metric has been developed in order to assess the configurations' ability to respond to the changes in demand mix within each period of the lifecycle.

These objectives are then incorporated in a fuzzy multiple objective optimization tool using fuzzy membership functions in order to incorporate the decision maker's preferences into the model. In addition, the various cost parameters are represented as fuzzy numbers in order to reflect the uncertainty of future investments.

The outcome of this tool is a system configuration for each period that satisfies the lifecycle cost, responsiveness, and complexity objectives within the targeted planning horizon. The resulting configurations are optimized simultaneously for lifecycle costs, responsiveness performance, and system structural complexity.

A case study is presented to demonstrate the use of the developed approach. A set of deterministic demand scenarios are used to generate RMS configurations over a planning horizon of 8 periods. In addition, FMS configurations were generated to satisfy the same demand scenarios over the total life of RMS, in order to compare the FMS versus RMS cost and performance.

In order to validate the results of the developed tool, a simulation model has been developed using ARENA to simulate the lifecycle cost and throughput performance of RMS and FMS configurations generated by the developed tool.

1.6. Dissertation outline

The dissertation consists of nine chapters:

- Chapter one includes the motivation, research objective, thesis, and approach
- Chapter two presents a review of the related literature and opportunities for contribution in this area of research are determined

- Chapter three gives a description of the overall RMS lifecycle evaluation methodology where the inputs, the objectives and the outputs are defined

- Chapter four describes the notion of complexity in manufacturing systems. A structural configuration complexity metric is proposed for assessing the complexity of various components such as machines, buffers, and material handling systems. An example is provided to illustrate the use of the metric in comparing manufacturing system configurations.

- Chapter five presents a metric to assess the responsiveness of manufacturing systems within a fixed configuration. The metric is illustrated with an example.

- Chapter six describes the developed cost model for RMS. It includes the operational costs such as variable and fixed costs and inventory holding costs. In addition, reconfiguration cost is described and modeled based on the configuration characteristics described in chapter three

- Chapter seven illustrates the overall methodology by comparing the cost and performance of RMS and FMS configurations generated using the developed model. In addition, sensitivity analysis is performed on unit reconfiguration time in order to see the effect of reconfiguration period's length on system performance. The results of the lifecycle evaluation tool are validated by the simulation model built in ARENA. The resulting manufacturing system configurations from the lifecycle evaluation model are simulated in order to compare the lifecycle cost and throughput performance.

- Chapter eight concludes the dissertation, highlights the scientific contribution and provides directions for future research.

- Appendices include the machine related data, a sample model for the developed model in GAMS (www.gams.com), and the simulation result report based on ARENA (www.arenasimulation.com).

CHAPTER TWO

LITERATURE REVIEW

The literature directly related to the lifecycle cost modeling and economic justification of reconfigurable manufacturing systems is limited. There are four subtopics which can be related to the modeling of reconfiguration of manufacturing systems:

1. FMS selection where technological obsolescence of the machines has been considered
2. Equipment replacement subject to technological change
3. RMS capacity expansion modeling using real options analysis
4. RMS configuration selection

2.1. FMS selection problems subject to obsolescence

Abdel-Malek and Wolf (1994) developed a methodology that ranks candidate FMS designs based on strategic financial and technological criteria. Although they use lifecycle cost measure without taking reconfiguration into account, they point out the importance of technological obsolescence of manufacturing equipment using an index for the system's technological improvement rate. However, this index is used to compute overall lifetime of a system and the systems with short lifetimes are eliminated.

Yan et al. (2000) applied a modified integrated product and process development (IPPD) approach for the design of an FMS, including the modeling of machine upgrades that are necessary due to technological obsolescence. In their paper they state: "If the technology of a particular FMS component develops quickly, it may reduce the company's ability to adjust rapidly to the market in the long term. Since investment in flexible technologies is usually large, the obsolescence potential requires careful consideration at the time of component selection". In the updated version of the study Yan and Zhou (2003), the authors give more insight on the methodology and possible solution algorithms applicable to their methodology, such as best-first search method and backtracking.

The integrated product and process development methodology is explained as follows..

The lifecycle for an FMS is similar to other products. The first step in the methodology is to set up an expected lifecycle structure.

Figure 2.1 An expected lifecycle structure for FMS (Yan et al., 2000)

The second step in the methodology is to define a set of criteria as indexes. In their paper, Yan and Zhou have identified cost, benefit and environmental impact as indexes to evaluate alternatives. The next step in the methodology is to create a timed life locus tree where all the possible processes in each life phase of an FMS's lifecycle are represented. The final step in the methodology involves searching in the tree for an optimal life locus with regard to the objective function consisting of a weighted sum of three indexes defined.

Table 2.1: Initial configurations for FMS (Yan et al., 2000)

Process	A	R	C	M	V	D
D1	*	*	*	*	-	-
D2	*	*	*	*	-	*
D3	*	*	*	-	-	-
D4	-	*	*	*	*	-
D5	*	*	*	-	-	*

* means selected, - means not selected.
Abbreviations: A - AGVs, R - robots, C - CNC machines,
M - machining centers, V - conveyor systems, D - database systems.

The search algorithms proposed to find the optimal life locus in the tree are best-first-search and backtracking methods. Incorporating uncertainty about the future and the risk of investment and extending the methodology to multiple products and part mixes are some future research directions mentioned by the authors.

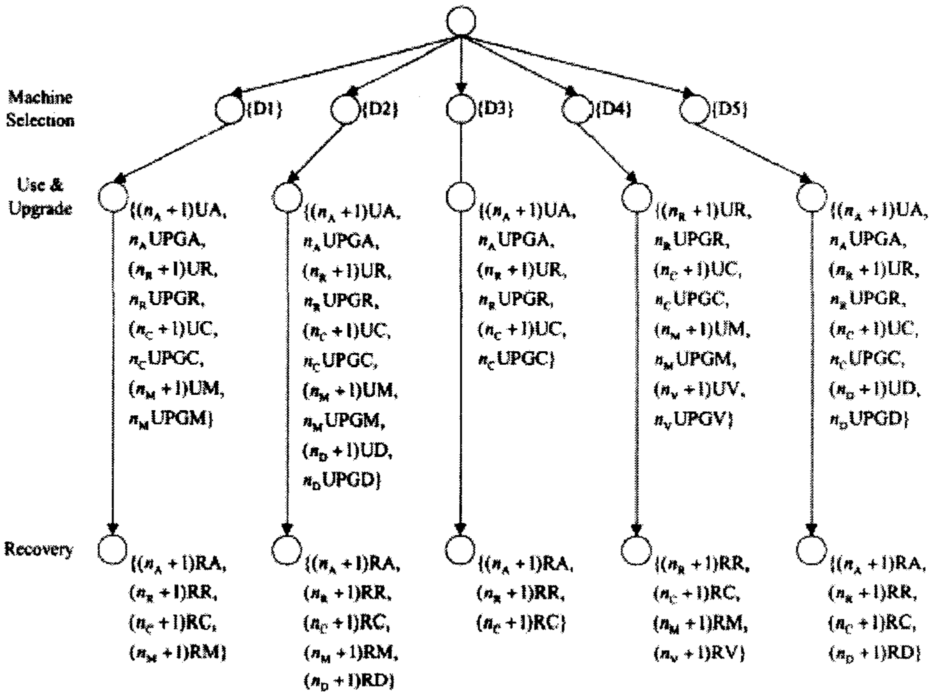


Figure 2.2 A timed life locus tree for FMS(Yan et al., 2000)

2.2. Equipment replacement models subject to technological change

A machine replacement problem under technological change is another related topic where upgrade or reconfiguration is involved. Rajagopalan et al. (1998) consider a problem where sequences of technological breakthroughs are anticipated but their magnitude and timing are uncertain.

They consider a situation where the evolution of technology is modeled as Markov process with high probability of evolution in the early periods and a decrease as time passes. The problem is regarded as a sequence of acquisition, replacement, and disposal decisions. Disposal of unused capacity is considered only when a new technology becomes available. Acquisition and replacement are considered only when the firm has no unused capacity. The objective of the proposed model is to minimize the total acquisition cost of capacity purchased to satisfy demand increments, the carrying cost, and the salvage cost of disposing used and unused capacity of a certain technology in the production period. A stochastic dynamic programming formulation is proposed to solve this model. As a result of their study they conclude that it is optimal to:

- Purchase, dispose, and replace capacity in amounts equal to the demand increments.
- dispose excess capacity only in periods when a new technology appears
- replace used capacity only in acquisition periods

Although Rajagopalan et al.'s method represents the technological changes with uncertain timing, the demand behavior is deterministic and the only objective considered is the cost function.

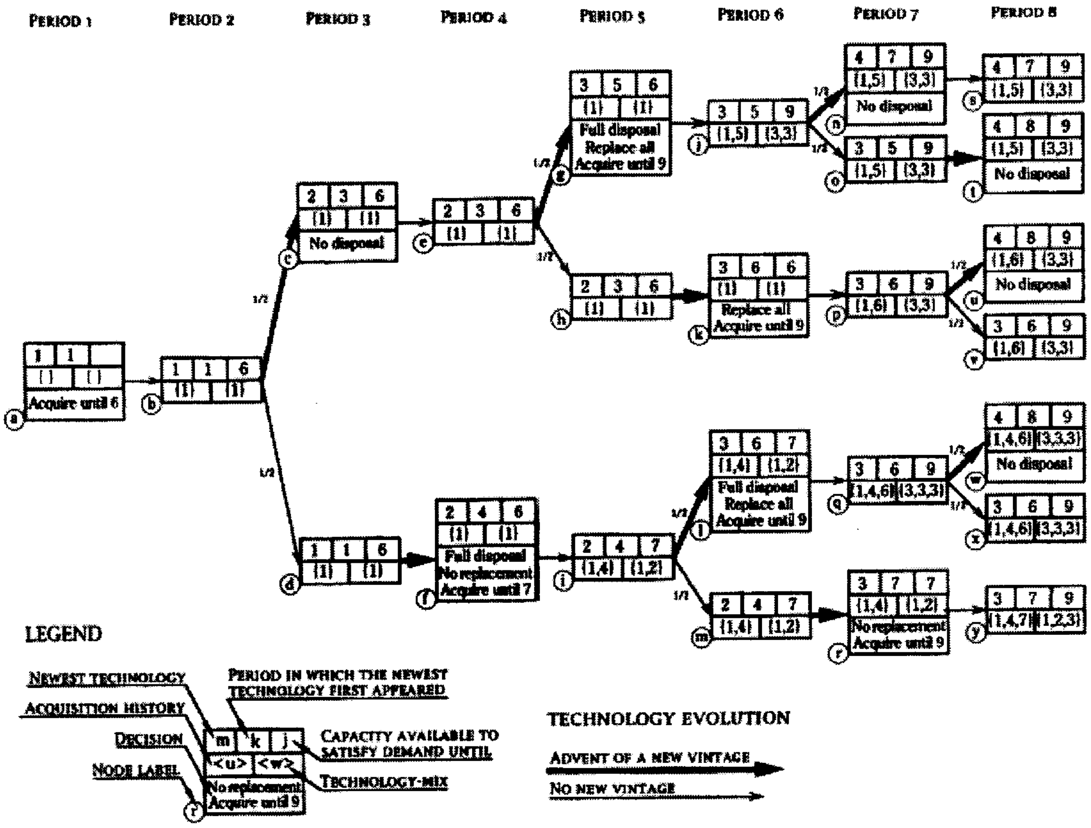


Figure 2.3 Optimal decisions for different technological evolution paths (Rajagopalan et al., 1998)

Bokhorst et al. (2002) addresses the issue of investment appraisal of new technology, specifically computer numerical control (CNC) machine tools in conjunction with optimal allocation of parts and operations on CNC machines as the investments take place. The authors combine the replacement problem of existing machines with new CNC modules acquisition through an integer programming model. The model simultaneously determine the optimal allocation of parts and operations to conventional machines and to new CNC machine tools; and determine the optimal investment sequence and timing of investments in CNC machine tools. The optimality criterion is based on a maximization of net present value (NPV) over a specified planning horizon. The authors' approach is similar to RMS lifecycle pattern, in terms of adding and removing machines to the system. However, they force the removal of existing machines and addition of new machines by implementing constraints into the model rather than letting the objective function optimizes these changes. In addition, the model does not take into account the intangible aspects of investing in new technologies.

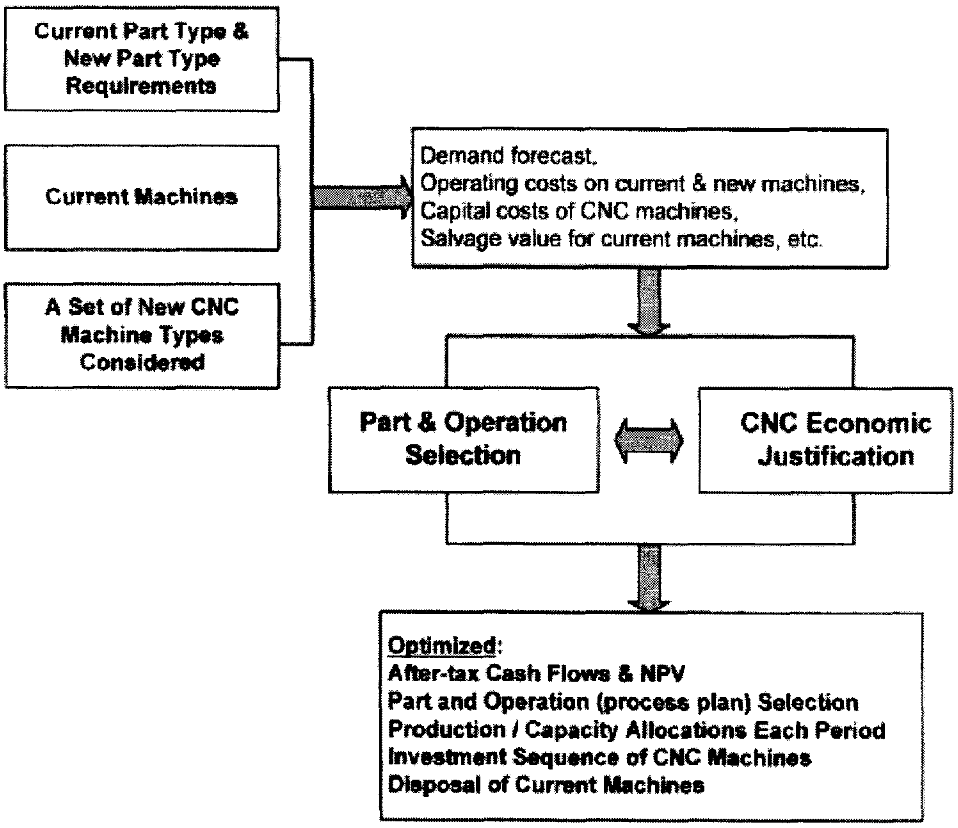


Figure 2.4 Economic justification model (Bokhorst et al., 2002)

2.3. Investment evaluation of RMS using real options

In order to evaluate advanced manufacturing technology investments, there is a need to incorporate strategic benefits and uncertainty of the future investments. The traditional method of calculating the net present value (NPV) of the projects and selecting the project with the highest NPV ignores the strategic benefits such as flexibility. Another way to evaluate advanced manufacturing technology investments is to use real options analysis. Real option analysis, by explicitly capturing the flexibility and its effects on uncertainty, provide for a consistent treatment of investment in production systems.

An option gives the holder an opportunity without the corresponding obligation to take action for it. Apart from financial options, the theory is also applicable to options constituted by "real opportunities". As in the case of expansion flexibility for manufacturing systems, one has opportunity to easily expand the capacity but no obligations to do so. Therefore, expansion flexibility can be interpreted as different types of options, but the pay-off function is more complex than the pay-off function of the financial options. The following table gives a comparison between financial options and options in the manufacturing framework:

Table 2.2: Financial and manufacturing frameworks in Real Options

Financial Framework	**Manufacturing Framework**
Price of the financial asset	Expected value of returns from the expansion investment project
Exercise price	Expected value of the cost of expansion investment
Uncertainty of the financial asset price movements	Uncertainty in cost and benefits resulting from the expansion investment
Time to expiration	Time to the investment expansion decision
Risk free interest rate	Risk free interest rate

Amico et al. (2003) applied real options theory to RMS investment evaluation. In their approach, they use the demand as the main source of uncertainty and modeled it as a stochastic variable following a Geometric Brownian Motion. The pay-off function is the expected NPV of the additional investment to increase the capacity at the time of expansion.

A simple manufacturing scenario has been considered, a Dedicated Manufacturing Line (DML), an FMS, and an RMS able to manufacture the same single product. The systems are designed at the outset depending on the product demand forecasted for a 6-year time horizon, and then the expansion option has been considered at a certain time during this period. The parameters of the expansion option, namely the new capacity and the investment needed to purchase it, depend on the demand forecast at the expansion time. The developed real option tool is finally used to add the option value to the investment NPV calculated on the demand forecast, so that the three investments can be compared using their extended NPV.

As a result of their study they highlight the advantage of RMS investments over FMS and DML when considering the scalability and convertibility of RMS. The real options analysis is useful in the sense of quantifying these characteristics of RMS. As a limitation of the approach in this paper, one might say that an RMS experience more than one reconfiguration over its lifecycle; therefore, a real options analysis with multiple reconfiguration options is needed to fully represent the lifecycle of an RMS.

2.4. RMS configuration selection and lifecycle cost models

Spicer (2002) addresses the issue of designing scalable machining systems in his study. He introduces some principles to design scalable reconfigurable machines. In order to solve the scalable system design problem, the author's approach is a two phased multi period integer linear programming (ILP) methodology. In this procedure, the individual product demands, the system set-up time, and the batching policy are taken as inputs. The output is the minimum cost scalable system configuration path that can meet the demand requirements of all products. The first ILP phase consists of minimizing the investment cost subject to the constraint of meeting demand through the planning horizon. The second phase ILP formulation maximizes the production capacity with the least cost configuration obtained from the 1st phase.

The reconfiguration cost is a non-linear function of the work required to buy, sell-off, or move machine bases and machine modules. It is considered as the sum of only physical arrangement costs and lost capacity costs. Since it is a non-linear function, the calculation of reconfiguration cost is made separately from the ILP model.

In order to apply the methodology, Spicer (2002) introduced a software tool named CASCADE (Computer Aided SCAlable system DEsign) where the major inputs are:

- A variable but deterministic demand scenario
- Machine production rates as a function of the number of modules at each machining operation
- Machine module investment costs
- Machine operating costs as a function of the machine configuration and stage
- Reconfiguration information

The most important outputs of the software are the number of machines at each machining operation, the configuration of each machine in the system, the reconfiguration time, and the lifecycle cost.

Although Spicer's work is a significant contribution that provides a mathematical formulation of reconfiguration cost computation and system configuration path generation, the proposed model has some limitations. It was not possible to incorporate non-linear models therefore the reconfiguration costs were computed in a separate model, which resulted in a sub-optimal solution. As stated by the author, genetic algorithms might be a good approach to add non-linear equations to the problem formulation. The methodology developed by Spicer is purely based on economic evaluation. Due to that reason, the potential strategic benefits of RMSs are not included in the evaluation methodology.

Narongwanich (2002) investigates the conditions under which it would be economically advantageous to invest in reconfigurable capacity compared with a dedicated system. In the author's modeling framework, the decision maker can purchase either a dedicated or a reconfigurable machine; there is uncertainty as to when the reconfigurable machine will be reconfigured to produce a different product than the one being currently produced. The reconfigurable machines considered in this study are assumed to produce one product at a time. He introduced a dynamic programming model where the company is assumed to make one of the following decisions: To keep the existing system, to invest in a dedicated machine, or to invest in a reconfigurable system. The new product arrivals are modeled first by using geometric probability distribution and then using increasing failure rate type (IFR) distribution. The demand has been introduced in the model both with stable situation and stochastic behaviour. As with most of the lifecycle modeling studies, the objective function consists of purchase costs, operating and maintenance costs.

Amico et al. (2001) developed an investment model for each kind of manufacturing systems namely Dedicated Manufacturing Line (DML), Flexible Manufacturing System and RMS. The theoretical model developed involves the comparison among these systems using net present value of the lifecycle costs and benefits for a determined period. In their model, they relate the systems using a parametric approach. However, the only comparison criterion among manufacturing systems is discounted cash flow and the model is highly theoretical as stated by the authors.

Zhang and Glardon (2001) compare four types of manufacturing system empirically. Although several criteria such as adaptability, complexity, production rate, reconfiguration time, ramp-up time and lifecycle cost have been used in their analysis, there is a need to build an analytical tool to compare different manufacturing system alternatives.

Abdi and Labib (2004) presented a Fuzzy Analytic Hierarchy Process tool for tactical design justification of RMS. They focused on the first step of tactical design, in which the feasibility of manufacturing operations and economic requirements are evaluated. The feasibility study is intended not only to evaluate the possibility of implementation of an RMS design, but also to produce a reference base for its evaluation through the design loop over planning horizons. Manufacturing reconfigurability has been defined as the feasibility of manufacturing process to deal with capacity changes and functionality changes.

2.5. Summary of the literature review

In summary, the previous studies related with the lifecycle modeling of manufacturing systems don't fully capture the reconfiguration process of RMS case. In the studies related with FMS selection, both strategic and financial performance of the alternatives is considered. The studies also include determining the number of necessary upgrades of the FMS; however, they fall short of capturing the uncertain nature of future investments, and do not include the reconfiguration costs. In the case of equipment replacement models under technological change, the demand behavior is modeled as a deterministic scenario and the objective is to minimize the overall cost of the system through its lifetime. It should be noted that advanced manufacturing technologies need to be evaluated by including not only their financial performance but also their strategic benefits. Narrow financial evaluation may lead to rejection of an FMS investment, for instance, whereas non-investment in FMS may be deemed as highly risky from a business strategy perspective. This is especially true when FMS contributes significantly towards closing the competitive and opportunity gaps. Real options analysis capture this strategic value by converting it into an option value and it has the benefit of using a stochastic market demand; however, there is room for improvement as to include multiple options/reconfigurations in the analysis.

RMS lifecycle cost evaluation studies are the most comprehensive work in terms of computing the reconfiguration cost. One of the main drawbacks of these studies is the data used for cost computation are estimates only since there is no RMS system commercially available. Therefore, the studies that rely only on cost computation of RMS might be misleading.

Due to the uncertain nature of future investments of an RMS, the anticipated costs related with its operation can only be estimates. Additional criteria, which are expressed by the system's features, can decrease the effect of having inaccurate cost figures. In addition to that, the ability to easily reconfigure the system should be included in the analysis to fully express the benefits of such system. Otherwise, the investment analysis in RMS technologies would be infeasible.

The lifecycle cost alone is not enough to evaluate RMS, and there is a need to incorporate other evaluation criteria, such as system complexity, and responsiveness. These additional measures and indexes, which are based on the system configuration and its components' features, would result in a more comprehensive and objective comparison metric.

Table 2.3: Summary of the literature review

		Yan and Zhou (2003)	Wiendahl and Heger (2003)	Xiaobo *et al.*, (2000)	Rajagopalan *et al.*, (1998)	Bokhorst et al., 2002)	Spicer (2002)	Narongwanich (2002)	Amico et. al. (2003)	Amico et. al. (2001)	Son, (2000)	Abdi and Labib (2004)	Abdel-Malek and Wolf (1994)	Zhang and Gardon (2001)
General Methodology	Linear Prog.					√	√							
	Nonlinear Prog.													
	Dynamic. Prog				√			√						
	Evolutionary Alg.	√					√			√	√			
	Stochastic Model			√					√					
	Other		√									√	√	√
Features	Single Objective		√	√	√	√	√	√	√	√	√			
	Multiple Objective	√										√	√	√
	Reconfiguration Cost Computation		√	√		√	√							
	Uncertainty Incorporated		√	√					√			√		
	Manufacturing systems studied	FMS	RMS	RMS	Replacement.	FMS	RMS	RMS	RMS	RMS FMS DML	RMS	RMS	FMS	RMS

CHAPTER THREE

PROPOSED METHODOLOGY

This chapter presents an overview of the proposed methodology, its assumptions, inputs and outputs of the lifecycle evaluation tool that was developed in order to analyze RMS investments.

As indicated in section 2.5, the economic justification of advanced manufacturing technologies should incorporate both the economic and strategic objectives. Since RMS involve changing the configurations of the facility according to the fluctuating market conditions, the economic investment analysis should include multiple periods rather than initial investments only. Based on these characteristics of the problem, we can define the general requirements of a lifecycle evaluation methodology. The following section gives a description of the manufacturing system model and its basic assumptions. It will be followed by the description of the inputs, the outputs and the performance criteria. The overall model will then be represented using an IDEF0 model.

3.1. Manufacturing system representation

The premise of RMS is to provide the exact capacity and functionality required when needed to satisfy the demand level for a group of products. As mentioned in section 1.4, using the modular hardware and software capabilities of RMSs enables the means of adjusting capacity and functionality of the manufacturing system. Besides the fact that the RMS can be reconfigured to modify its characteristics, it can be considered as a conventional manufacturing system within a fixed configuration period.

The RMS model considered in this study includes a series of machines where each stage is represented by a unidirectional piece flow. Each stage consists of a set of machines assigned to accomplish a set of tasks defined according to a process plan. The types of the machines used within a stage can be different but the combined capacity and capability of the stage should provide the required demand level. A manufacturing system that consists of modular multi-spindle machine tools is considered. Each machine consists of a base structure to which several modules can be added or removed as capacity requirements change (Spicer, 2002). An addition or removal of a module might change the processing capability and/or capacity of the machine. An example of this is the addition of a spindle or machine head. It is assumed that the machine modules are functionally parallel; i.e., a machine can continue to operate even if one module fails. However, modules are functionally serial with the machine base. Therefore, if "the base" of the machine, which supports, integrates, and controls all modules fails, the whole machine and its modules fail. Figure 3.1 is an example configuration capable of producing multiple product types. The machines' processing capabilities change depending on the number of modules attached to each machine and this allows the production of a variety of parts.

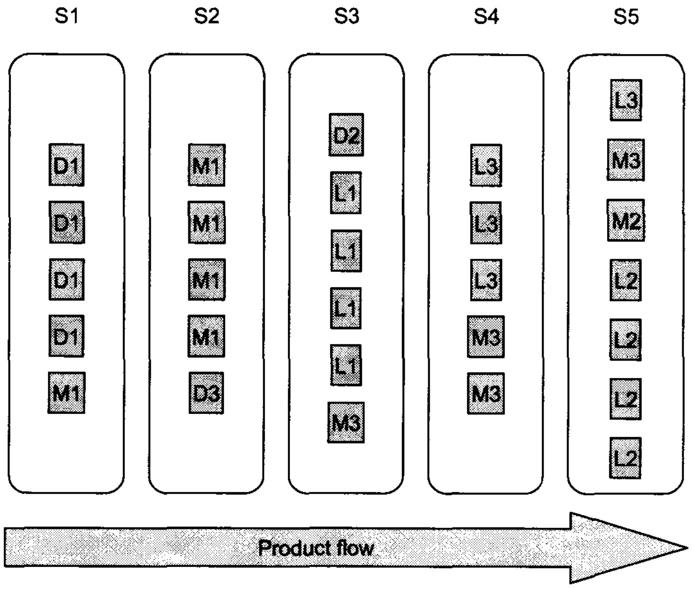


Figure 3.1 An example of Manufacturing System Configuration

As depicted in Figure 3.1, a system configuration consists of a series of stages where the same types of operations are performed within each stage. The stages can contain a set of machines that can be similar or identical. S stands for stage, while D, M, and L represent three types of machine bases which represent drill, mill and lathe respectively. The numbers associated with each machine base represent the number of modules attached to the base. For example, D3 represents a machine of drill base type with three modules. The modules that can be attached to each machine base type are limited to three and each module increases the ability to process operations and/or the production rate. The numbers and types of machines for each stage are determined based on the workload of each period.

3.2. Input parameters

The following information and parameters are assumed to be available in order to perform the proposed methodology.

3.2.1 Production periods

It is assumed that a candidate part family to be produced has been identified for a planned time horizon of T periods. During the planning horizon, the company must meet the demand requirements, D_{it}, for each product type i at each period t. It is assumed that a candidate part family to be produced has been identified for a planned time horizon. Usually, manufacturing companies cope with demand changes using other alternatives than reconfiguration of a manufacturing system. These alternatives are overtime, adding additional shifts, or outsourcing the excess demand to subcontractors. In order to incorporate these alternatives, the outsourcing option is considered in the lifecycle evaluation.

At each period, the sales price (P_{it}), materials cost (MC_{it}), and outsourcing cost (OC_{it}) for each product type is known. Based on this, information about annual profit from total sales can be calculated.

Table 3.1: Indices and parameters for sales related information

$i=1,\dots,I$	Product index
$j=1,\dots,J$	Operation index
$t=1,\dots,T$	Period index (e.g. week, month, year)
D_{it}	Demand of part type i at period t
P_{it}	Sales price of part type i at period t
MC_{it}	Material cost of part type i at period t
OC_{it}	Unit outsourcing cost of product i

3.2.2 Product processing and machine related input

The operations required for a product type *i* are denoted by the set *j*. These operations are performed by a machine type set *m* having a configuration *k* for each of its possible configurations. The machine type *m* represents three machine base types as described in section 3.1, and configuration state *k* represents the number of modules that a machine type has.

The operation capabilities are represented by an incidence matrix z_{ijmk} which assumes a value of one if operation *j* of part type *i* (i.e. operation (i,j)) can be processed by machine type m at configuration state k (i.e. machine (m,k)), and zero otherwise. During each production period, it is assumed that each machine type has a fixed available time denoted by AH_{mk}. In addition, the steady state availability of each machine (m, k) is denoted by r_{mk}. The setup and operation times of each operation (i, j) on machine (m, k) are denoted by ST_{ijmk} and p_{ijmk}, respectively. Since some setup is required to change over from one product type to the next, the orders are assumed to be processed in equal lot sizes noted as L_t. Similarly, the setup cost SC_{ijmk}, unit variable cost (VC_{ijmk}), and a fixed cost element (FC_{ijmk}) are specified for every operation capability. The following parameters listed in Table 3.2 provide the information on demand periods and product information.

Table 3.2: Parameters for process and machine related information

m=1,..., M	Machine type m
k=1,..., K	Machine configuration state k
r_{mk}	Steady state availability of machine (m, k)
AH_{mk}	Available time of machine (m, k)
z_{ijmk}	$\begin{cases} 1, \text{ if operation (i, j) can be processed on machine (m, k)} \\ 0, \text{ otherwise} \end{cases}$
p_{ijmk}	Process time of operation (i, j) on a machine (m, k)
L_t	Lot size
ST_{ijmk}	Setup time of operation (i,j) on a machine (m, k)
SC_{ijmk}	Setup cost of operation (i,j) on a machine (m, k)
FC_{jjmk}	Fixed cost of operation (i,j) on a machine (m, k)
VC_{jjmk}	Variable cost of operation (i,j) on a machine type (m, k)

3.2.3 Investment cost and reconfiguration activity inputs

During the lifecycle evaluation of RMS, activities such as reconfiguration, initial investment of machines, additional investments throughout the lifecycle and depreciation factors should be taken into account. The investment cost for each machine (IC_{mkt}) represents the actual sale price at the beginning of a period. Similarly, when a machine needs to be sold, because it is not needed, its sale value is defined by SV_{mkt}. The machines that are being used at each period are subject to depreciation according to accounting principles and this depreciation allows companies to reduce their income taxes paid. This results in additional cash flows to the company, therefore it should be included in the analysis. In this research, we assume that the machines are subject to straight line depreciation method with a rate defined by d_{mk}.

Reconfiguration activities during the lifecycle of a manufacturing system involve adding and/or removing machines and/or machine modules in order to adjust the configuration to the next period's demand requirements. In order to calculate the reconfiguration cost, the time to install and/or remove one machine base t_b and the time to install and/or remove one machine module t_{md} should be defined. In addition, the available workforce W_t and the labour rate LR are needed to compute the reconfiguration cost and duration. The reconfiguration cost is explained in detail in Chapter 6.

Table 3.3: Parameters for investment and reconfiguration cost

IC_{mkt}	Investment cost of a machine type (m, k) in period t
SV_{mkt}	Salvage value of a machine type (m, k) in period t
d_{mk}	Straight line depreciation factor for machine type (m,k)
LR	Labour rate ($/hr)
W_t	Available workforce in period t
t_b	Time to install/remove a machine base
t_{md}	Time to install/remove a machine module

3.3. Output / Decision variables

The output of the lifecycle evaluation approach is a group of manufacturing system configurations for each period of the planning horizon. The developed tool helps to determine in house production and outsourced product level that meets the required demand. In addition to the configuration details at each period by providing the number of machine types (m, k), the operations required for the products are allocated to the selected machines. This feature makes it possible to evaluate the RMS investments simultaneously considering the part allocation problem, which is usually analyzed separately from the investment analysis.

Based on the system configurations required in two consecutive periods, the tool provides the reconfiguration cost, the number of machine bases and machine modules needed to install/remove. The decision variables of the proposed model are presented in Table 3.4.

Table 3.4: Decision variables

X_{mkt}	Number of machine type m at configuration k in period t
M_{it}	Production quantity for part type i in period t
Q_{it}	Number of products i outsourced in period t
Y_{ijmkt}	Production quantity for operation (i,j) on machine (m,k) in period t
B_{mt}	Number of machine bases of type m in period t
MD_{mkt}	Number of modules for machine type m of configuration k in period t
DP_{mkt}	Depreciation charge for machine type (m,k) in period t
BV_t	Book value of the assets at the end of period t
RT_t	Reconfiguration task in period t
RC_t	Reconfiguration cost in period t
RD_t	Reconfiguration duration in period t

3.4. Performance criteria

As indicated in section 2.5, in order to analyze the investments in Advanced Manufacturing Technologies such as RMSs, both financial and strategic criteria should be considered. The following criteria have been selected in order to optimize the RMS lifecycle performance:

- Net Present Value (NPV) of after-tax cash flows
- Structural System Complexity
- Configuration responsiveness

As a financial performance criterion, the present worth of after-tax cash flows is the most suitable metric for a manufacturing system that requires investments or disinvestments along its lifecycle. The benefit of using the after-tax cash flows is that the reconfiguration activities can be incorporated into the metric, and it is a popular representation of the manufacturing system activities. The formulation details of this criterion are explained in chapter six.

The idea of implementing a production system that can be re-configured for the unexpected market changes in order to achieve the desired agility may result in systems suffering from an increased number of decisions that need to be made in order to meet the production requirements. This trend is one of the reasons why manufacturing systems have become more complex and difficult to manage. The structural system complexity criterion, helps selecting configurations that are simple and easy to manage. The proposed structural complexity metric is explained in chapter four.

Another strategic factor for today's manufacturing systems is to be able to respond to sudden demand changes. The responsiveness metric used in the proposed methodology evaluates the ability to change over from one product to the next one within a given configuration. The detail of this metric is given in chapter five.

Figure 3.2 provides an IDEF0 representation of the proposed methodology:

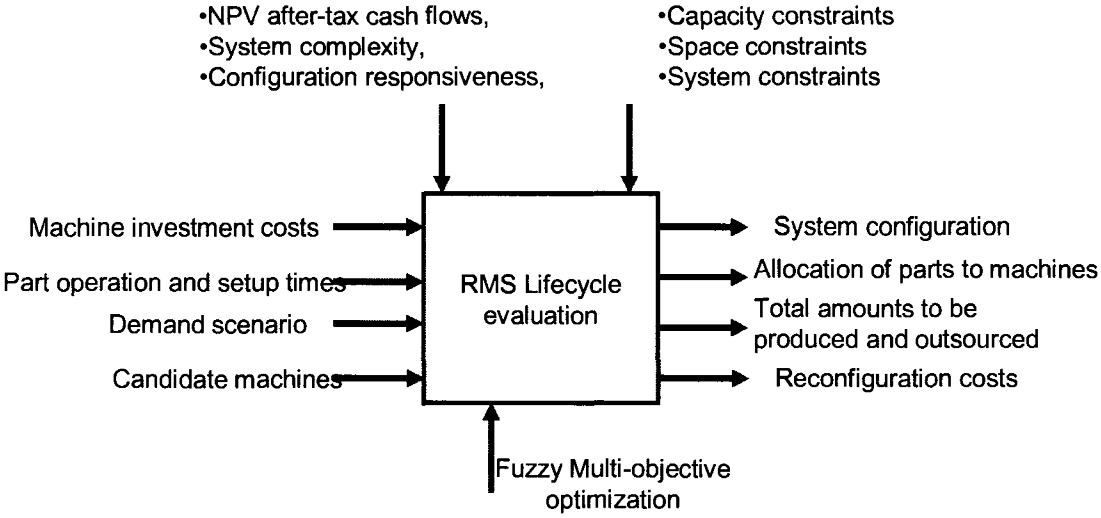


Figure 3.2 IDEF0 representation of the proposed methodology

3.5. Mathematical model

Real world situations are usually not deterministic, especially for justification problems involving future costs. In order to deal with the uncertainty issue, the cost parameters associated with RMS investments can be represented using fuzzy set theory. The uncertain nature of future investments can be represented by applying fuzzy set theory to the defined objective functions.

Incorporating uncertainty and the decision maker's preferences into the model can be done by converting the objective functions into fuzzy membership functions. Fuzzy membership functions are also important in terms of expressing the degree of satisfaction with the obtained solution. Furthermore, having each objective function's value within [0, 1] interval helps eliminate the drawback of using different scales and units.

Fuzzy linear programming was first introduced by Zimmermann (1978) to formulate the vagueness inherent in decision making problems in an efficient way. Consider the linear programming formulation given below:

$$\begin{aligned}&\text{Min } f(x)\\&\text{Max } g(x)\\&\text{Subject to:}\\&Ax \le b\\&x \ge 0\end{aligned} \tag{3.1}$$

When the objective function and the constraints are fuzzy, the corresponding fuzzy linear programming model is expressed as follows:

Find x such that

$$\begin{aligned}f(x) &\mathrel{\tilde{\le}} f_{\min}\\ g(x) &\mathrel{\tilde{\ge}} g_{\max}\\ Ax &\mathrel{\tilde{\le}} b\\ x &\ge 0\end{aligned} \tag{3.2}$$

where f_{min} and g_{max} defines the level to be achieved by the objective, and $\tilde{\le}$ implies the fuzziness of the objective function. In other words, an achievement level is determined for each objective function and the decision-maker allows for the violation of these levels. In order to introduce the fuzziness into the model, the following membership functions that express the vagueness are used.

$$\mu_i : \mathbf{R}^n \to [0,\ 1]$$

$$\mu_i(f(x)) = \begin{cases} 1 & \text{if } f(x) < f_{\min} \\ 1 - \dfrac{f(x) - f_{\min}}{f_{\max} - f_{\min}} & \text{if } f_{\min} \le f(x) \le f_{\max} \\ 0 & \text{if } f(x) > f_{\max} \end{cases} \tag{3.3}$$

$$\mu_i(g(x)) = \begin{cases} 0 & \text{if } g(x) < g_{\min} \\ \dfrac{g(x) - g_{\min}}{g_{\max} - g_{\min}} & \text{if } g_{\min} \le g(x) \le g_{\max} \\ 1 & \text{if } g(x) > g_{\max} \end{cases} \tag{3.4}$$

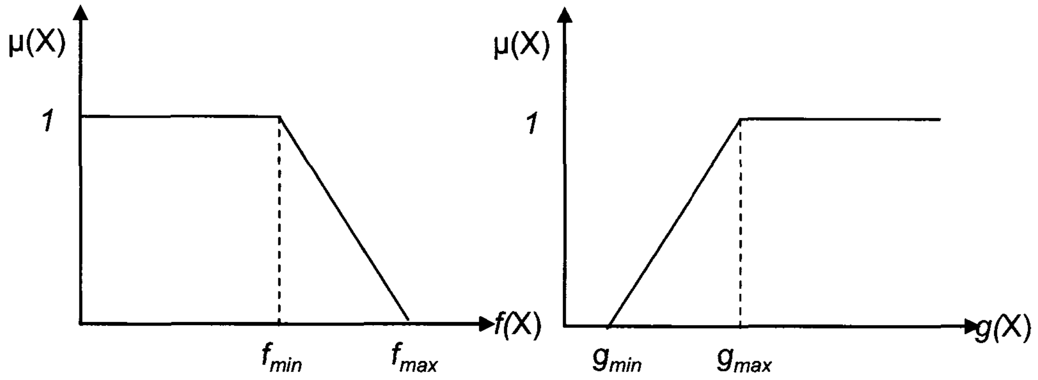


Figure 3.3 Membership functions for maximizing and minimizing type of objective functions

Maximising a decision in a fuzzy environment has been defined by Bellman and Zadeh (1970) using the following principle. Suppose there are a fuzzy objective function *f* and a fuzzy constraint *C* in a decision space *X*, which are characterized by their membership functions $\mu_f(X)$ and $\mu_C(X)$, respectively. The combined effect of those two can be represented by the intersection of the membership functions as shown in Figure 3.4 and the following formulation:

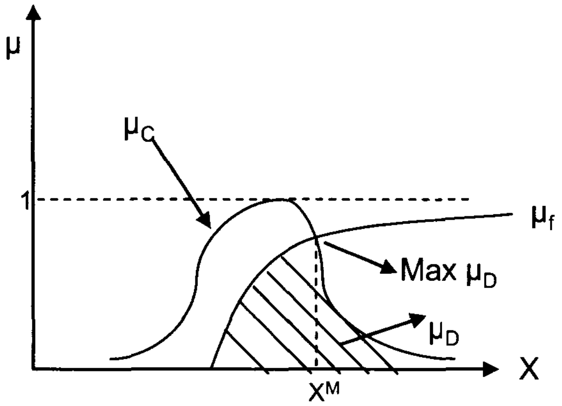


Figure 3.4 The relationship of μ_f, μ_C and μ_D in fuzzy decision making

$$\mu_D(x^*) = \max_x \min_i \left[\mu_1(x), \ldots, \mu_m(x)\right] \tag{3.5}$$

A fuzzy linear program can be transformed to a classical linear programming formulation as follows

$$\begin{aligned} &\text{Max } \lambda \\ &\text{Subject to:} \\ &\lambda \le 1 - \frac{f(x) - f_{\min}}{f_{\max} - f_{\min}} \\ &\lambda \le \frac{g(x) - g_{\min}}{g_{\max} - g_{\min}} \\ &0 \le \lambda \le 1 \\ &Ax \le b \\ &x \ge 0 \end{aligned} \tag{3.6}$$

As seen in (3.6), a fuzzy multiple objective optimization model allows incorporating several objectives along with constraints. Model (3.7) represents the proposed methodology by the decision variables and the objective functions depicted in Figure 3.2.

$$
\begin{aligned}
&Max\ \lambda \\
&\text{Subject to:} \\
&\lambda \leq 1 - \frac{Complexity(X_{mkt}) - Complexity_{\min}}{Complexity_{\max} - Complexity_{\min}} \\
&\lambda \leq \frac{Responsiveness(X_{mkt}) - Responsiveness_{\min}}{Responsiveness_{\max} - Responsiveness_{\min}} \\
&\lambda \leq \frac{NPV(X_{mkt}, Y_{ijmkt}, M_{it}, Q_{it}, RC_t, BV_t) - NPV_{\min}}{NPV_{\max} - NPV_{\min}} \\
&0 \leq \lambda \leq 1 \\
&Ax \leq b \\
&x \geq 0
\end{aligned}
\tag{3.7}
$$

The maxmin approach allows satisfying each objective with an overall satisfaction degree of λ. In addition, the use of fuzzy membership functions permits representing various types of objectives with different scale units. The approach is also useful in terms of incorporating the decision maker's preferences on the desired performance levels for each objective. In summary, the model can help solve the problem depicted in Figure 3.2. The next chapter presents the first objective in the proposed methodology, structural complexity of manufacturing system configurations.

CHAPTER FOUR

COMPLEXITY IN MANUFACTURING SYSTEMS

Today's competitive manufacturing environment forces companies to be responsive to changes in the market and satisfy the need for mass customization through flexibility and adaptability in order to survive and be globally successful. Companies strive to increase their range of products and implement a production system that can be re-configured for the unexpected market changes in order to achieve the desired agility. This trend is one of the reasons why manufacturing systems have become more complex and difficult to manage. Wiendahl and Scholtissek (1994) have reviewed the sources of complexity in production systems and pointed out the various approaches adopted by industry as well as those developed by the research community to cope with complexity in manufacturing systems.

4.1. Reconfigurable manufacturing systems and complexity

Unlike traditional manufacturing systems, RMS can be achieved by using reconfigurable hardware and software, such that its capacity and/or functionality can be changed over time. The reconfigurable components include machines and material handling systems, mechanisms and modules for individual machines, as well as sensors, process plans, production plans, and system control algorithms for entire production systems.

The reconfiguration of a manufacturing system is considered whenever there is a new circumstance that warrants such a change. These circumstances may be changing product demand, the introduction of new products, or the integration of new process technology into existing manufacturing systems. There might be several configuration alternatives to consider before selecting a new configuration. The objective is to adapt to the new conditions without unduly increasing the system cost or complexity, or degrading the resulting product quality.

4.1.1 Manufacturing systems complexity

Manufacturing systems are often described as being complex. The dynamic nature of the manufacturing environment greatly increases the number of decisions that need to be made and the integration of many software and hardware functions makes it difficult to predict the effect of a decision on the system performance.

A complex system is one whose static structure or dynamic behavior is counterintuitive or unpredictable (Deshmukh et al., 1998). Complex systems share certain features such as comprising a large number of elements, having high dimensionality, and representing an extended space of possibilities. The causes of complexity should be analyzed in order to be able to cope with decision-making difficulties in integrated manufacturing systems. The increase in complexity due to the introduction of new technologies and the integration of different components of manufacturing systems is only justifiable by improved system performance otherwise complexity should be minimized.

4.1.1.1 Entropy/Information content approach

There are two main approaches in published literature to quantify systems complexity. The first uses Shannon's (1949) information theory/entropy approach. Researchers such as Deshmukh et al. (1998), Frizelle and Woodcock (1995), and Sivadasan et al. (2006) define the notion of static complexity and dynamic complexity based on the entropy formula. Static complexity accounts for the structure of the components of a system and the relationships among them whereas dynamic complexity deals with the operational behavior and schedule changes of the system. The static complexity of a system S can be measured by the amount of information needed to describe the system and its components

$$H(S) = -\sum_{i=1}^{M}\sum_{j=1}^{N} p_{ij}\log_2(p_{ij}) \tag{4.1}$$

where

S = System S

M = number of resources

N = number of possible states for the ith resource

p_{ij} = probability of resource i being in state j

Information entropy is derived from the concept of information. This concept is developed in information theory, primarily as applied to communications. Since the base is 2 in (4.1), then $H(S)$ has units of bits. Because of its simplicity, information content or information entropy has been applied in many areas where measuring uncertainty is important.

Zhang and Efstathiou (2004) assess the complexity of mass customization systems consisting of a push line and a pull line where an inventory area is used as a decoupling point between the two. In their multi-product supply chain model, the probability of each resource state is defined by the probability of producing a product at a specific time. The authors assumed, due to the lack of data, the worst-case scenario where all events have the same probability of occurrence, which leads to maximum complexity.

Another entropy approach to measure complexity is the information content concept in Axiomatic Design (Suh, 1999). Suh's complexity metric is defined as a measure of uncertainty in achieving the functional requirements of a design task.

Based on this definition, the variable p in equation (4.1) is defined as the probability of success of the design parameters in meeting the functional requirements. Suh classifies complexity into two categories: time-independent complexity and time-dependent complexity. This is similar to Frizelle and Woodcock's (1995) classification of static and dynamic complexity. In addition, time-independent complexity is further decomposed to add the complexity arising from the designer's perception. The time-dependent complexity is either combinatorial or periodic. It has been proposed that converting combinatorial complexity to a periodic one re-sets and reduces the time dependent complexity. This approach to modeling dynamic complexity provides insight and guidelines to reduce complexity rather than assessing it with a metric. The metrics provided by using Axiomatic Design are for both time-independent real and imaginary complexities.

Information theory based measures of system complexity provide objective data. However, two important issues should be considered when applying the entropy approach. The first is related to determining which event to use in order to describe the state of a system component. The second is the deficiency arising from the assumptions of independence between system components made in the entropy approach to simplify the formulation. In reality, system components usually have some interdependencies; hence, Bayesian probabilities should be used. The resulting equation to measure the information content would be very complex for a system with many components. In Suh's (1999) approach, similar issues arise for decoupled designs where it may be difficult to define the design requirements' range.

4.1.1.2 Heuristic approaches/indices

The second approach to quantify systems complexity is to use heuristics and develop indices. Kim (1999) addresses the issue of manufacturing systems complexity considering the increase in product variety and the need to reduce the system complexity arising from it. The author claims that in lean manufacturing, system complexity as affected by increased product variety is much less than in an equivalent mass production system. In order to prove this thesis, a series of system complexity measures were proposed based on a complexity model developed from a systems theory perspective including:

- *Relationships between system components*
  - Number of flow paths
  - Number of crossings in the flow paths
  - Total travel distance of a part
  - Number of combinations of products and matching machines
- *Elementary system components*
  - Number of elementary system components
  - Inventory level

Each one of the above variables provides some insight into the effect of various components of a manufacturing system structure. The fact that these elements are not combined into a single system complexity metric makes it difficult to compare system configuration alternatives. In addition, a classification or relative importance of these factors was not developed, hence it is difficult to compare.

ElMaraghy and Urbanic (2004) provide a heuristic model where a process complexity metric is proposed and used to compare different manufacturing methods for a single product. This model differs from the previous studies by combining the absolute quantity of information, the diversity of information and information content, i.e., the “relative” measure of effort, and the human operator perception of an operation complexity to achieve the required result. The three elements of manufacturing complexity are decoupled and re-linked using a systematic, simple, and concise methodology. From this point of view, the metric provides a hybrid approach that combines indices and entropy to measure the complexity for manufacturing operations and processes and takes into consideration the human perception. The proposed process complexity does not take into account some system level components such as transporters and buffers, and the complexity arising from their operation and management.

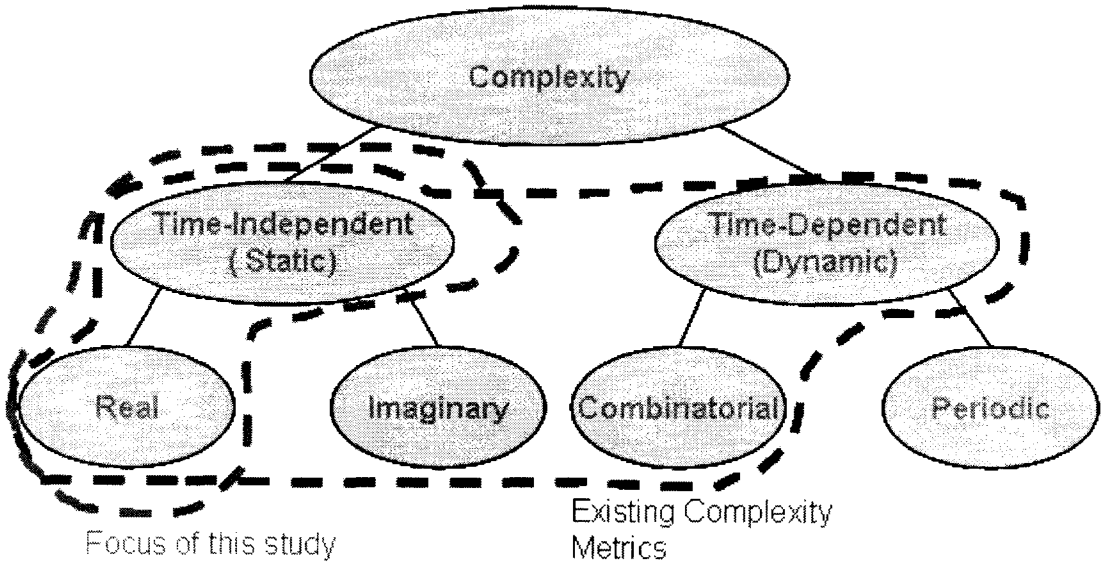


Figure 4.1 Classification of Complexity (ElMaraghy et al., 2005)

Previous studies on assessing the complexity of manufacturing systems have focused on: a) the entropy based generalized objective metrics, and b) case dependent subjective indices. The entropic measures provide objective means of comparing systems, whereas the heuristic indices provide a better insight into the effects of system elements. There seems to be a lack of a comprehensive metric that combines both the amount of information and the type of information needed to describe a system complexity.

4.2. Measuring the manufacturing systems complexity

The reported research (Kuzgunkaya and ElMaraghy, 2006; ElMaraghy et al., 2005) addresses the time-independent structural complexity of the building blocks of a manufacturing system including machines, transporters, and buffers. It captures the complexity arising due to their structural characteristics, used technologies and degree of operational difficulty. These inherent complexities are particularly important at the initial system design stages where alternative equipment and technologies may be considered with potentially major different cost implications. There are two phases in designing a manufacturing system. The first is the selection of the type, features and number of pieces of equipment that all have varying degrees of complexity based on the amount of information required to operate, program and use them. This is the static structural design phase, where the proposed complexity metric would be used to help select equipment keeping their inherent complexity in mind. The second phase further details the system design, equipment placement, the flow pattern and fine tune the number of pieces of equipment based on the operation characteristic of the system as a whole and its dynamic behavior and interaction between its modules. This is where discrete events and other simulations and several tools such as balancing techniques would be used. The proposed manufacturing system configuration complexity metric does not assess complexities arising from the system dynamic behavior including scheduling, bottleneck, throughput, production capacity and the like.

The manufacturing system complexity notion is defined by the uncertainty level related to determining its state. Internal and external disturbances are a source of complexity in a manufacturing system. Disturbances such as equipment failure or shortage of WIP increase the operational difficulty. Hence, a system structure that is more likely to generate such disturbances, due to its technology or structural design, is considered more complex. The results of this work will help designers/researchers in their effort to quantify the effect of this complexity on the system performance.

The following section defines the manufacturing system representation for evaluating the complexity, and it will be followed by an explanation of how the various components and technologies contribute to the overall complexity of manufacturing systems.

4.2.1 Proposed system complexity metric

Since the selection of a manufacturing system configuration is made in the early design stages, a structural complexity index provides a good description of the inherent complexity of its components, the relationship among them, and their influence. Dynamic complexity is more applicable to the system time-dependent behavior and requires data normally obtained during actual operations or simulation of the shop floor. The proposed complexity measure is an entropy-based index that uses the reliability of each machine to describe its state in the manufacturing system, combined with an equipment type code index coefficient to incorporate the effect of the various hardware and technologies used. In addition to the state of each machine in the system, transporters and buffers also introduce complexity since their utilization needs to be managed in order to run the production without disruption. Since each resource in a manufacturing system is a potential source of uncertainty (i.e., complexity), the buffers should be considered as well as the material handling systems and their type. Based on these considerations, the total complexity of an RMS is a function of (Kuzgunkaya and ElMaraghy, 2006):

- Number, type, and state of machines
- Number, type, and the state of buffers
- Number, type, and state of the material handling system and its components

$$H_{RMS} = w_1 H_M + w_2 H_{Buffer} + w_3 H_{MHS} \tag{4.2}$$

where H_M represents the complexity arising from the machines, H_{Buffer} is the complexity of buffers, and H_{MHS} represents the material handling system complexity. w_1, w_2, and w_3 represent the relative weight of the elements that contribute to the overall complexity. It is believed that all three contributors to the structural complexity are equally important. For example, in a manufacturing system where the components are functionally serial, the failure of the material handling system can cause the disruption of the production and increase the complexity. However, these weights can be used should a reason exist to differentiate between various elements by varying the components' relative degree of importance (Fujimoto *et al.*, 2003). These weights can be used to reflect the system designer's subjective preferences based on experience and where tools such as the Analytic Hierarchy Process (AHP) can be used to determine them.

4.2.1.1 Machine complexity metric

The following equation expresses the complexity due to the machines:

$$H_M = \sum_{i=1}^{M} \sum_{j=1}^{N} X_{ij} a_{ij} \sum_{k=1}^{2} p_{ijk} \log_2\left(\frac{1}{p_{ijk}}\right) \tag{4.3}$$

where

p_{ijk}= Probability of a machine's state at stage i of machine configuration j

a_{ij} = Type index of machine X_{ij}

X_{ij} = number of machines in stage i at machine configuration j

N = maximum number of modules installed in a machine

M = number of stages in a system configuration

The probability of a machine that is in operating condition, p_{ijk} is calculated based on the machine configuration assumptions explained in section 3.1. Each machine consists of a base structure to which several modules can be added or removed as capacity requirements change (Spicer, 2002). An addition or removal of a module might change the processing capability and/or capacity of the machine. An example of this is the addition of a spindle or machine head. It is assumed that the machine modules are functionally parallel; i.e., a machine can continue to operate even if one module fails. However, modules are functionally serial with the machine base. Therefore, if "the base" of the machine, which supports, integrates, and controls all modules fails, the whole machine and its modules fail. Figure 4.2 represents the functionality relationship of described machines. It is assumed that any component of a machine can have two states: operation or failure. The failure and reliability calculation for each machine configuration is represented in (4.4).

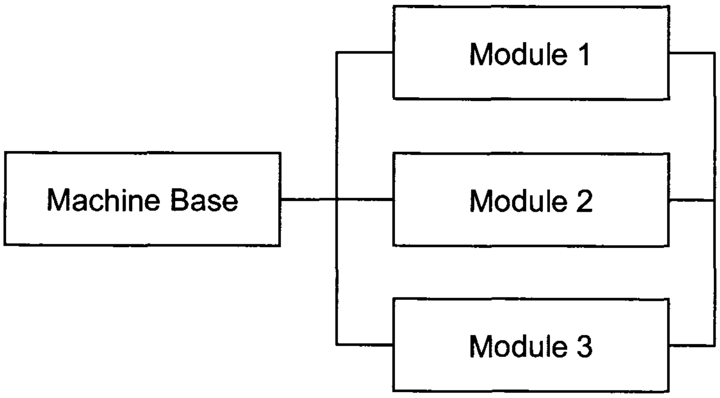


Figure 4.2 Functional relationship of machine components

$$\begin{cases} p_{ij1} = R_B\left(1-\prod_{i=1}^{n} U_i\right) & \text{, Reliability of a machine with configuration j} \\ p_{ij2} = 1 - p_{ij1} & \text{, failure probability of a machine with configuration j} \end{cases} \qquad (4.4)$$

where

R_B = the reliability of the base

U_i = failure probability of a module i

n = the number of modules installed in the machine

Based on equation(4.3), the machine complexity metric has been defined by the entropy of a two-event system, the states of which have been defined by (4.4). Since the entropy of any two events state system is symmetric about ½, two identical machines with reliability values of 0.7 and 0.3 represent the same uncertainty level. If the dynamic system behavior is considered, then the machine that has higher reliability should be selected based on its throughput performance. However, for the static complexity notion of a manufacturing system, which is defined by the uncertainty level with respect to defining its state, the two machines are equally complex.

As stated previously, the type of each machine and its features affect the complexity of a manufacturing system. A multi-purpose machine has many features and each feature can offer different options. The increase in different setting possibilities will also increase the complexity of operating and programming a machine; therefore, the more flexible the machine, the more complex it is. The index a_{ij} used in equation (4.3) reflects the differentiation between various equipment types and their technologies, and its computation is presented in section 4.2.2.

4.2.1.2 Buffer type complexity

The second component of a manufacturing system complexity is related to the buffers. In a manufacturing system consisting of M stages there could be a maximum of (M-1) locations for the buffers. It is assumed that the number of product variants that can exist in the system is k, and that the variants are being produced in batches. In order to describe the state of the buffers, two aspects are analyzed (Zhang and Efstathiou, 2004):

$$H_{Buffer} = H_{B1} + H_{B2} \tag{4.5}$$

H_{B1}, The state of the buffer i.e. whether it is empty or not.

H_{B2}, The product variant in the system

The complexity caused by the empty/non-empty state in each location, H_{B1} is calculated as follows:

$$H_{B1} = \sum_{i=1}^{M-1} b_i (p_{ine} \log_2(\frac{1}{p_{ine}}) + p_{ie} \log_2(\frac{1}{p_{ie}})) \tag{4.6}$$

where

p_{ie} = Probability of ith buffer being empty

p_{ine}= Probability of ith buffer being non-empty

b_i= Buffer type index

M-1 = number of buffers = number of stages - 1

The role of buffers in a manufacturing system is to provide storage for WIP and also to ensure that the downstream operations are not starved and the production is not disrupted. The key concern is to have sufficient quantity of WIP in order to run the production. In a push type manufacturing system, an empty state of a buffer means the accumulation of WIP in the upstream processes, starvation of downstream processes, and as a result, the disruption of the production. This state of a system would lead to complexity related to managing its use, programming and operation to ensure sufficient supply of parts.

Therefore, the two "empty" and "non-empty" buffers states represent two critical states, which affect the complexity of using and operating these modules of a production system.

The probability of a buffer being empty or non-empty may not be available at the early design stages of a manufacturing system. These probabilities can be estimated by using simulation approaches or can be set to a pre-determined value. Other studies related with finding the steady state probabilities for buffer states used simulation, Markov chain and Markov process formulations, which are beyond the scope of this study (Kouikoglou, 2002; Baral, 1993). This shows that such quantities can be estimated for various types of manufacturing scenarios including push, pull, cellular etc...

The metric proposed in this work (Kuzgunkaya and ElMaraghy, 2006) deals with push type and batch style manufacturing where it can be assumed that the production stops when WIP level at any location is zero. Moreover if we look at the economic order quantity (EOQ) model where a deterministic constant demand scenario is considered, the average level of inventory is ½ of the inventory capacity. This means that the frequency of having an empty and full buffer is equally probable. A paper by Zhang and Efstathiou (2006) has been recently published where they analyze the complexity of different types of inventory strategies with EOQ model. Another way of defining these probabilities is to consider the worst-case scenario for the buffers where, in the limit, it reaches the maximum level of complexity.

In a system where two events exist to describe the state of buffers, the maximum complexity arises when their probabilities of occurrence are equal. Figure 4.3 shows that the maximum complexity is equal to 1 for each buffer location. As a result, H_{B1} would be equal to the number of buffers in that system.

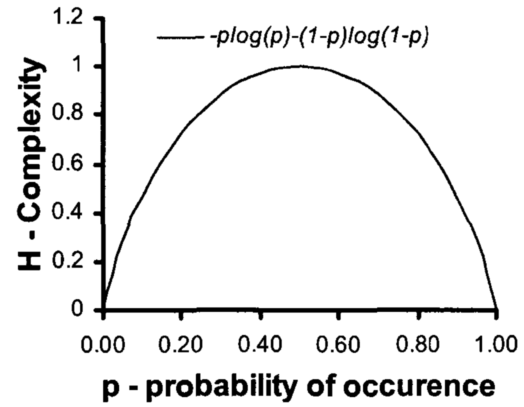


Figure 4.3 Entropy reaches maximum when both events have equal probability of occurrence

In order to calculate H_{B2}, the complexity caused by the assignment of the product variant in the system can be expressed as:

$$H_{B2} = \sum_{i=1}^{M-1} \sum_{j=1}^{k} p_{ij} \log_2(\frac{1}{p_{ij}}) \qquad (4.7)$$

where

p_{ij} = Probability of the ith buffer containing product variant j

k = Number of product variants

M-1 = number of buffers

In batch production, the buffers can contain any product variant at a point of time where a decision needs to be made regarding the schedule and the sequencing of the production. Hence, it is necessary to know which variant exists in a buffer. The uncertainty here is represented by the quantity of information that is required to determine the amounts of WIP in various buffers of a system for a specific product variant.

In a dedicated storage buffer system, each item is stored in specific locations in the factory, which, from a configuration design perspective, means that the capacity at each location must be sufficient to accommodate its highest expected inventory level. However, automated storage and retrieval systems (AS/RS) provide a centralized random access strategy where the items are stored in any available location. The flexibility of AS/RS's reduces the floor space used for storage. In addition, automated systems improve the control and management of inventory levels, thanks to their computerized control system.

The index b_i used in equation (4.6) differentiates between various storage technologies and strategies used in manufacturing systems based on their type complexity. A higher digit value for buffer Type Code represents increased options for managing buffers, and hence, increases their complexity. The introduction of this new type index captures the complexities inherent in different buffer strategies, technologies, and management, in addition to the state of buffers that was accounted for earlier.

4.2.1.3 Material handling systems complexity

Material handling systems (MHS) provide flexibility depending on their features. A uni-directional conveyor would only provide one fixed route whereas a self-guided AGV can provide several options for alternate process plans as well as alternative routing to cope with machine failures. In order to capture these differences, the complexity of various MHS technologies and types is represented similarly to the machine types.

The complexity of material handling systems is calculated as follows:

$$H_{MHS} = \sum_{t=1}^{T} m_t \sum_{k=1}^{2} p_{tk\,MHS} \log_2(\frac{1}{p_{tk\,MHS}}) \qquad (4.8)$$

where

$p_{tk\,MHS}$= Reliability of MHS

m_t = MHS type index

T = number of transporters used in MHS

k = state of transporter t

The T in (4.8) represents the number of transporters used in the system. In the case of conveyors, it is the sum of the number of conveyor segments used. For example, three conveyors are required in a system that includes three parallel machines. For a uni-directional flow line where the stations are placed along the conveyor, it is considered as one transporter only. In a manufacturing system where AGVs are used, T is the total number of AGVs.

4.2.2 Type Complexity of Machines, Buffers, and MHS

A new manufacturing system Group Technology like code developed by ElMaraghy (2006) represents the information required to describe the various types of equipment. Digits within each field are used to represent: 1) Type and general structure, 2) Controls, 3) Programming, and 4) Operation of a system component or module. The number of such resources and variety within a class all add to the overall required quantity of information to use and control them.

The classification part of the developed type code is only summarized here as it is used to formulate the modules type complexity index. The code uses a string representation to capture the main sources of inherent structural machine complexity. The first field describes the component type or structure. The control, programmability and operation features are captured in the second, third and fourth fields respectively. The developed code accounts for the main modules in manufacturing systems: machines of various types, transporters and buffers. Any other components that cannot be considered under these categories are not included at present. The type fields for machines, buffers, and material handling systems are shown below. *V* represents the total number of the sub-components represented by each digit.

4.2.2.1 Machine type code

Table 4.1: Machine Type Code Representation

Machine Type Code – Field 1									
				Tooling			Fixtures		
Structure	Axes	Heads	Spindles	Fixed	Adjust.	Tool Magazine	Fixed Pin	Special	Buffers
V_{d1}	V_{d2}	V_{d3}	V_{d4}	V_{d5}	V_{d6}	V_{d7}	V_{d8}	V_{d9}	V_{d10}

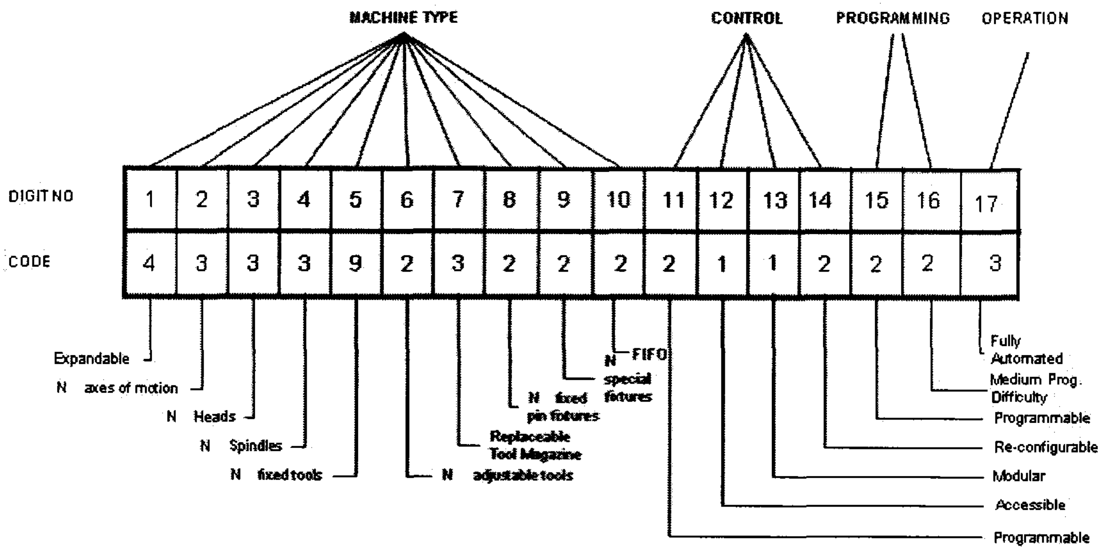


Figure 4.4 A complete machine code complexity string for a multi-axis multi-spindle machine tool (ElMaraghy, 2006)

Table 4.2: The Machines Complexity Type Code (ElMaraghy, 2006; ElMaraghy et al., 2005)

Digit No.	Value	Description
1		*Structure*
	1	fixed/dedicated
	2	fixed/modular
	3	expandable/dedicated
	4	expandable/modular
2	1	axes of motion
3	2	heads installed
4	2	spindles
5	0	fixed tools
6	60	adjustable tool
7		*Tool Magazine*
	0	none
	1	fixed
	2	replaceable
8	4	fixed pin fixtures
9	0	moving pin/supports fixtures
10		*Integrated Buffers*
	0	none
	1	FIFO
	2	indexing table

In order to compute the coefficient a_{ij} in (4.3), the type and general structure field is converted/aggregated into a single number using the following formulation, which normalizes the value of each digit and each field:

$$a_{ij} = \frac{\sum_{d=1}^{ND} \frac{V_d}{MV_d}}{ND} \tag{4.9}$$

where

V_d = Value of digit d

MV_d = Maximum value of digit d

a_{ij} = Type of machine X_{ij}

ND = Total Number of Digits for the field

The converted type coefficient a_{ij} represents the relative complexity of a machine compared to the most complex machine type defined by the proposed code representation. The following values are considered reasonable maximum values for the features represented in the code. The numbers used in the coding system are based on best available data and experience. As more research and data become available, these numbers can be refined. But since the same numbers are used for all systems being considered, they are good enough for the purpose of comparing systems, much like the constants used in applying the DFA analysis method. These upper limits may change as machine technology evolves. In the type complexity code, the degree of complexity of various pieces of equipment in each range has been defined and ranked to capture the increasing number of choices and decisions to be made for that characteristic of a machine, buffer, or MHS.

Maximum Machine Type Code									
				Tooling			Fixtures		
Structure	Axes	Heads	Spindles	Fixed	Adjustable	Tool Magazine	Fixed Pin	Special	Buffers
4	5	4	4	100	160	2	20	10	2

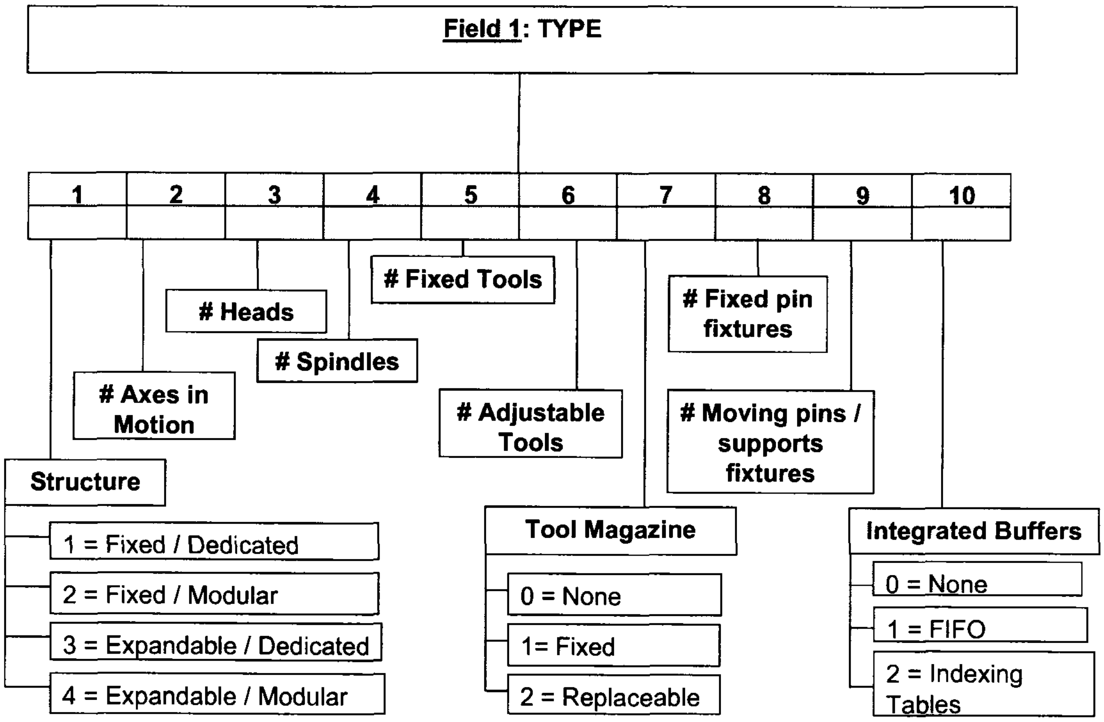


Figure 4.5 Machine complexity code, type field (ElMaraghy, 2006)

As an example, consider the multiple-spindle horizontal machining centre shown in Figure 4.6 (www.sw-machines.com/en/indexe.html). The corresponding machine type code would be:

1. A machine with fixed structure
2. 4 axes of motion
3. 2 heads installed
4. 2 spindles
5. 0 fixed tools
6. 60 adjustable tool
7. 1 - Fixed tool magazine
8. 4 fixed pin fixtures
9. 0 moving pin/supports fixtures
10. 0 - no integrated buffers

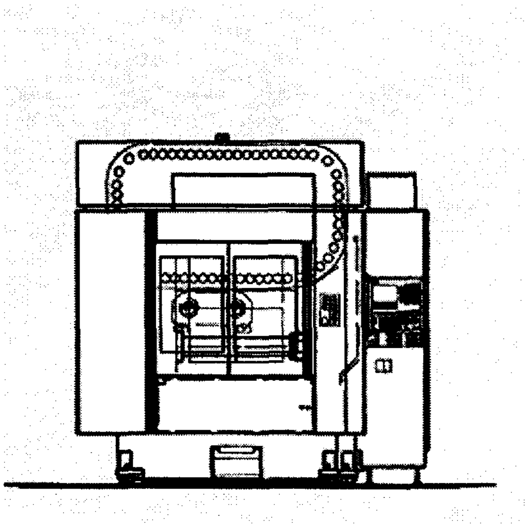


Figure 4.6 Horizontal Machining Centre

The type code string for this machine is:

1	4	2	2	0	60	1	4	0	0

Using the formula in Equation(4.9), the machine type complexity index is evaluated as follows:

$$a_{ij} = \frac{\left(\frac{1}{4}+\frac{4}{5}+\frac{2}{4}+\frac{2}{4}+\frac{0}{100}+\frac{60}{160}+\frac{1}{2}+\frac{4}{20}+\frac{0}{10}+\frac{0}{2}\right)}{10} = 0.31 \qquad (4.10)$$

Another machine configuration, shown in Figure 4.7, has been described using the type code index

http://www.komaprecision.com/tsudakoma/%20Tsudakoma%20Main.htm):

1. 4 A machine with modular expandable components
2. 3 axes of motion on the spindle column
3. 1 head installed
4. 4 Horizontally mounted modular spindles with automatic tool changers with the capability to have 1 to 4 spindles
5. 4 fixed tools
6. 160 adjustable tools
7. 1 Capability to machine one face of a cylinder head at one angle of orientation per fixture set-up. Fixed tool magazine
8. 4 fixed pin fixtures
9. 6 moving pin/supports fixtures
10. 0 no integrated buffers

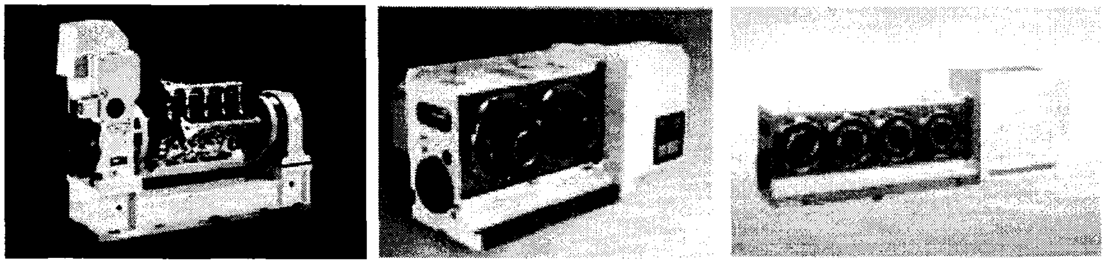


Figure 4.7 Multi spindle rotary table machining centre

The type code string for this machine is:

1	4	2	2	0	60	1	4	0	0

Using the formula in Equation(4.9), the machine type complexity index is:

$$a_{ij} = \frac{\left(\frac{4}{4}+\frac{3}{5}+\frac{1}{4}+\frac{4}{4}+\frac{20}{100}+\frac{160}{160}+\frac{1}{2}+\frac{4}{20}+\frac{6}{10}+\frac{0}{2}\right)}{10} = 0.54 \qquad (4.11)$$

The comparison of these two machines shows that as the capability of a machine increases, the value of the machine type code index also increases. The first machine has a fixed structure, fewer numbers of spindles, and a reduced tool holding capacity. The second machine is able to handle more tasks than machine 1 based on increased number of heads, installed spindles, and fixture features; hence, the value of the type code is higher as illustrated in Figure 4.8.

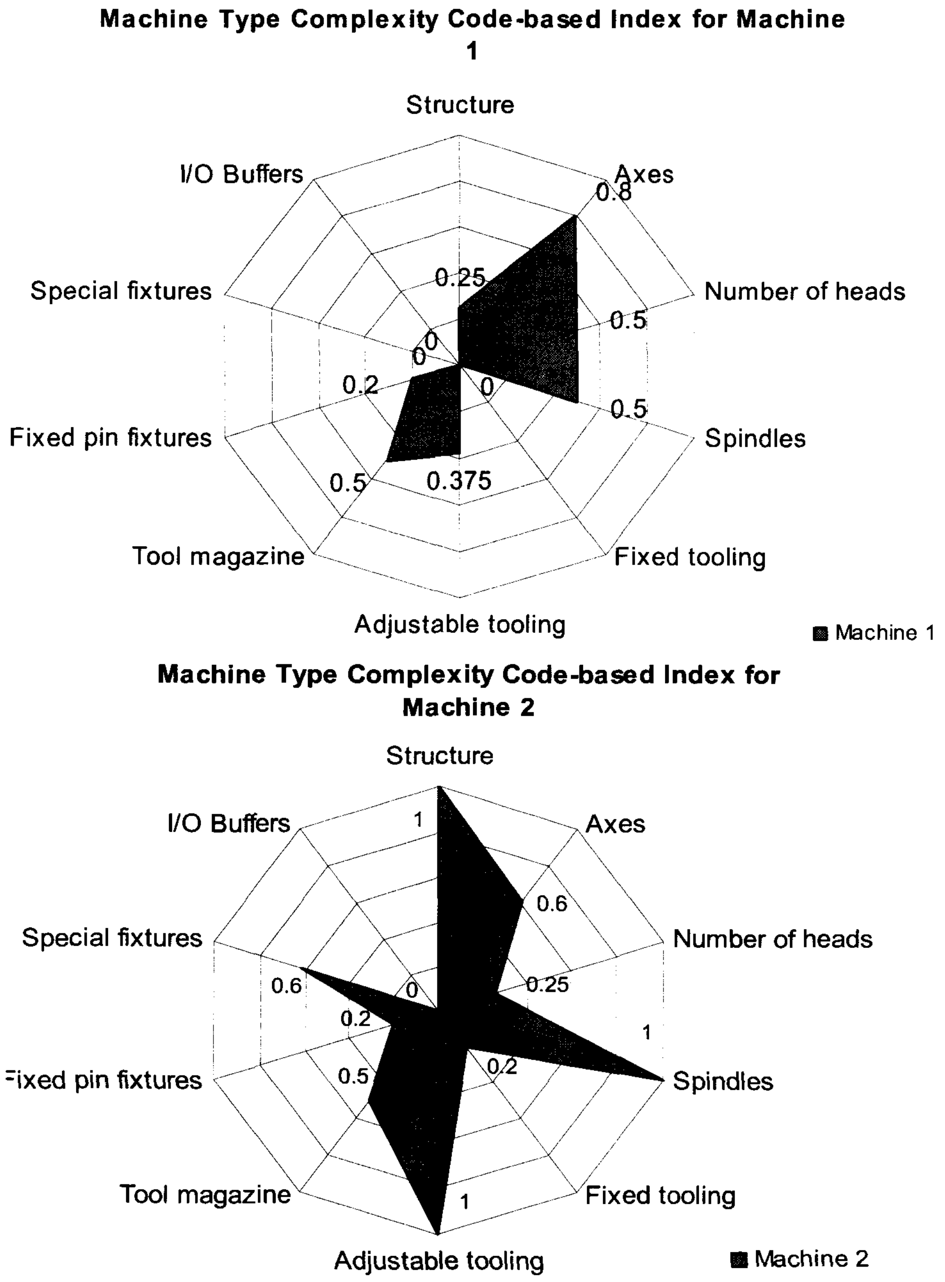


Figure 4.8 Relative Complexity presentation of different machine types

In Figure 4.8, the shaded area represents the overall complexity degree of each machine with respect to the most complex instance of machine. The larger the shaded area in a machine code representation, the more complex the machine is. The type complexity code index of machine 2 is equivalent to 0.54 on a 0 to 1 scale. The higher the value of each digit the more complex the machine, and this index means that the type complexity of the considered machine is 54% compared with the most complex machine that can be represented by this code format, which is a function of the maximum value of each code digit.

4.2.2.2 Buffer type code

The type index b_i, in Equation (4.6), is used in order to differentiate between the various types and technologies of buffer used in a system. It is calculated in a manner similarly to the machine type index using the following buffer type code representation (ElMaraghy, 2006) and Equation (4.9):

Table 4.3: Buffers Type Code Representation

Buffers Type Code – Field 1		
Buffer Structure	Equipment Technology	Capacity
V_{d1}	V_{d2}	V_{d3}

Table 4.4: Buffer Type Code (ElMaraghy, 2006)

Digit No.	Value	Description
1		*Buffer Structure*
	1	manual
	2	FIFO
	3	LIFO
2		*Equipment Technology*
	1	Magazine(dedicated)
	2	Carousel (dedicated)
	3	Random access system
3		*Capacity*
		Storage capacity

4.2.2.3 MHS Type code

The type index for MHS, m_t, is calculated using the following code representation and Equation(4.9).

Table 4.5: MHS type code representation

Material Handling Systems Type Code – Field 1		
Structure	MHS equipment used between stages	MHS equipment used within process/cell
V_{d1}	V_{d2}	V_{d3}

Table 4.6: MHS Type Code (ElMaraghy, 2006)

Digit No.	Value	Description
1		*Conveyor Structure*
	1	un-powered (gravity)
	2	powered, unidirectional, synchronous
	3	powered, unidirectional, asynchronous
	4	powered, bi-directional, synchronous
	5	powered, bi-directional, asynchronous
2		*Equipment Technology among processes*
	1	Manual
	2	Conveyor
	3	Gantry robots
	4	Guided rail vehicles
	5	Automated guided vehicles
3		*Equipment Technology within process/cell*
	1	Manual
	2	Conveyor
	3	Gantry robots
	4	Guided rail vehicles
	5	Automated guided vehicles

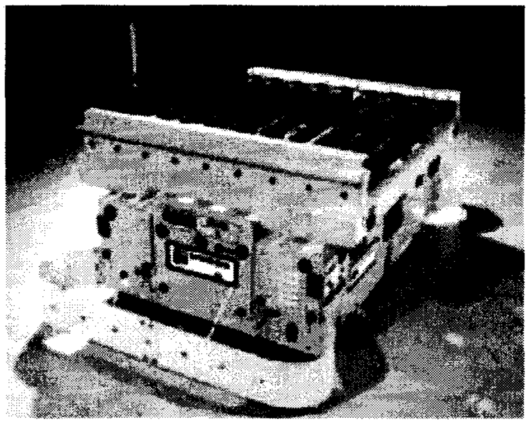


Figure 4.9 AGV
(http://www.hksystems.com/brochures/products/unit_load_agv.pdf)

The type index code captures various MHS technologies used in a manufacturing environment. A belt conveyor can transport work-in-process inventory between the stages; however, its failure would result in a serious disruption of the material flow. The use of AGVs provides several benefits such being part of a centralized storage retrieval system, more flexible routing of products, and ability to continue production despite the failure of single AGV.

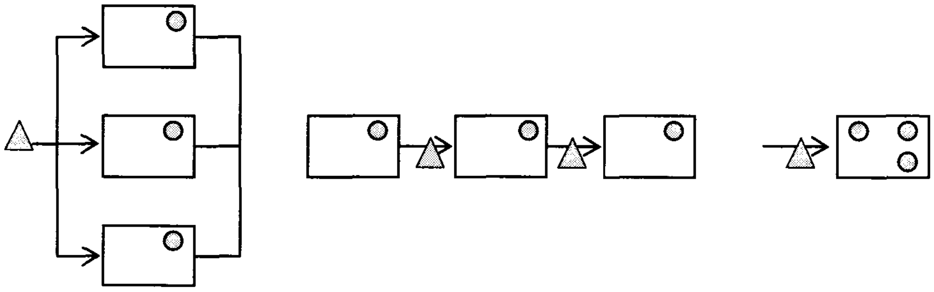
4.3. Complexity Metric Application and Case Studies

In the following section, the application of the developed complexity metric will be illustrated using three simple system configurations. The illustrative example will demonstrate the effect of using various components and configurations on the system complexity. In section 4.3.1 the metric has been applied to a case study in order to compare feasible but different manufacturing system configurations.

4.3.1 Effect of Machine Configurations and Layout

The effect of machine configuration on the complexity can be illustrated by comparing two stand-alone machines, one with a base and a single module and the other with three modules. The machine type index code and the reliability figures for each machine are needed in order to calculate their machine complexity. The type index codes for the two machines are 4341201402 and 4343201402 respectively. Their corresponding type complexity code indices which are 0.46, and 0.51, were calculated using Equation(4.9). Equation(4.4) provides the reliability figures for each machine as 0.81 and 0.9 respectively. These numbers are then substituted in Equation(4.3), and the resulting complexity indices of the single-module machine and the three-module machine are respectively 0.32 and 0.24. These results show that a machine with three identical modules (e.g. heads or spindles) introduces less complexity than a single machine module. This is because a three-module machine can continue to operate, albeit at reduced capacity, while one or two of its modules are down. When a single module machine fails it is not possible to continue production and this would result in queues and introduce operation, maintenance, re-programming, and re-setting difficulties which increase complexity.

The following basic system configurations are used to illustrate the effect of system layout patterns on the developed complexity index:



(a) Single-module parallel machines

(b) Single-module serial machines

(c) Multiple-module single machine

Figure 4.10 Different system configurations

In Figure 4.10, three system configurations are illustrated. A circle in each box of the figure represents a module installed onto the machine base. All three configurations have equivalent capacity and capability. They differ in individual machine configurations and system configuration layout. Figure 4.10(a) represents a system consisting of three single module machines in a parallel configuration. Figure 4.10(b) shows three single module machines with a serial configuration; Figure 4.10(c) is a stand alone machine with three modules. In configuration Figure 4.10(a), three conveying modules are required to provide material handling, whereas in Figure 4.10(b) and Figure 4.10(c), one conveyor is sufficient. It is assumed that the machine modules used in these configurations are identical and each component's reliability is 0.9. The data and the results for these three cases are as follows:

Table 4.7: Data for Machine Configurations in Figure 4.10

Systems **Data**	**Single module** **Parallel MCs**	**Single module** **Serial MCs**	**Multiple module** **Single MC**
Number of machines	3	3	1
Machine Type Index	0.46	0.46	0.51
Machine component reliability	0.9	0.9	0.9
Number of Buffers	1	2	1
Buffer Type Index	0.61	0.61	0.61
Buffer state probability	0.5	0.5	0.5
Number of Transporters	3	1	0
MHS Type Index	0.33	0.33	0
MHS Reliability	0.999	0.9	0

Table 4.8: Complexity of the machine configurations shown in Figure 4.10

Systems / Complexity	**Figure 4.10 (a)**	**Figure 4.10 (b)**	**Figure 4.10(c)**
Machine - H_M	0.968	0.968	0.241
Buffer - H_{B1}	0.610	1.220	0.610
MHS - H_{MHS}	0.010	0.150	0
System Complexity	1.588	2.338	0.851

The machine complexity part for the machine in Figure 4.10(c), H_M, shows that the system that has a single machine with three identical modules is less complex due to the elimination of the additional machine bases, and their reduced number of buffers and transporters. The difference between the serial and parallel configurations can be explained by analyzing the MHS complexity. In a parallel configuration, the failure of a conveyor does not disrupt the production; therefore, it is a less complex system.

4.3.2 Complexity of an Engine Cylinder Head Manufacturing System

This case study provides more details of the complexity metric, and illustrates its ability to capture the complexity of manufacturing systems. We assume that all components that contribute to overall complexity are equally important, i.e. $w_1=w_2=w_3=1$.

The raw data for this case study such as the demand scenarios, machine concepts, production rate of each machine, and the number of stages required to finish the product is taken from Spicer's work (2002), which deals only with the economic evaluation of RMS alternatives and does not consider their complexity.

In the following case study, manufacturing system configurations A1 and C1 were taken from Spicer's work and a third configuration A2 was generated based on the same set of data.

Consider an engine cylinder head manufacturing system. The processing of the cylinder head involves several operations such as boring, tapping, and drilling performed on different faces at different angle orientations. These machining operations can be performed on two different machine types: A and C. Machine type A has the following features:

1. Three axes of motion on the spindle column
2. Horizontally mounted modular spindles with automatic tool changers and the capability to have 1 to 4 spindles
3. Ability to machine one face of a cylinder head at one angle of orientation per fixture set-up.

The machine type C has additional capability to process the cylinder head by accessing multiple orientations with respect to a single face using its pivoting spindles. The machine types A and C are both reconfigurable in the sense that their capacity can be changed by adding or removing the modular spindles.

The production system that was built using machine type A requires 13 different stages in order to accomplish the set of machining tasks required for the cylinder head, whereas using machine type C requires only 6 different stages. The anticipated market demand is 1800 engines/shift, and the facility would operate at 10 hours per shift.

Figure 4.11 to Figure 4.13 represent the manufacturing system configuration alternatives A1, A2, and C1 which are considered as design alternatives, and will be compared from system complexity perspective. Systems A1 and A2 consist of machines of type A and system C1 consists of machines of type C. Systems A1 and A2 have the same total number of machine modules but different number of machine bases, and both meet the capacity requirements. The system alternative A2 is generated in order to highlight the difference between using simple machines with fewer modules and using more complex machines with larger number of modules per machine.

Buffers are located between stages. The buffer types used in systems A1 and A2 are FIFO buffers with carousels holding up to 180 parts. System C1 has indexing tables with random access systems to use with AGVs. The buffer capacity is set a priori to a maximum of 180 parts. This buffer level is selected to accommodate one hour of production without disruption.

The material handling system used in systems A1 and A2 consist of gantry robots within each stage and a conveyor for transportation between the stages. System C1 uses 5 AGVs to transport materials within and among stages.

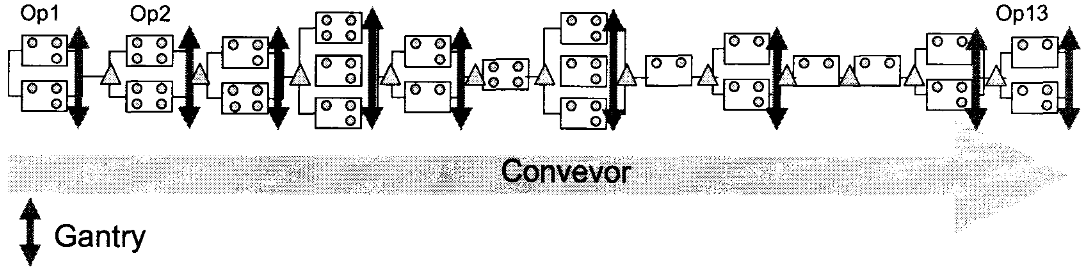


Figure 4.11 Engine Cylinder Head Manufacturing System Configuration A1

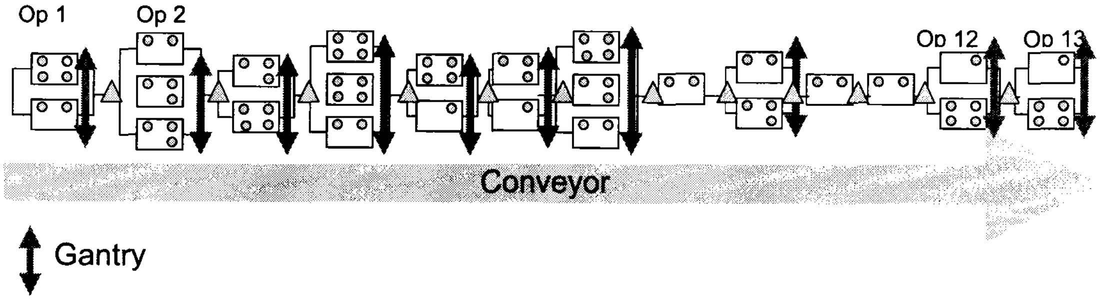


Figure 4.12 Engine Cylinder Head Manufacturing System Configuration A2

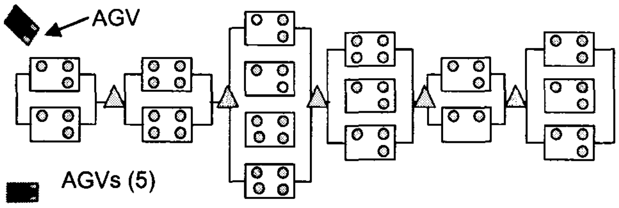


Figure 4.13 Engine Cylinder Head Manufacturing System Configuration C1

The above information about the structure and components of each system are used to calculate their machine, buffer and material handling system complexity using the proposed complexity metric and indices. In this case study, it is assumed that each component's reliability is 0.9. The probability of operational or failure states for a machine with n modules can be calculated using Equation(4.4). Table 4.9 represents these probabilities.

Table 4.9: Reliability of machines with different configurations

Number of Modules (n)	p_{ij2} **Failure**	p_{ij1} **Operational**
1	0.190	0.810
2	0.109	0.891
3	0.101	0.899
4	0.100	0.900

According to the complexity code, machines type A and C have the following type representation codes:

Table 4.10: Classification code strings for machine types A and C

	Machine A	**Machine C**
Machine Type Code	4344201402	4444202442

Using Equation(4.9), machines A and C have a type complexity index of 0.53 and 0.64 respectively.

4.3.2.2 Buffer complexity

Since there is only one product to be manufactured in all systems, A1, A2, and C1, the buffer complexity component H_{B2} becomes equal to 0. The evaluation of the system configuration alternatives is an early design stage activity; therefore, there is normally no data available to predict the states of the buffers. As a worst-case scenario, it is assumed that each buffer state (empty, non-empty) has equal probability of occurrence.

4.3.2.3 Material handling system complexity

The material handling systems in configuration A1 and A2 consist of nine and ten gantries respectively for moving parts within the stages. A uni-directional conveyor is used to move the parts from one stage in the system to the next. Since the process plan requires a uni-directional parts flow, the failure of any MHS equipment would result in the disruption of the overall production line. Assuming that all elements in the material handling system should be operational for the entire system to run, the reliability of the material handling system in configuration A1 and A2 is:

$$p_{MHS\_A1} = 0.9^{10} = 0.35 \qquad (4.12)$$

$$p_{MHS\_A2} = 0.9^{11} = 0.31 \qquad (4.13)$$

System C1 uses 5 AGVs with a free routing capability. Since the AGVs have this feature, the failure of one AGV does not disrupt the production system since it can be replaced or the others can be re-routed to accommodate the failure. The material handling system's reliability for the system C1 is equal to:

$$p_{MHS\_C1} = 1 - 0.1^{5} = 0.999 \qquad (4.14)$$

As defined in Equation(4.9) and section 4.2.1.3 the complexity type code m for material handling systems in A1, A2, and C1 are 332, 332, and 525 respectively. Equation(4.9) has been used to convert the codes to the corresponding indexes to be used in Equation(4.8). These indices are 0.53 for system A1 and A2 and 0.80 for system C1.

Table 4.11: Engine cylinder head manufacturing systems configuration complexity

System Configuration / System Characteristics	**A1**	**A2**	**C1**
# Machine bases	24	26	18
# Modules	70	70	60
# Buffers	12	12	5
# MHS elements	9 + 1	10 + 1	5
Machine Type Index	0.53	0.53	0.64
Buffer Type Index	0.61	0.61	1
MHS type index	0.53	0.53	0.8
Machine Complexity H_M	6.11	7.11	4.86
Buffer Complexity H_B	7.33	7.33	5
MHS Complexity H_{MHS}	4.98	5.27	0.05
System Complexity	18.42	19.71	9.91

The system structural complexity results for the three different system configurations show that using multi-module machines reduces complexity compared to using single module machines. The comparison of systems A1 and

A2 reveals that the machine complexity increases while the total number of modules in both systems remains equal. The reason for this increase is due to the increased number of machine bases, which means having additional equipment to be managed, programmed, or controlled.

System C1's machine complexity is less than A1 and A2's machine complexity due to the fact that machine concept C is more capable than machine concept A. The use of more capable machines reduces the number of stages to accomplish the required processing tasks. The percentage reduction in number of machines from 24 to 18 (25%) results in the reduction of machine complexity by (20%). This is a result of using more capable machine type in system C1, which is reflected on the equations via the machine type code indices.

We should also mention that using more capable type of machines reduces the overall complexity by eliminating the number of buffers required in the system. This would result in fewer resources to manage and hence it reduces complexity.

The results in Table 4.11 show that one of the major contributors to systems complexity is the material handling. The material handling system complexity in system A1 and A2 is much higher than system C1's as a result of using functionally serial equipment. The failure in any material handling system component of configuration A1 and A2 would result in a halt in the production. System C1 has the ability to continue to produce with reduced capacity in case of failure in one of the MHS elements. Using individual, more flexible material handling elements allows the system to continue operation with the least disruption.

4.4. Discussion and Conclusions

In this chapter, the existing approaches for measuring manufacturing systems complexity have been reviewed and a new approach was proposed to assess the complexity of a manufacturing system configuration. A comprehensive structural complexity metric has been developed which takes into consideration the main components of a manufacturing system such as machines, buffers, and material handling equipment, and their relationship or system structure, for a multi-product environment. The proposed method can be used to compare systems the components of which may be different. For example, a system that contains machines and transporters but does not include buffers may be compared with one that has all three types of modules using the developed complexity metric where the term that accounts for the complexity arising from the presence of buffers will be eliminated for the former. The manufacturing systems may be different but their comparison using the proposed metric is still valid and accounts for the difference between them as explained above. This metric provides insight into the inherent complexity of system components and structure, and the manageability of manufacturing systems configurations. As well, this metric assists in selecting a less complex system at the early design stages. The various types and technologies of buffers, machines, and MHS can be expressed quantitatively using the type index based on a newly developed manufacturing systems classification code (ElMaraghy, 2006). The proposed entropy-based metric is capable of incorporating the amount of information, as well as the diversity of information inherent in complex systems using the classification codes. It also has the ability to detect the differences in structural, time-independent complexity between a serial and parallel configuration as well as simple and multi-purpose machines. While this metric has been developed for manufacturing systems involving machining operations, it is equally applicable to other types of manufacturing systems, such as assembly lines. The application of the developed manufacturing systems complexity metric was illustrated with several examples. Its use becomes even more important for larger manufacturing systems where the effect of changes in system structure and configuration, its modules/components and their relationships is less intuitive.

The results of the case studies show that using more capable machines in a manufacturing system would reduce the overall complexity by decreasing the required number of machines. Another result of using more capable machines is to decrease complexity by reducing the number of required buffers. The metric shows that the use of AGVs as MHS creates free routing, which results in a less complex material handling system since the failure of one transporter does not disrupt the production. However, using more capable equipment may also mean higher initial investment; therefore, there should be a trade-off between the complexity level and the required investment.

The proposed structural complexity metric was shown to be sensitive to changes in manufacturing system configuration components and their inter-relationships. Its use would be beneficial in the early systems design syntheses and analyses in considering the relative merits of reconfigurable and flexible manufacturing systems (ElMaraghy, 2005).

The structural complexity metric explained in this chapter will be used as one of the strategic criteria in the RMS lifecycle evaluation methodology as depicted in Figure 3.2. The next chapter describes the second strategic criterion, which measures the responsiveness of manufacturing system configurations.

CHAPTER FIVE

RESPONSIVENESS IN MANUFACTURING SYSTEMS

This chapter represents the metric developed to assess the responsiveness of manufacturing systems in order to use it as an objective function in the lifecycle evaluation methodology.

In the most basic sense, manufacturing systems consist of various machines (processing or assembly equipment, material handling equipment, inspection stations, etc.) and the operating and control algorithms used to determine how the equipment is to be operated. Together, these items determine the capability and capacity envelope for the system.

A manufacturing system may move from one configuration to another in two ways. First, the configuration may be changed intentionally, to adopt a more favorable match between what capabilities or capacity is required (desired) and what is available. A certain amount of effort (time, cost, etc.) will be required to effect such changes. The second is when the configuration changes on its own due to component wear (e.g., changes in process capabilities, processing rates, etc.) or unreliability (e.g., machine breakdowns).

5.1. Responsiveness

Production responsiveness is concerned with the achievement of production system goals, which describe desirable behaviors or states of the system seen as a whole. The major categories of such goals can be summarized as quality, safety, delivery and cost.

The responsiveness defined by Matson and McFarlane (1999):

Responsiveness is the ability of a production system to respond to disturbances (originating inside or outside the manufacturing organization) which impact upon production goals.

Disturbances can be found at the supply and customer interfaces of a production system, as well as internally and in its environment.

A disturbance is a change occurring internally or externally to a production system, which can affect its operational performance, and is either outside its control or has not been planned by the system.

Disturbances outside the control of a production operation include variations in demand, supplier delivery problems and power failures. Disturbances within its control are changes which have not been planned, yet it nevertheless in theory has some degree of control over, such as operator, planning and communication errors.

To behave in a responsive manner, however requires effective system-wide response mechanisms. The system must act in a manner which takes into account the particular ways in which the disturbances can affect its goals. In order to achieve its goals in the presence of disturbances, the system must either respond after the disturbance has occurred and/or have responded in advance to the known possibility of its occurrence. Thus response mechanisms may either be in reaction to or in anticipation of the occurrence of disturbances, or some combination of the two (e.g. materials buffers are built with disturbances in mind and then used to compensate for them when they occur).

The key capabilities required for good responsiveness are summarized in Figure 5.1. It is emphasized that, in addition to a combination of flexible process capabilities and buffers, it is important that: disturbances and plant conditions are recognized and evaluated effectively; and appropriate decisions are made regarding the use of the available flexibilities and buffers in the face of disturbances. The degree and quality of information available concerning the occurrence and nature of disturbances has a major effect on responsiveness, in that it greatly influences the achievable quality of response decisions. Decision-making must be made in a timely fashion which takes into account goals, side effects and current plant conditions.

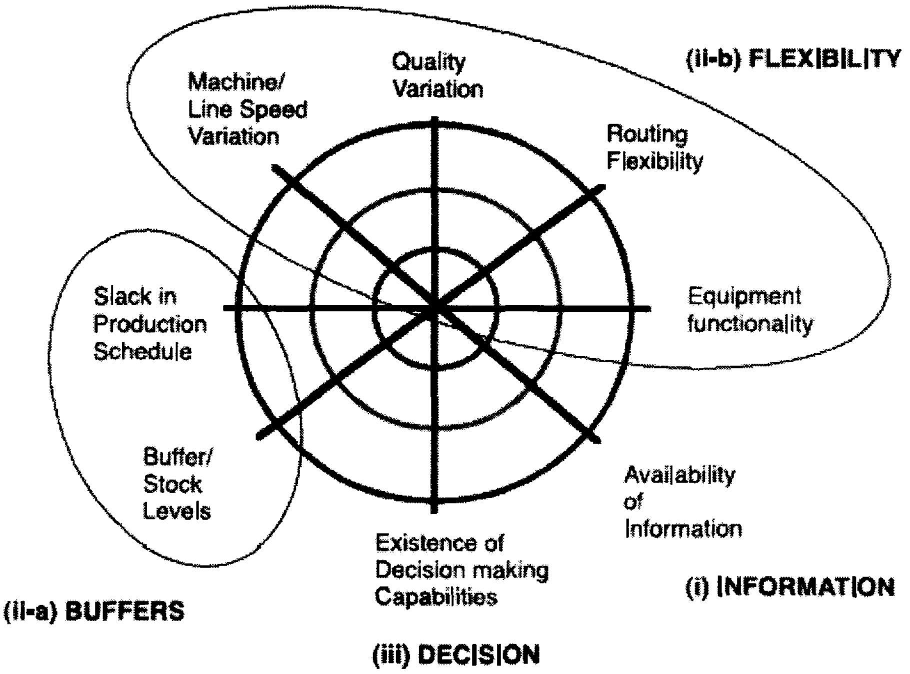


Figure 5.1 Factors influencing production responsiveness (Gindy and Saad, 1998)

The distinction between responsiveness and flexibility is that the flexibility represents the inherent properties of the manufacturing system and its components rather than describing the dynamic system behavior in response to change. Flexibility can be seen as one key capability enabling the system responsive and agile behavior.

5.2. Convertibility

Responsiveness includes both convertibility and capacity scalability. Convertibility is defined as the capability of a system to rapidly adjust production functionality, or change from one product to another. This can include everyday product changeovers to meet part mix demands, periodic design changes, and the introduction of new products over time. Capacity scalability is directly related with the throughput of the system.

Convertibility metrics expresses the intrinsic characteristics of the components and configuration that make one system inherently more convertible than another. For example a system with high intrinsic convertibility is more likely to have capabilities for quick changeovers, easy technological updates, and efficient introduction of new products.

Maier Speredelozzi (2003) proposes the following convertibility metric

$$C_S = w_1C_C + w_2C_M + w_3C_H \tag{5.1}$$

where C_C, C_M, and C_H, are convertibility metrics associated with the configuration, machine, and material handling, respectively, which are further defined in subsequent sections such that each metric has a scale of 1-10. The weights, w1, w2, and w3 can be adjusted.

The intrinsic metrics for convertibility are useful when detailed information about products and process plans is not available. The measure of system convertibility includes contributions due to machines, their arrangements or configuration, buffers and material handling devices. The configuration, machine, material and buffer properties of a system provide varying levels of convertibility to the system which affects adaptability for future uses of the same system.

5.3. Responsiveness metrics

Responsiveness can be investigated at two different levels: the responsiveness of the current system with regard to unpredictable changes in demand of current products, and the responsiveness of a system configuration which represents the ease of reconfiguring the system to accommodate new product introductions.

Gindy and Saad (1998) state that manufacturing responsiveness relates to the ability of manufacturing systems to make a rapid and balanced response to the predictable and unpredictable changes that characterize today's manufacturing environments. It is argued that the root to improving the responsiveness lies in maximizing the utilization of the inherent flexibility of its available resources in order to:

1. achieve the "best" possible operational performance in terms of meeting performance targets while coping with unpredictable internal and external disturbances; and
2. Operate the manufacturing system such that the allowances added to product processing time are minimized (tightest possible due dates).

The development of appropriate measures and methods of assessment for the various facets and attributes of manufacturing responsiveness is an important step towards being able to optimize the utilization of available system resources to improve performance and responsiveness. They develop the following flexibility measures based resource elements (RE).

In a machining facility resource elements (REs) are defined as facility-specific capability units, which capture information relating to the distribution (commonality and uniqueness) of form generating schema among the available machine tools. The available machine tools in a manufacturing system can be described using a set of REs where each RE represents a collection of form generating schema such that the exclusive and the shared capability boundaries between all the available machine tools comprised in a manufacturing facility are uniquely identified.

Bateman et al. (1999) considers mix response flexibility as the difficulty of processing different products on the same equipment. Mix response flexibility is represented by the ability to change the product being manufactured within the pool of products. It is measured as the inversion of set-up time when the product is required to process on the machine.

Mix response flexibility of a single machine system for all possible processing sequences of product is measured through the mean and the standard deviation for sensitivity to change of the machine. The mix response flexibility is referred as the difficulty of processing different products in terms of the inversion of set-up time, i.e. whenever set-up time is large, the sensitivity to change of the system increases, and hence the difficulty to change from one product to another will be higher corresponding to low mix response flexibility. However, the difficulty in switching between products is not only set-up time but also machine capability and capacity in terms of operation, range, cost, and efficiency.

Van Hop (2004) proposes a mix response flexibility metric that addresses both capability and capacity of a manufacturing system configuration. The capability of a manufacturing system is defined as the number of states a system can perform. The state could be represented as an operation, a set-up, or a process to produce a kind of product, etc. The capacity of a manufacturing system means that how economic (fast, easy) the system can operate or change from one state to another. The capacity of a system could be measured in terms of efficiency, cost, set-up time, etc.

5.4. Proposed Responsiveness metric

The ability of a manufacturing system to change according to external or internal disturbances has been defined in the literature as response flexibility, product mix flexibility, mix response flexibility and responsiveness.

In the literature, the ability to change with uncertainty is often referred to as the flexibility degree of the system. The higher flexibility the company has the higher competitiveness in the market cutting edges will be. The flexibility ability of a company is not only the capability to change with outside factors such as demand fluctuation, competitor, market share and so on, but also the adaptability of the company with the inside fluctuations, especially the manufacturing variations.

For the meaning of flexibility, we might be able to infer that each related term contains two abilities, in terms of capability and capacity (Chang et al., 2001). Therefore, it is possible to conclude that flexibility in a manufacturing system is also embodied in, or consists of, these two abilities. Capability, meaning how many different kinds of state a system can perform, is defined as the scope, range or envelope of the states embodied in the tasks that a system can perform; whereas capacity, meaning how fast or how easy the system can operate, is defined as the efficiency of performing the states, either doing the changeover between the states arbitrarily or completing a specific state.

Slack (2005) suggests that flexibility has two dimensions. According to Slack's definition, it is necessary to include not only the range of states a system can adopt, but also the ease of moving from one state to another, in terms of time and/or cost. Slack further explained the meaning of range as `the total envelope of capacity or range of states which the operations system is capable of achieving'. This implies the term versatility. Therefore, versatility and efficiency could measure manufacturing flexibility. Versatility expresses the capability, whereas efficiency expresses the capacity, of the systems.

Convertibility metrics deal with the characteristics of a manufacturing system components that will make it easily convertible. The metrics include contributions due to machines, their arrangements or configuration, and material handling devices.

The following figure is an overall framework for responsiveness in manufacturing. Since responsiveness is related with the response of a manufacturing system to external and internal disturbances with a rapid and cost effective manner, it has overlapping definitions with notions such as flexibility and convertibility. We can also claim that flexibility and convertibility are the enablers of manufacturing system responsiveness. As a conclusion, we can use these features in order to define the responsiveness of manufacturing systems.

In the literature, the flexibility or responsiveness metrics have been developed using two main approaches: operational measures where the metric evaluates the system based on dynamic and operational aspects of a manufacturing system, and structural measures where it uses machine components and their characteristics in order to represent the inherent features that would make a system more responsive,

The responsiveness of a manufacturing system is directly proportional to the process capabilities of the machines. A more capable machine would eliminate the need to re-set for another product. The machine set-up times have a major effect on the responsiveness of a manufacturing system. A system that has a capability of quickly changing over from one product to another would have a competitive advantage.

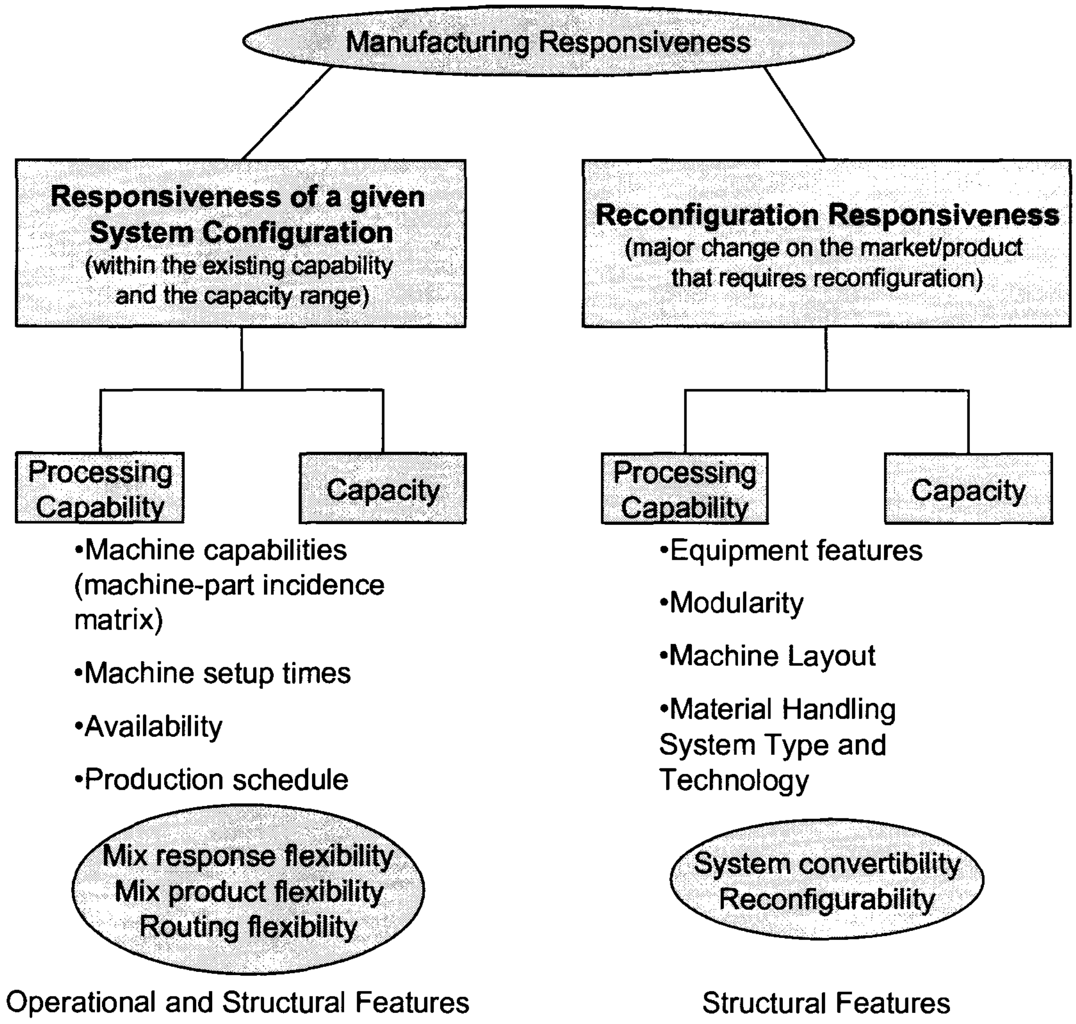


Figure 5.2 Responsiveness metrics framework

This metric is based on Van Hop's (2004) mix response flexibility metric. The missing point in this study was to define the efficiency of a machine with regard to an operation of a product. The following equations will define the efficiency of a machine in terms of its set-up time and processing time efficiencies.

Consider a manufacturing system that is capable of producing a variety of products. The production schedule for such a system requires a product type launch sequence in order to meet the deadlines. Usually, these schedules are disturbed by new orders that have higher priority. In that case, the system needs to be re-set for the new order. A systems' ability to respond to these schedule changes is defined as response ability (RA). Each machine's response ability can be calculated by analyzing their ability to process a variety of operations and their changeover ability. A manufacturing system that consists of machines that are capable to perform various types of operations with minimal changeover time will be more responsive than a system that consists of dedicated machines that are only capable of processing one type of operation. The response ability of a machine with respect to a product type is defined as follows (Van Hop, 2004):

$$RA_{imk} = \frac{\sum_{j=1}^{J} z_{ijmk} e_{ijmk}}{J} \tag{5.2}$$

where

RA_{imk}	Response ability of machine (m, k) for product *i*
z_{ijmk}	1 if machine (m, k) can process operation (i, j), 0 otherwise
e_{ijmk}	Efficiency of machine (m, k) for operation (i, j)
J	Total number of operations for product *i*

The response ability metric has a range between 0 and 1. As RA's value is closer to 1, it indicates that machine (m, k) can process product i the most responsive way. This is due to the fact that the equation (5.2) takes into account the total number of operations for product i and checks the efficiency of each operation with respect to the machine (m, k).

Based on Gindy and Saad (1998), efficiency formula for REs, we can define the efficiency of a machine by the ratio of set-up times and processing times to the minimum setup and processing time required for operation (i, j).

$$e_{ijmk} = \frac{\min\limits_{m,k}(ST_{ijmk})}{ST_{ijmk}} \times \frac{\min\limits_{m,k}(p_{ijmk})}{p_{ijmk}} \tag{5.3}$$

where

p_{ijmk} Process time of operation (i, j) on a machine (m, k)

ST_{ijmk} Setup time of operation (i,j) on a machine (m, k)

The above formula takes the ratio of a minimum setup time for operation (i, j) among the candidate set of machines (m,k), to the setup time required for that machine. The higher the setup time is the lower the efficiency of the machine. Same ratio is applied to processing times and the two ratios are multiplied in order to obtain the efficiency of the machine (m,k) for operation (i, j).

Equation (5.2) helps to determine the response ability of each machine with respect to a product. However, the schedule of a manufacturing system is uncertain and it is incorporated using the following equation (Van Hop, 2004):

$$P_{imk} = P_i \frac{RA_{imk}}{\max\limits_{m,k}\{RA_{imk}\}} \tag{5.4}$$

where

P_i Demand ratio of product i

P_{imk} Probability of assigning product i to machine (m, k)

The expected responsiveness of a manufacturing system is then calculated by multiplying the response ability of each machine by the probability of assigning the product to that machine.

$$\text{Responsiveness} = \sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{k=1}^{K} P_{imk} RA_{imk} X_{mk} \tag{5.5}$$

where

P_{imk}	Probability of assigning product i to machine (m, k)
RA_{imk}	Response ability of machine (m, k) for product *i*
X_{mk}	Number of machines (m, k)

The proposed responsiveness metric captures the responsiveness ability through two formulations: response ability and efficiency. The relative efficiency of each machine with respect to the processing and setup time for each operation, capture the effectiveness of changeover for the machines. In addition, response ability captures the overall capability of each machine, considering the variety of operations it can handle. Combining these two aspects with the overall demand ratio of each product, gives an indication of any manufacturing system's responsiveness.

5.5. Numerical example

The following example is based on the configurations generated from the proposed methodology. The following configurations meet the same production quantity requirements for two products in demand. Each configuration is designed to meet 1,500,000 parts/year of product 1, and product 2 each. The detailed information about machine information and processing requirements can be found in Appendix A. The machines that are used is expressed in Table 5.1. Figure 5.3 and Figure 5.4represents the assignment of these machines into stages.

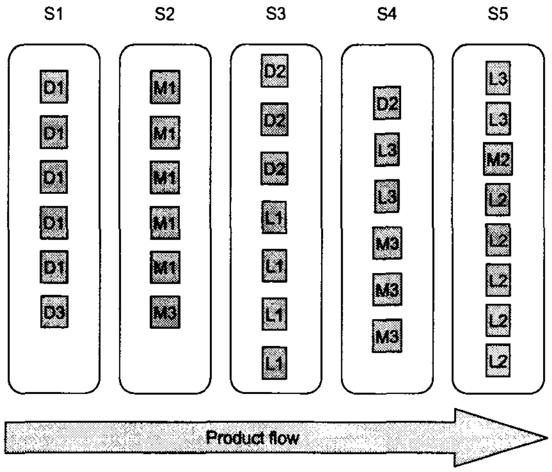


Figure 5.3 Configuration A

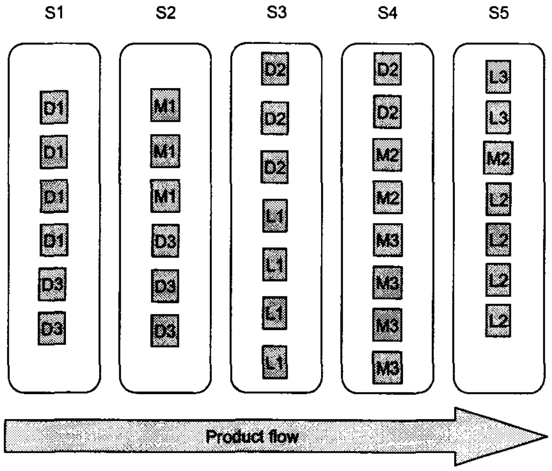


Figure 5.4 Configuration B

Table 5.1: Machines used in configuration A and B

Base Type	Module	Configuration A	Configuration B
Drill	1mod	5	4
	2mod	4	5
	3mod	1	5
Lathe	1mod	4	4
	2mod	5	4

	3mod	4	2
Mill	1mod	5	3
	2mod	1	3
	3mod	4	4

As explained in section 5.4, the efficiency of each machine with respect to a product's operation is calculated using equation (5.3). These machines are assumed to be the candidates for generating system configurations. The efficiency of each candidate machine is represented in table below:

Table 5.2: Efficiency Matrix

		Machine Base Type and Configuration State								
Operation (i,j)		Drill			Mill			Lathe		
i	j	1	2	3	1	2	3	1	2	3
1	1	0.25		0.83						
	2			0.50	0.08		0.95	0.05		
	3		0.22				1.00			
	4		0.07			0.11	1.00			1.00
	5					0.07			0.09	1.00
2	1	0.18		1.00	0.18					
	2			1.00	0.09		1.00			
	3						1.00	0.32		
	4		0.06			0.05	0.44			1.00
	5					0.09	0.95		0.11	0.50

Table 5.2 shows the efficiency of each machine with respect to an operation. For example, for the operation 4 of the product 1, the mill machine with three

modules, and the lathe machine with three modules have the highest efficiency, thanks to their minimal setup and processing time for this operation. Similarly, a drill with two modules has the least efficiency for this operation.

The next step, is to compute the response ability of each machine relative to each product using equation (5.2). The results are illustrated in Table 5.3 show that as the number of modules increase, the response ability increases. This is due to the increasing processing capabilities of added modules.

Table 5.3: Response ability of machine (m, k) relative to product i

	RA_{i11}	RA_{i12}	RA_{i13}	RA_{i21}	RA_{i22}	RA_{i23}	RA_{i31}	RA_{i32}	RA_{i33}
Product 1	0.05	0.06	0.27	0.02	0.04	0.59	0.01	0.02	0.4
Product 2	0.035	0.01	0.4	0.05	0.03	0.68	0.06	0.02	0.3

Using equation (5.4) and (5.5) the responsiveness of configuration A and B is 3.57 and 3.88 respectively. The results show that configuration B is more responsive compared to configuration A. Under the current demand requirements and product mix, configuration B responds better to changes in demand. This is mainly due to having more capable machines in its structure.

The proposed responsiveness metric captures the responsiveness ability through two formulations: response ability and efficiency. The relative efficiency of each machine with respect to the processing and setup time for each operation, capture the effectiveness of changeover for the machines. In addition, response ability captures the overall capability of each machine, considering the variety of operations it can handle. Combining these two aspects with the overall demand ratio of each product, gives an indication any manufacturing system's responsiveness. The following chapter describes the third criterion in the RMS lifecycle evaluation methodology, namely after-tax cash flows.

CHAPTER SIX

RMS COST MODEL

This chapter describes the financial objective function used in the proposed methodology and the related constraints.

6.1. Net present value of after tax cash flows

The financial objective function used in the proposed methodology is the net present value (NPV) of after-tax cash flows. This function is especially useful since it includes all the costs and benefits that occur during the lifecycle of a manufacturing system. The elements of NPV are as follows:

NPV (Cash Flow) = + Sales Profit

+ Salvage Value of Disposed Machines

+ Tax savings from Depreciation of Machines

- Initial Investment and Capital cost of added modules

- Reconfiguration cost

- Variable and Fixed Costs on machines used (operation costs)

- Outsourcing cost

- Setup Costs

+ Book value of the assets at the end of the planning horizon

The following section will describe each element and their mathematical expression will be presented.

6.1.1 Sales profit

The first term is the gross profit obtained from in-house production and the profit generated from outsourced production. The formulation of sales profit is as follows:

$$+\sum_{t=1}^{T}\sum_{j=1}^{J}(P_{it}-MC_{it})M_{it}(1-TR)(\mathrm{P/F,\,I,\,t})+\sum_{t=1}^{T}\sum_{j=1}^{J}(P_{it}-OC_{it})Q_{it}(1-TR)(\mathrm{P/F,\,I,\,t}) \quad (6.1)$$

where

(P/F,I,t)	Present worth factor
TR	Tax rate
P_{it}	Sales price of product i in period t
MC_{it}	Unit material cost for in-house production for product i in period t
OC_{it}	Unit outsourcing cost for product i in period t
M_{it}	Production quantity of product i in period t
Q_{it}	Outsourced quantity of product i in period t

The first term represents the profit generated from in-house production. It is assumed that the demand in each period will be met either by internal production or by outsourcing. The profit from outsourcing is represented by the second term in Equation(6.1).

6.1.2 Salvage value of disposed machines

During the lifetime of the manufacturing system, the machines that are no longer needed will be disposed and some revenue from the sale of these machines are included in the objective function using the following term:

$$+\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{k=1}^{K} SV_{mkt} Max(0, X_{mk(t-1)} - X_{mkt})(\text{P/F, I, t}) \tag{6.2}$$

where

SV_{mkt}	Salvage value of machine (m, k) in period t
TR	Tax rate
P_{it}	Sales price of product i in period t
X_{mkt}	Number of machines of base type m and module k in period t

The term $Max(0, X_{mk(t-1)} - X_{mkt})$ denotes the number of machine type m configuration k disposed of in time t. It ensures that only positive difference of $(X_{mk(t-1)} - X_{mkt})$ is considered in this equation; otherwise the term is equal to zero.

6.1.3 Tax savings from machine depreciation

At the end of each year companies depreciate their assets according to accounting principles. The depreciation amount of assets is then used to decrease the taxable income therefore; it creates a positive cash flow for a company. For the assets (i.e. machines), straight-line depreciation method is assumed. The savings obtained by asset depreciation are expressed by the following term.

$$+\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{k=1}^{K} DP_{mkt} TR(\text{P/F,I,t}) \tag{6.3}$$

where

DP_{mkt}	Depreciation amount of machine (m, k) in period t
TR	Tax rate

6.1.4 Initial investment and capital cost of added machines

This term represents the initial investment cost and capital cost of added machines during the lifecycle of a manufacturing system.

$$-\sum_{m=1}^{M}\sum_{k=1}^{K} IC_{mk1}X_{mk1} - \sum_{t=2}^{T}\sum_{m=1}^{M}\sum_{k=1}^{K} IC_{mkt}Max(0, X_{mkt} - X_{mk(t-1)})(\mathrm{P/F, I, t}) \qquad (6.4)$$

where

IC_{mkt} Investment cost of machine (m, k) in period t

X_{mkt} Number of machine (m, k) in period t

6.1.5 Reconfiguration cost

The modular structure of a reconfigurable manufacturing system allows changing production equipment in order to adapt to the changes in market demand. There are different sources of cost that emerge due to reconfiguration. The reconfiguration task involves purchasing required modules and/or machine bases as well as physical and logical rearrangement of the system components for the next period. Figure 6.1 shows a classification of the reconfiguration cost for a manufacturing system.

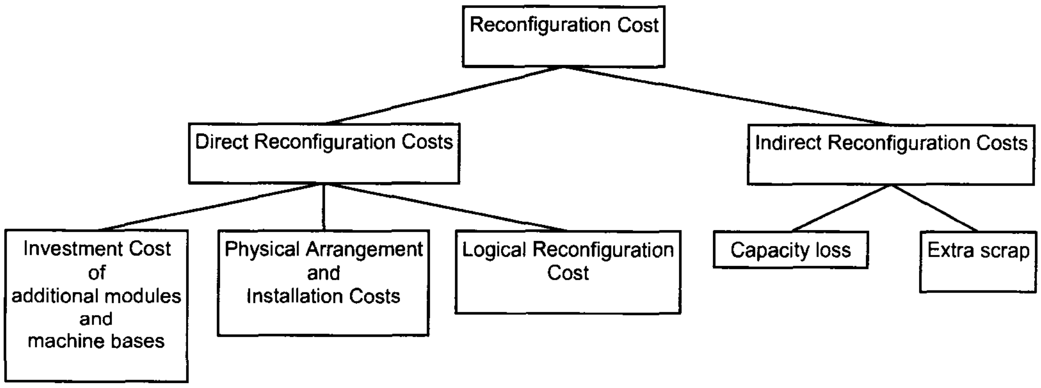


Figure 6.1 Reconfiguration cost classification

The investment cost of additional modules and machine bases is already included in the investment cost function. In order to calculate the physical arrangement and logical configuration cost, we need to determine the reconfiguration tasks performed while changing the system from period (t) to period (t+1). We can assume that during the changeover of the system, two different periods are involved: reconfiguration and restoration of performance (ramp-up).

Indirect reconfiguration cost depends on the time required to finish the reconfiguration tasks and the ramp-up time. The loss of capacity during reconfiguration and ramp-up will result in decreased sales. During the ramp-up period, it should be expected that there will be higher scrap rate than usual while the system problems are being fixed. The following equation defines the reconfiguration cost of a manufacturing system:

Reconfiguration Cost = Purchasing Cost for additional Modules and Machines + Cost of Physical Arrangement and Installation/Removal of added/removed modules. (6.5)

In order to define the tasks accomplished in a reconfiguration period the number of equipment removed/replaced in that period must be determined. In this model, three different types of machines had been proposed on which three different modules can be added in order to modify the capability and/or capacity of a machine type. Based on these assumptions, the number of machine bases and modules are expressed using the following formulation:

$$\mathrm{B}_{\mathrm{mt}} = \sum_{k=1}^{K} X_{mkt} \quad \text{for } m = 1,..,M \tag{6.6}$$

$$\mathrm{MD}_{\mathrm{mkt}} = kX_{mkt} \quad \text{for } m = 1,..,M \text{ and } k = 1,..,K \text{ and } t = 1,...,T \tag{6.7}$$

Based on the number of machine modules and bases installed or removed during reconfiguration, the total time required to accomplish the reconfiguration task can be defined. The reconfiguration task is equal to the total time required to add/remove all machine bases and modules between two consecutive periods.

$$Task_{\mathrm{Rec}} = RT_t = \sum_{m=1}^{M} t_B * \left| B_{mt} - B_{m(t-1)} \right| + \sum_{m=1}^{M} \sum_{k=1}^{K} t_{MD} * \left| MD_{mkt} - MD_{mk(t-1)} \right| \qquad \forall t \qquad (6.8)$$

where

t_B	time to install/remove a machine base
t_{MD}	time to install/remove a machine module

The absolute value terms in (6.8) represent the number of machine bases and modules installed or removed between two consecutive periods. Based on the total reconfiguration task we can express the reconfiguration cost and duration for the following equations:

$$Cost_{\mathrm{Re}configuration} = RC_t = LR(RT_t) \qquad \forall t \qquad (6.9)$$

where

LR	hourly labour rate (\$/hour)

$$Time_{\mathrm{Re}configuration} = RD_t = \frac{RT_t}{W_t} \qquad \forall t \qquad (6.10)$$

and where

W_t	Available workforce in period t [man.hours]

The following term represents the sum of all the reconfiguration costs throughout the lifecycle of an RMS.

$$-\sum_{t=1}^{T-1} RC_t (P/F/i/t)(1-TR) \qquad (6.11)$$

6.1.6 Operational costs

The following equations represent the costs of operational activities during a period. These costs include variable and fixed costs of operations and setup costs for machines. The variable and fixed operation costs are represented as follows:

$$-\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{k=1}^{K}(VC_{ijmk}Y_{ijmkt}+FC_{ijmk}X_{mkt})*(1-TR)*(P/F,I,t) \qquad (6.12)$$

The variable operating costs depend on the number of units produced at each machine type m at configuration k, and fixed operating cost depends on the number of machines of type m configuration k available in period t.

Setup costs depend on the number of setups performed in a period, and a cost of setting up various machines of various types in every system changeover.

$$-\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{k=1}^{K}\frac{SC_{ijmk}*Y_{ijmkt}}{L_t}(1-TR) \qquad (6.13)$$

where

L_t	Lot size in period t
SC_{ijmk}	setup cost of operation (i, j) on machine (m, k)
Y_{ijmkt}	number of operations (i, j) performed on machine (m, k) during period t

6.1.7 Book value of assets

In order to include the value of assets at the end of the planning horizon, the book value of assets should be added to lifecycle evaluation of manufacturing system. Due to the characteristic of reconfiguration, new machines can be added at any period of the planning horizon. The book value of the assets at the end of the planning horizon will complete the cash flow equation of a company's life cycle and is expressed as follows:

$$+BV_T*(P/F,I,T) \tag{6.14}$$

where

BV_T Book value of assets at the end of planning horizon (T)

6.1.8 Total cash flow formulation

The summation of all positive and negative cash flows form the financial objective function, as indicated in section 6.1, is expressed as follows

NPV (After Tax Cash Flows) =

$$+\sum_{t=1}^{T}\sum_{j=1}^{J}(P_{it}-MC_{it})M_{it}(1-TR)(\mathrm{P/F,I,t})+\sum_{t=1}^{T}\sum_{j=1}^{J}(P_{it}-OC_{it})Q_{it}(1-TR)(\mathrm{P/F,I,t})$$

$$+\sum_{\mathrm{t}=1}^{\mathrm{T}}\sum_{m=1}^{M}\sum_{k=1}^{K}S_{mkt}Max(0,X_{mk(t-1)}-X_{mkt})(\mathrm{P/F,I,t})+\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{k=1}^{K}DP_{mkt}*TR*(\mathrm{P/F,I,t})$$

$$-\sum_{\mathrm{m}=1}^{M}\sum_{k=1}^{K}IC_{mk1}*X_{mk1}-\sum_{t=2}^{T}\sum_{m=1}^{M}\sum_{k=1}^{K}IC_{mkt}Max(0,X_{mkt}-X_{mk(t-1)})(\mathrm{P/F,I,t})$$

$$-\sum_{t}^{T}RC_t(1-TR)(P/F,I,t)$$

$$-\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{k=1}^{K}(VC_{ijmk}*Y_{ijmkt}+FC_{ijmk}X_{mkt})*(1-TR)*(P/F,I,t)$$

$$-\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{k=1}^{K}\frac{SC_{ijmk}*Y_{ijmkt}}{L_t}(1-TR)*(P/F,I,t)+BV_T*(P/F,I,T)$$

The NPV function contains nonlinear terns such as $Max(0,X_{mkt}-X_{mk(t-1)})$ and

$Max(0, X_{mk(t-1)} - X_{mkt})$ in order to calculate the number of added and removed machines respectively between two consecutive periods. The linearization of these terms is achieved using some additional constraints and variables. These constraints and general implementation constraints are explained in the following section.

6.2. Implementation constraints

In chapters 4, 5, and section 6.1, the criteria for the lifecycle evaluation of RMS were presented. This section represents the necessary constraints in order to generate feasible system configurations throughout the planned horizon and additional logical constraints in order to maintain the validity of the results.

6.2.1 Assignment of production and outsourcing quantities

First, the annual demand for part type i is split into a quantity produced in house and that is outsourced. In addition, it will be assumed that the outsourced amount should not exceed a specified percentage of the total annual demand.

$$M_{it} + Q_{it} = D_{it} \qquad \forall i,t \tag{6.15}$$

$$Q_{it} \leq \alpha D_{it} \qquad \forall i,t \tag{6.16}$$

Production for an operation (i,j) in period t, can be assigned to a machine only if it is capable of performing the operation:

$$Y_{ijmkt} \leq z_{ijmk} M_{it} \qquad \forall i,j,m,k,t \tag{6.17}$$

A given operation (i, j) may be assigned to different machine types, but the total quantity produced should be equal to M_{it}

$$\sum_{m=1}^{M}\sum_{k=1}^{K} Y_{ijmkt} = M_{it} \qquad \forall i,j,t \qquad (6.18)$$

The capacity on each machine should be available to meet the demand to be met within the available time in one period.

$$\sum_{i=1}^{I}\sum_{j=1}^{J} p_{ijmk} Y_{ijmkt} + \left(\frac{ST_{ijmk}}{L_t}\right) Y_{ijmkt} \le AH_{mk} X_{mkt} - RD_t \quad \forall m,k,t \qquad (6.19)$$

The first term represents the total processing time, and the second is the total time lost due to system setup on machine (m,k). This total required time to be assigned to machine type (m,k) should be less than the total time available on machines (m, k). The reconfiguration period is deducted from the available time because it is assumed that the machines do not operate during reconfiguration period. In addition, the following constraint ensures that the machines are utilized at least at a rate of 85%.

$$\sum_{i=1}^{I}\sum_{j=1}^{J} \left(p_{ijmk} Y_{ijmkt} + \left(\frac{ST_{ijmk}}{L_t}\right) Y_{ijmkt} \right) \ge 0.85(AH_{mk} X_{mkt} - RD_t) \quad \forall m,k,t \qquad (6.20)$$

6.2.2 Reconfiguration activities

Reconfiguration task, duration and cost were formulated in equations (6.6) to (6.10). In addition to reconfiguration activities in the system, the capital cost of added machines and the revenues obtained from the sales of the machines were expressed in (6.4) and (6.2) respectively. Due to the fact that reconfiguration tasks involve comparison of two consecutive periods' configuration, several non-linear terms were used in order to express the variation in number of machines, number of bases and number of modules used. In order to linearize these terms the following set of constraints and variables are added to formulations.

6.2.2.1 Difference in number of machines

In order to calculate the cost of added machines and the revenue from sold machines we need to calculate the positive and negative difference in the number of machines between two consecutive periods. The following constraints and variables determine these values.

$$RX_{mkt} = X_{mkt} - X_{mk(t-1)} \tag{6.21}$$

$$RX_{mkt} = RX^{+}_{mkt} - RX^{-}_{mkt} \tag{6.22}$$

$$RX^{+}_{mkt} \leq \delta_{mkt} M \tag{6.23}$$

$$RX^{-}_{mkt} \leq (1-\delta_{mkt}) M \tag{6.24}$$

$$RX_{mkt} \in \Re, RX^{+}_{mkt}, RX^{-}_{mkt} \in \mathbb{Z}^{+}, \delta_{mkt} \in \{0,1\} \quad \forall m,k,t$$

Constraint (6.21) allows to calculate RX_{mkt}, which represents the difference in the number of machines of (m, k) between period t and (t-1). Since RX_{mkt} is a real number, constraint (6.22) allows separating into two positive variables where RX^{+}_{mkt} represents the positive difference and RX^{-}_{mkt} represents the negative difference. Constraints (6.23) and (6.24) ensures that either RX^{+}_{mkt} or RX^{-}_{mkt} is positive. The terms $Max(0, X_{mk(t-1)} - X_{mkt})$ in (6.2) and $Max(0, X_{mkt} - X_{mk(t-1)})$ in (6.4) can be replace by RX^{-}_{mkt} and RX^{+}_{mkt} respectively.

6.2.2.2 Difference in number of machine bases and modules

Similar to the difference in number of machines, the absolute value of difference in number of machine bases and machine modules used in (6.8) can be linearized using the following set of constraints:

$$RB_{mt} = B_{mt} - B_{m(t-1)} \tag{6.25}$$

$$RB_{mt} = RB^{+}_{mt} - RB^{-}_{mt} \tag{6.26}$$

$$RB^{+}_{mt} \le \theta_{mt} M \tag{6.27}$$

$$RB^{-}_{mt} \le (1-\theta_{mt}) M \tag{6.28}$$

$$RB_{mt} \in \Re, RB^{+}_{mt}, RB^{-}_{mt} \in \mathbb{Z}^{+}, \theta_{mt} \in \{0,1\} \quad \forall m,t$$

For the machine modules we add the following constraints:

$$RMD_{mkt} = MD_{mkt} - MD_{mk(t-1)} \tag{6.29}$$

$$RMD_{mkt} = RMD^{+}_{mkt} - RMD^{-}_{mkt} \tag{6.30}$$

$$RMD^{+}_{mkt} \le \omega_{mkt} M \tag{6.31}$$

$$RX^{-}_{mkt} \le (1-\omega_{mkt}) M \tag{6.32}$$

$$RMD_{mkt} \in \Re, RMD^{+}_{mkt}, RMD^{-}_{mkt} \in \mathbb{Z}^{+}, \omega_{mkt} \in \{0,1\} \quad \forall m,k,t$$

Using the set of constraints (6.25)-(6.32), the terms, $|B_{mt} - B_{m(t-1)}|$ and $|MD_{mkt} - MD_{mk(t-1)}|$ in (6.8), can be replaced by $(RB^{+}_{mt} + RB^{-}_{mt})$, and $(RMD^{+}_{mkt} + RMD^{-}_{mkt})$, respectively.

6.2.3 Book value and depreciation

The book value of the assets at the end of the planning horizon was added to the financial objective function using the term expressed in (6.14). In order to calculate the book value of assets at each period we need to calculate the depreciation of each machine of the system at each period.

Assuming a straight line depreciation method and eight years of economical life, the depreciation of each machine type in one period is expressed as follows:

$$DP_{mkt} = DP_{mk(t-1)} + RX_{mkt} IC_{mkt} d_{mk} \qquad \forall m,k,t \qquad (6.33)$$

where

d_{mk} Straight line depreciation rate of machine (m, k)

The book value of assets at each period is equal to the book value of the previous period less the depreciation, salvage value of disposed assets, and plus the value of purchased assets in each period. Book value at each period is calculated using the following equation:

$$BV_t = BV_{t-1} + \sum_{m=1}^{M}\sum_{k=1}^{K}(RX^{+}_{mkt} IC_{mkt} - RX^{-}_{mkt} SV_{mkt} - DP_{mkt}) \qquad \forall t \quad (6.34)$$

6.3. Overall optimization model

The following set of constraints and functions represent the final form of the fuzzy optimization methodology for the lifecycle evaluation of RMS systems.

NPV (ATCF) =

$$
\begin{aligned}
&+\sum_{t=1}^{T}\sum_{j=1}^{J}(P_{it}-MC_{it})M_{it}(1-TR)(\mathrm{P/F,\ I,\ t})+\sum_{t=1}^{T}\sum_{j=1}^{J}(P_{it}-OC_{it})Q_{it}(1-TR)(\mathrm{P/F,\ I,\ t})\\
&+\sum_{\mathrm{t}=1}^{\mathrm{T}}\sum_{m=1}^{M}\sum_{k=1}^{K}S_{mkt}RX^{-}_{mkt}(\mathrm{P/F,\ I,\ t})+\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{k=1}^{K}DP_{mkt}TR(\mathrm{P/F,I,t})\\
&-\sum_{\mathrm{m}=1}^{M}\sum_{k=1}^{K}IC_{mk1}*X_{mk1}-\sum_{t=2}^{T}\sum_{m=1}^{M}\sum_{k=1}^{K}IC_{mkt}RX^{+}_{mkt}(\mathrm{P/F,\ I,\ t})\\
&-\sum_{t}^{T}RC_{t}(1-TR)(\mathrm{P/F,I,t}) \qquad (6.35)\\
&-\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{k=1}^{K}(VC_{ijmk}*Y_{ijmkt}+FC_{ijmk}X_{mkt})*(1-TR)*(\mathrm{P/F,I,t})\\
&-\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{k=1}^{K}\frac{SC_{ijmk}*Y_{ijmkt}}{L_{t}}(1-TR)*(P/F,I,t)\\
&+BV_{T}*(P/F,I,T)
\end{aligned}
$$

Minimize Complexity

$$
Complexity=\frac{\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{k=1}^{K}a_{mk}X_{mkt}\sum_{n=1}^{2}p_{mkn}\log_2(\frac{1}{p_{mkn}})}{T} \qquad (6.36)
$$

Maximize Responsiveness

$$
Responsiveness=\frac{\sum_{t}^{T}\sum_{m}^{M}\sum_{k}^{K}\sum_{i}^{I}P_{imk}*RA_{imk}*X_{mkt}}{T} \qquad (6.37)
$$

The above objective functions are represented with fuzzy membership functions, and incorporated to the constraint set using the maxmin approach explained in section 3.5

Max λ

Subject to:

$$\frac{NPV(ATCF) - \min NPV}{\max NPV - \min NPV} \geq \lambda \tag{6.38}$$

$$\frac{\max C - Complexity}{\max C - \min C} \geq \lambda \tag{6.39}$$

$$\frac{Responsiveness - \min R}{\max R - \min R} \geq \lambda \tag{6.40}$$

$$0 \leq \lambda \leq 1 \tag{6.41}$$

$$M_{it} + Q_{it} = D_{it} \qquad \forall i,t \tag{6.42}$$

$$Q_{it} \leq \alpha D_{it} \qquad \forall i,t \tag{6.43}$$

$$Y_{ijmkt} \leq z_{ijmk} M_{it} \qquad \forall i,j,m,k,t \tag{6.44}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} p_{ijmk} Y_{ijmkt} + \left(\frac{ST_{ijmk}}{L_t}\right) Y_{ijmkt} \leq AH_{mk} X_{mkt} - RD_t \quad \forall m,k,t \tag{6.45}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} p_{ijmk} Y_{ijmkt} + \left(\frac{ST_{ijmk}}{L_t}\right) Y_{ijmkt} \geq 0.85 AH_{mk} X_{mkt} - RD_t \quad \forall m,k,t \tag{6.46}$$

$$DP_{mkt} = DP_{mk(t-1)} + RX_{mkt} IC_{mkt} d_{mk} \qquad \forall m,k,t \tag{6.47}$$

$$BV_t = BV_{t-1} + \sum_{m=1}^{M}\sum_{k=1}^{K} (RX_{mkt}^{+} IC_{mkt} - RX_{mkt}^{-} SV_{mkt} - DP_{mkt}) \qquad \forall t \tag{6.48}$$

$$RT_t = \sum_{m=1}^{M} t_B \left(RB_{mt}^{+} + RB_{mt}^{-} \right) + \sum_{m=1}^{M} \sum_{k=1}^{K} t_{MD} \left(RMD_{mkt}^{+} + RMD_{mkt}^{-} \right) \quad \forall t \tag{6.49}$$

$$Cost_{\text{Re}configuration} = RC_t = LR(RT_t) \qquad \forall t \tag{6.50}$$

$$Time_{\text{Re}configuration} = RD_t = \frac{RT_t}{W_t} \qquad \forall t \tag{6.51}$$

$$RX_{mkt} = X_{mkt} - X_{mk(t-1)} \quad \forall m,k,t \tag{6.52}$$

$$RX_{mkt} = RX_{mkt}^{+} - RX_{mkt}^{-} \quad \forall m,k,t \tag{6.53}$$

$$RX_{mkt}^{+} \le \delta_{mkt} M \quad \forall m,k,t \tag{6.54}$$

$$RX_{mkt}^{-} \le (1 - \delta_{mkt}) M \quad \forall m,k,t \tag{6.55}$$

$$RB_{mt} = B_{mt} - B_{m(t-1)} \quad \forall m,t \tag{6.56}$$

$$RB_{mt} = RB_{mt}^{+} - RB_{mt}^{-} \quad \forall m,t \tag{6.57}$$

$$RB_{mt}^{+} \le \theta_{mt} M \quad \forall m,t \tag{6.58}$$

$$RB_{mt}^{-} \le (1 - \theta_{mt}) M \quad \forall m,t \tag{6.59}$$

$$RMD_{mkt} = MD_{mkt} - MD_{mk(t-1)} \quad \forall m,k,t \tag{6.60}$$

$$RMD_{mkt} = RMD_{mkt}^{+} - RMD_{mkt}^{-} \quad \forall m,k,t \tag{6.61}$$

$$RMD_{mkt}^{+} \le \omega_{mkt} M \quad \forall m,k,t \tag{6.62}$$

$$RX_{mkt}^{-} \le (1 - \omega_{mkt}) M \quad \forall m,k,t \tag{6.63}$$

$$RB_{mt} \in \Re, RB_{mt}^{+}, RB_{mt}^{-}, B_{mt} \in \mathbb{Z}^{+}, \theta_{mt} \in \{0,1\} \quad \forall m,t \tag{6.64}$$

$$RMD_{mkt} \in \Re, RMD_{mkt}^{+}, RMD_{mkt}^{-}, MD_{mkt} \in \mathbb{Z}^{+}, \omega_{mkt} \in \{0,1\} \quad \forall m,k,t \tag{6.65}$$

$$RX_{mkt} \in \Re, RX_{mkt}^{+}, RX_{mkt}^{-}, X_{mkt} \in \mathbb{Z}^{+}, \delta_{mkt} \in \{0,1\} \quad \forall m,k,t \tag{6.66}$$

$$M_{it}, Q_{it}, Y_{ijmkt}, RD_{t}, RC_{t}, BV_{t}, DP_{mkt} \in \mathbb{Z}^{+} \tag{6.67}$$

The mathematical model above represents the lifecycle evaluation methodology explained in chapter 3. The three criteria explained have been converted to constraints using fuzzy membership functions. In order to combine all the objectives into the model, an overall satisfaction degree variable, λ, has been introduced. It is converted in standard form of mixed integer optimization by maximizing the overall satisfaction degree. The model can be implemented using any linear optimization software package. The following chapter represents a case study of the methodology, where the model has been implemented in GAMS software package.

CHAPTER SEVEN

CASE STUDY

This chapter presents a case study for the evaluation of RMS investments. The case study includes two different demand scenarios used to generate suitable RMS configurations and analyze the performance of such systems under a demand scenario with an increasing demand level, and a fluctuating demand scenario. Life cycle cost analysis is performed for both an RMS and an FMS, which can both meet the stipulated demands. Sensitivity analysis is carried out to analyze the effect of reconfiguration period on lifecycle performance and a simulation study was conducted to validate the performance of the generated configurations using the proposed methodology.

7.1. Lifecycle cost analysis of RMS investments

Two potential parts are to be produced for which 2 different demand scenarios are considered throughout the lifecycle of a manufacturing system following the example cited in Suresh (1992). In order to manufacture these parts, three types of machines need to be installed: Drill, mill, and lathe. All of these machine types have numerical control and a modular structure that allows adding/removing modules (e.g. spindles or axes of motion). It is assumed that each machine type can have three different configurations. Based on these changeable modules each machine type can be reconfigured to have additional capability and/or capacity.

A planning horizon of 8 years is considered. The selling prices for the two products are assumed to decrease while the material costs are expected to rise. The two demand scenarios reflect different market conditions. The first represents a demand scenario with an increasing trend where part 1 is introduced after 4 years. The second demand scenario represents a fluctuating market condition where both parts are being produced simultaneously.

7.1.1 Demand scenarios

By following the demand requirements, the available machine candidates, and their cost structures, the model will select the right machine configuration and the acquisition strategy, and determine the optimal production schedules. Since this is a multiple objective optimization, based on the satisfaction degree of each objective, the model will generate results that accomplish both the financial and strategic objectives. Appendix A includes various input data regarding the operational and cost structure used in this case study.

Two deterministic demand scenarios will be applied in order to evaluate RMS investments. Demand scenario 1, has an increasing trend with an addition of a new product in fifth year. Demand scenario 2 represents a fluctuating demand scenario where two products are produced simultaneously.

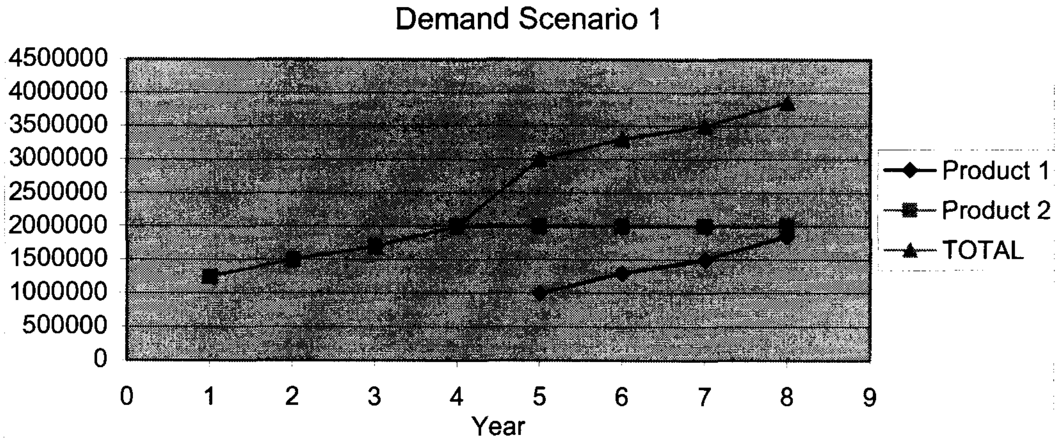


Figure 7.1 Demand scenario 1

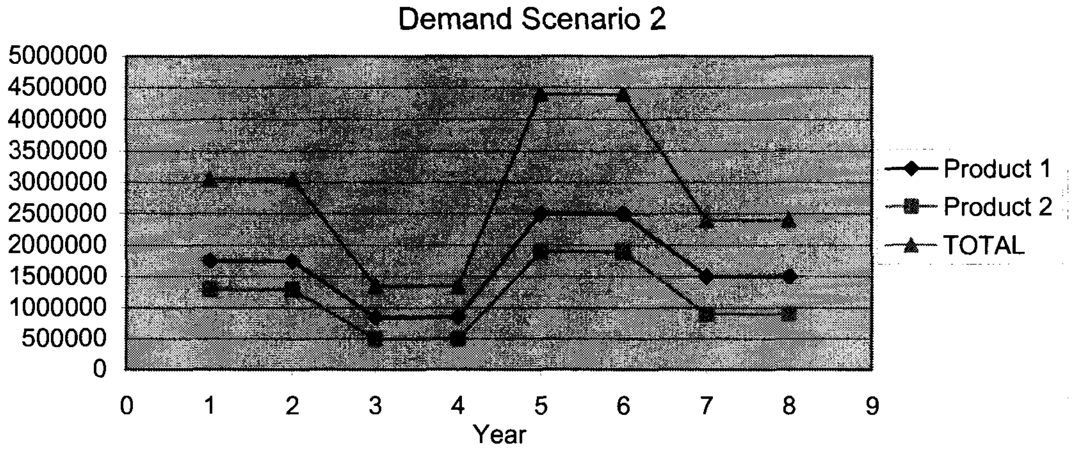


Figure 7.2 Demand Scenario 2

7.1.2 Case study assumptions and parameters

The following assumptions and parameters are used in this case study:

- There are three types of machine bases each of which can be in three different configuration states, i.e. m=1, 2, 3 and k=1, 2, 3.
- 8 years of planning horizon is considered.
- For each part, a maximum of 20% outsourcing is allowed.
- Each period consists of one production year, which consists of 250 days, and 7.5 hours / day production time.
- Each machine configuration has an availability value depending on the number of modules attached to the base. We assume 0.92, 0.9, and 0.88 availability for configuration states of 1, 2, and 3 respectively.
- Time required to install a machine base, t_b, is 300 man-hours, and time to install a machine module, t_{MD}, is 150 man-hours.
- Available workforce for reconfiguration, W_t, is 50 workers.

- Interest rate for each period is 12%.
- Tax rate is 40%.

The model has been implemented in GAMS software package and solved using CPLEX solver algorithm on SUN Unix workstations. For each demand scenario, seven different runs have been performed. Each objective function has been maximized and minimized subject to the case study's constraints in order to define the maximum and minimum values. These values have been used to determine the fuzzy membership functions of each objective, followed by the multiple objective optimization run. Each run's CPU time was 22 hours on average with a solution obtained within 2% of the relaxed solution.

7.1.3 RMS evaluation using single and multiple objective

7.1.3.1 Demand scenario 1

Table 7.1 and Table 7.2 show the results for Scenario 1, considering the three objectives. The satisfaction degree results for NPV, complexity, and responsiveness objectives are 0.867, 0.862, and 0.865 respectively. The number of machine configurations follows the demand trend. As a result of dynamically following the demand changes, some reconfiguration activities are performed with an average cost of $12,600. Table 7.3 and Table 7.4 represent the results obtained by using only the financial objective. As seen in Table 7.4, the NPV based solely on financial evaluation is higher than the NPV of multiple objective evaluation. However, the value of complexity and responsiveness metrics is better with configurations obtained by multiple objective evaluation, as shown in Figure 7.4 and Figure 7.5.

Table 7.1: Scenario 1 / Machine configurations / Multiple Objective

	0	1	2	3	4	5	6	7	8
Complexity		4.73	5.79	5.79	6.85	10.43	11.63	12.10	13.38
Responsiveness		1.74	3.09	3.09	3.46	4.49	4.49	4.48	4.48
Utilization		0.88	0.88	0.99	0.99	0.99	0.97	0.99	0.98
Outsourcing Level		20%	20%	20%	20%	20%	20%	20%	20%
Rec Cost Actual value		12	0	12	39.6	10.8	4.8	21	0
Capital Outlays Actual value($K)	-4,605	1,800	0	1,575	4,695	445	200	720	0
Cash Flows Present value($K)	-4,605	1,137	2,230	263	-2,206	1,548	1,103	322	1,915
Cumulative Cash flows Present value($K)	-4,605	-3,467	-1,236	-973	-3,179	-1,631	-528	-205	1,709
NPV(ATCF) ($K)	1,709								

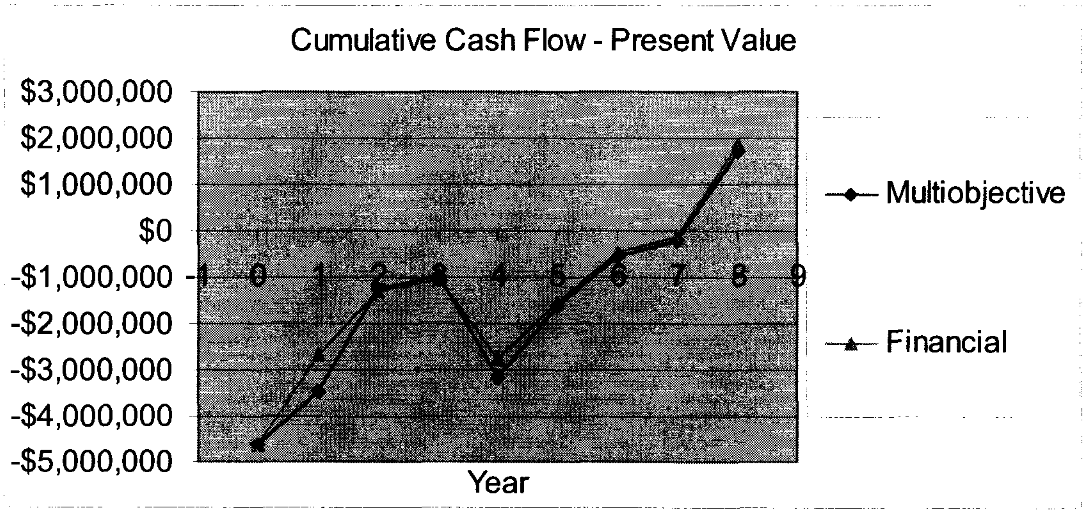


Figure 7.3 Cumulative Cash Flow/Scenario 1/ Financial vs. Multiple Objective

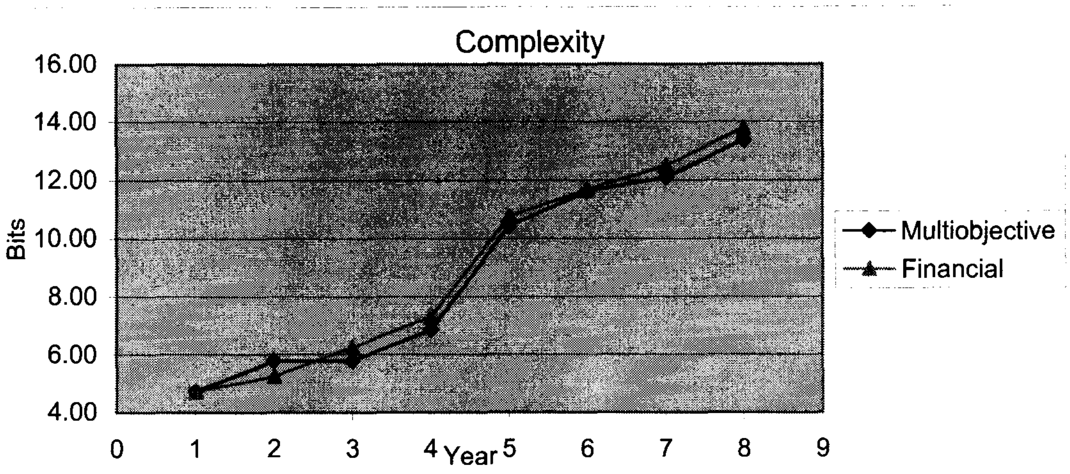


Figure 7.4 Scenario 1 / Complexity comparison Multiple objective vs Financial

Table 7.2: Scenario 1 / Machine configurations / Multiple Objective

		1	2	3	4	5	6	7	8
Drill	1mod	1	1	1	1	1	2	2	3
	2mod	1	1	1	1	1	1	1	2
	3mod	1	1	1	2	5	5	5	5
Lathe	1mod	1	1	1	1	2	3	3	4
	2mod	1	1	1	1	1	1	2	3
	3mod	1	1	1	2	5	5	5	5
Mill	1mod	1	1	1	1	1	2	2	2
	2mod	1	1	1	1	1	1	1	0
	3mod	2	4	4	4	4	4	4	4
Total		10	12	12	14	21	24	25	28

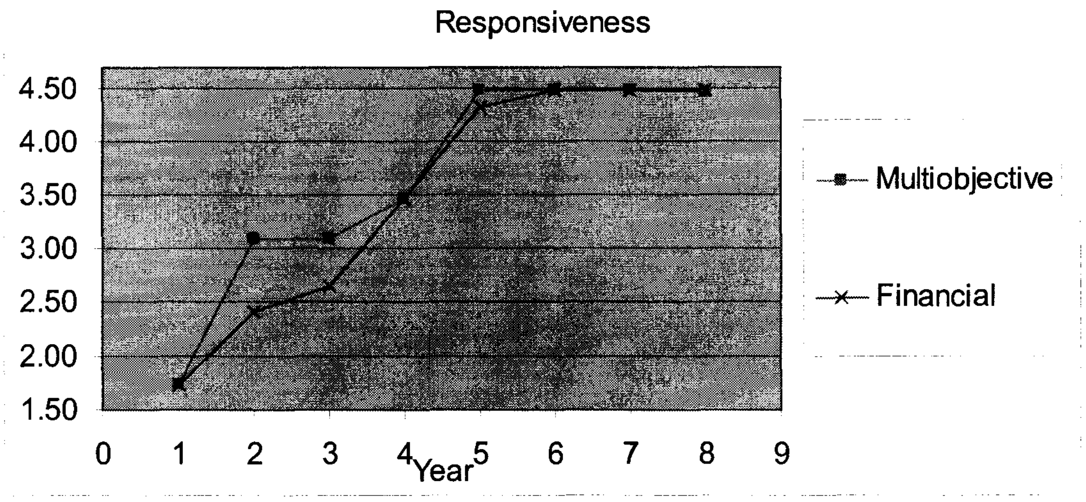


Figure 7.5 Scenario 1 / Responsiveness comparison Multiple Objective vs Financial

Table 7.3: Scenario 1 / System Performance Results/Financial Objective

	0	1	2	3	4	5	6	7	8
Complexity		4.73	5.26	6.26	7.32	10.77	11.70	12.50	13.78
Responsiveness		1.74	2.41	2.65	3.46	4.32	4.49	4.48	4.48
Utilization		0.88	0.95	0.89	0.89	0.92	0.94	0.94	0.95
Outsourcing Level		20%	20%	20%	20%	20%	20%	20%	20%
Rec Cost Actual value($K)		6	10.8	12.	37.2	9.6	7.2	14.4	0
Capital Outlays Actual value($K)		900	975	1,675	4,015	925	295	775	0
Cash Flows Present value($K)	-4,605	1,944	1,373	239	-1,721	1,235	1,090	312	2,020
Cumulative Cash flows Present value($K)	-4,605	-2,660	-1,286	-1,047	-2,768	-1,533	-442	-129	1,890
NPV(ATCF) ($K)	1,890								

Table 7.4: Scenario 1 / System Configurations / Financial Objective

		1	2	3	4	5	6	7	8
drill	1mod	1	1	1	1	1	2	2	3
	2mod	1	1	1	1	1	1	1	2
	3mod	1	1	2	2	5	5	5	5
lathe	1mod	1	1	1	1	3	3	4	4
	2mod	1	1	2	2	2	2	2	3
	3mod	1	1	1	2	4	5	5	5
mill	1mod	1	1	1	1	1	1	2	3
	2mod	1	1	1	1	1	1	1	0
	3mod	2	3	3	4	4	4	4	4
Total		10	11	13	15	22	24	26	29

The following figure represents the comparison of two configurations in terms of their utilization. Figure 7.6 shows that using multiple objectives generate configurations with higher utilization rate.

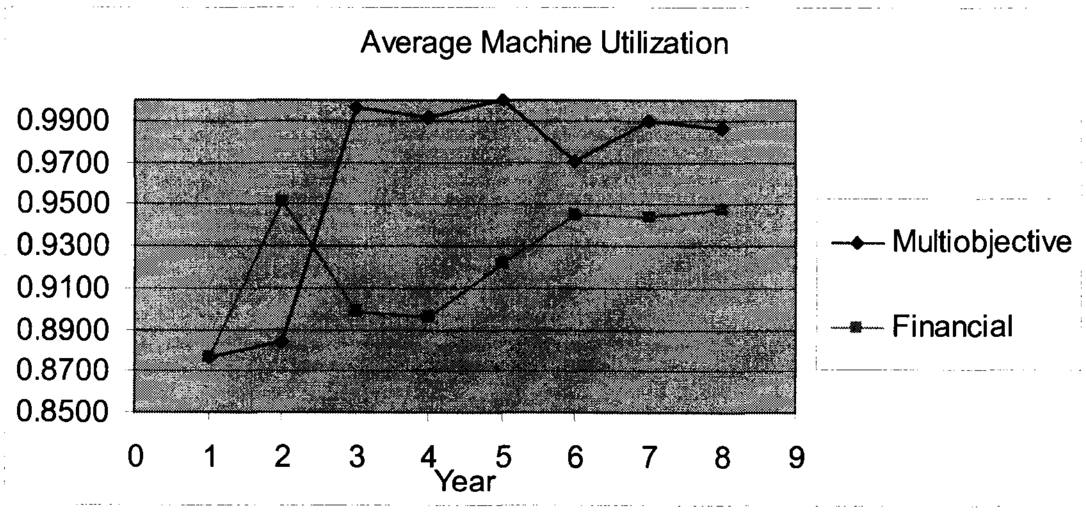


Figure 7.6 Scenario 1/ Machine Utilization / Multiple objective vs. Financial

7.1.3.2 Demand scenario 2

Demand scenario 2 represents a fluctuating market condition, which affects the resulting machine configurations as shown in Table 15. The satisfaction degree results for NPV, complexity, and responsiveness are 0.867, 0.862, and 0.872 respectively. As the variation in demand is higher than scenario 1, the reconfiguration costs are $34,050 on average. If we compare the investment level of Scenario 1 and Scenario 2 in multiple objective evaluation, the total investment levels are $11 and $19.2 million respectively. Although there is a 10% difference in total sales, the demand fluctuations required an investment level increase of 75%.

Table 7.5: Scenario 2 / System Configurations / Multiple Objective

		1	2	3	4	5	6	7	8
drill	1mod	2	1	1	1	3	5	2	2
	2mod	2	1	1	1	3	2	2	2
	3mod	4	5	1	1	4	4	3	3
lathe	1mod	2	3	1	1	3	5	1	1
	2mod	1	4	1	1	5	5	0	0
	3mod	4	2	1	1	4	5	5	5
mill	1mod	2	1	1	1	5	1	0	0
	2mod	1	1	1	1	1	1	0	0
	3mod	4	4	3	3	4	4	4	4
Total		22	22	11	11	32	32	17	17

Complexity and responsiveness metrics for configurations generated under demand scenario 2 are shown in Figure 7.8 and Figure 7.9. The complexity level follows the demand trend in both financial and multiple objective evaluations since it is dependent on the number of machines in the system. The responsiveness metric performance shows that optimizing the system based only on financial considerations results in a lower responsiveness performance.

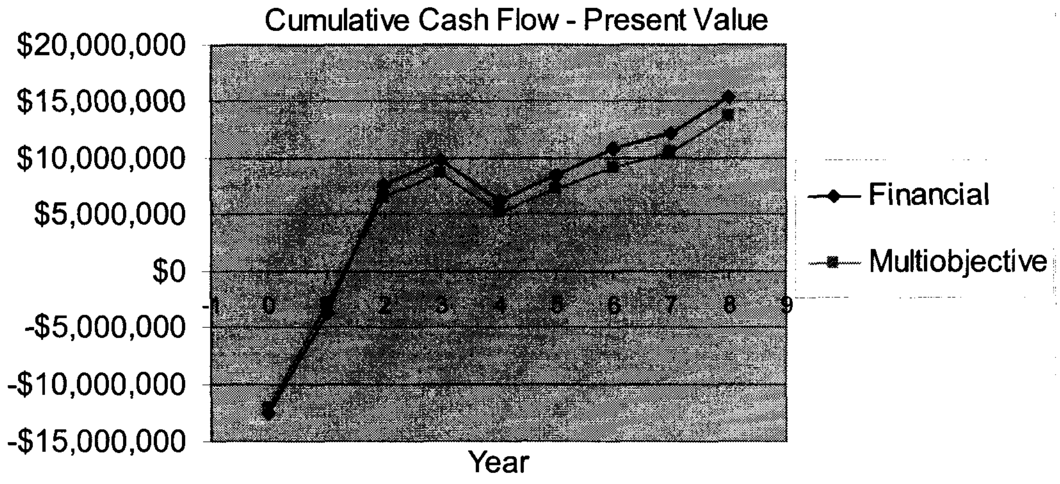


Figure 7.7 Cumulative Cash Flow/Scenario 2/ Financial vs. Multiple Objective

Table 7.6: Scenario 2 / System Performance Results / Multiple Objective

	0	1	2	3	4	5	6	7	8
Complexity		10.64	10.65	5.26	5.26	15.00	15.06	8.50	8.50
Responsiveness		4.06	3.80	2.26	2.26	4.08	4.29	4.10	4.10
Utilization		0.98	0.99	0.89	0.89	0.97	0.98	0.99	0.99
Outsourcing Level		0.2	0.2	0.199	0.199	0.2	0.2	0.2	0.2
Rec Cost Actual value ($K)		19	57.6	0	99.6	32.4	63.6	0	0
Capital Outlays Actual value ($K)		1,520	0	0	7,940	1,315	0	0	0
Cash Flows Actual value ($K)	-12,080	10,189	11,945	2,931	-5,486	3,593	3,954	2,698	8,037
Cumulative Cash flows Actual value ($K)	-12,080	-1,890	10,054	12,986	7,499	11,092	15,047	17,745	25,782
Cash Flows Present value ($K)	-12,080	9,097	9,522	2,086	-3,486	2,038	2,003	1,220	3,246
Cumulative Cash flows Present value ($K)	-12,080	-2,982	6,540	8,626	5,140	7,178	9,182	10,403	13,649
NPV(ATCF) ($K)	13,649								

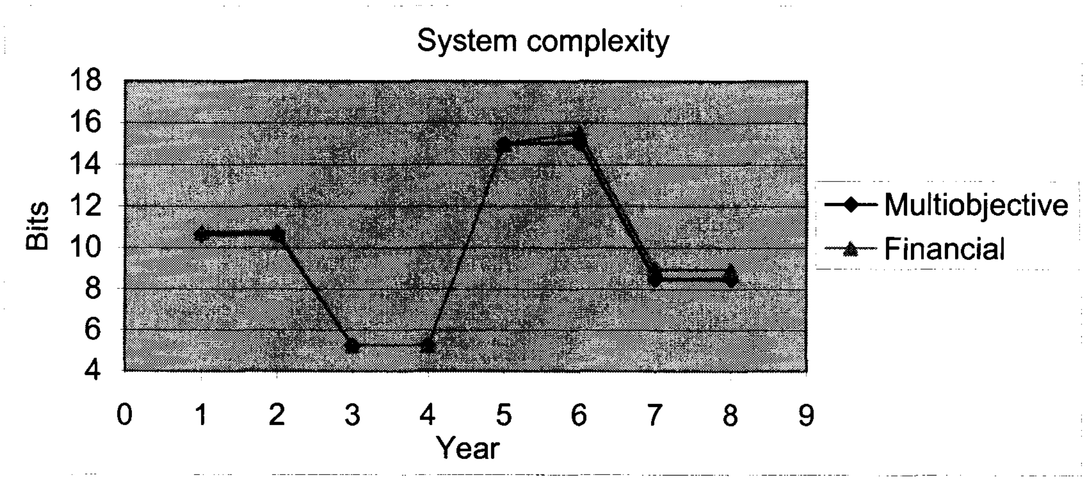


Figure 7.8 Scenario 2 / Complexity comparison / Multiple objective vs Financial

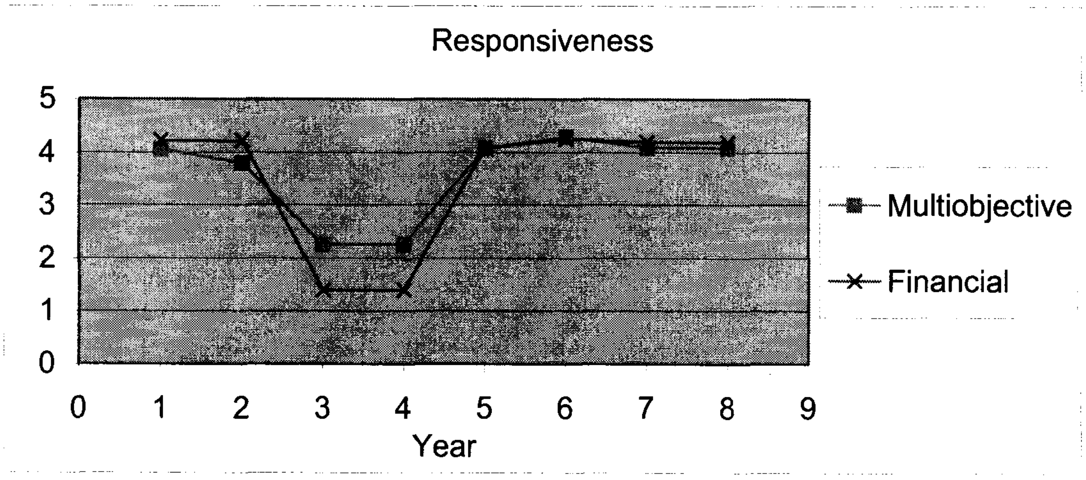


Figure 7.9 Scenario 2 / Responsiveness comparison / Multiple objective vs Financial

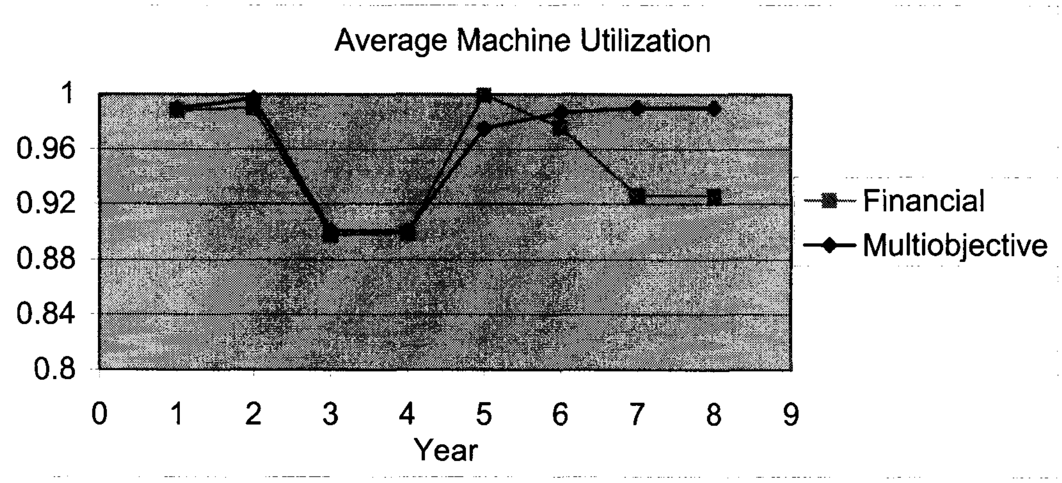


Figure 7.10 Scenario 2/ Machine Utilization / Multiple objective vs. Financial

7.1.4 RMS vs FMS implementation

In order to compare the performance of FMS and RMS configurations, for the same demand scenarios and all other conditions, the model has been modified to generate FMS configurations. In the FMS case, the reconfiguration aspect of configurations evaluation has been disabled, and the candidate machines have been replaced by FMS machine types, which have the flexibility to process various types of operations through out the considered periods, i.e. the whole system life cycle. The following results represent an FMS implementation for the same demand scenarios.

7.1.4.1 Demand scenario 1

Table 7.7 and Table 7.8 show the results for Scenario 1, considering three objectives for an FMS implementation. The satisfaction degrees for NPV, complexity, and responsiveness objectives are 0.782, 0.06, and 0.5 respectively. The membership function degree results show that while financial objective satisfaction is at higher levels, the satisfaction performance of complexity is low and responsiveness is at mid range. In scenario 1, the average complexity of RMS configurations is 8.84 bits where the FMS system configurations have a complexity level of 17.08 bits. This result shows that the FMS system is more complex due to the use of complex machine structures with redundant modules for additional capability. While the FMS configuration is more complex, the average responsiveness level of 12.79/system or 0.45/machine depicts that the FMS system is more responsive than an RMS system whose average responsiveness is 8.84/system or 0.21/machine. Since the responsiveness metric used in this methodology tries to capture the ability to changeover the production from one to another within the same configuration, the FMS system is more responsive considering that its machines are more flexible and having various built in capabilities.

Table 7.7: Scenario 1 / FMS Configurations

	1	2	3	4	5	6	7	8
CNC drill	6	6	6	6	6	6	6	6
CNC mill	16	16	16	16	16	16	16	16
CNC lathe	6	6	6	6	6	6	6	6
TOTAL	28	28	28	28	28	28	28	28

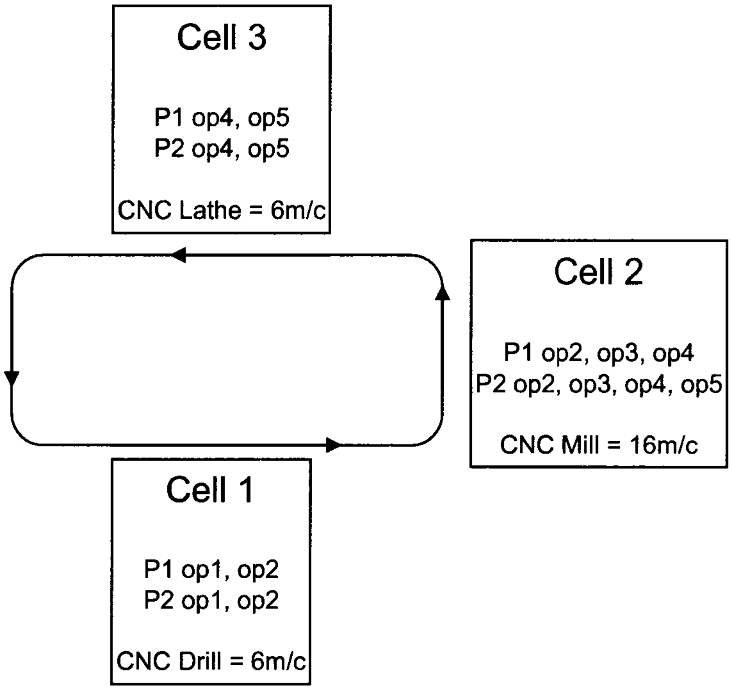


Figure 7.11 Scenario 1 / FMS Configuration

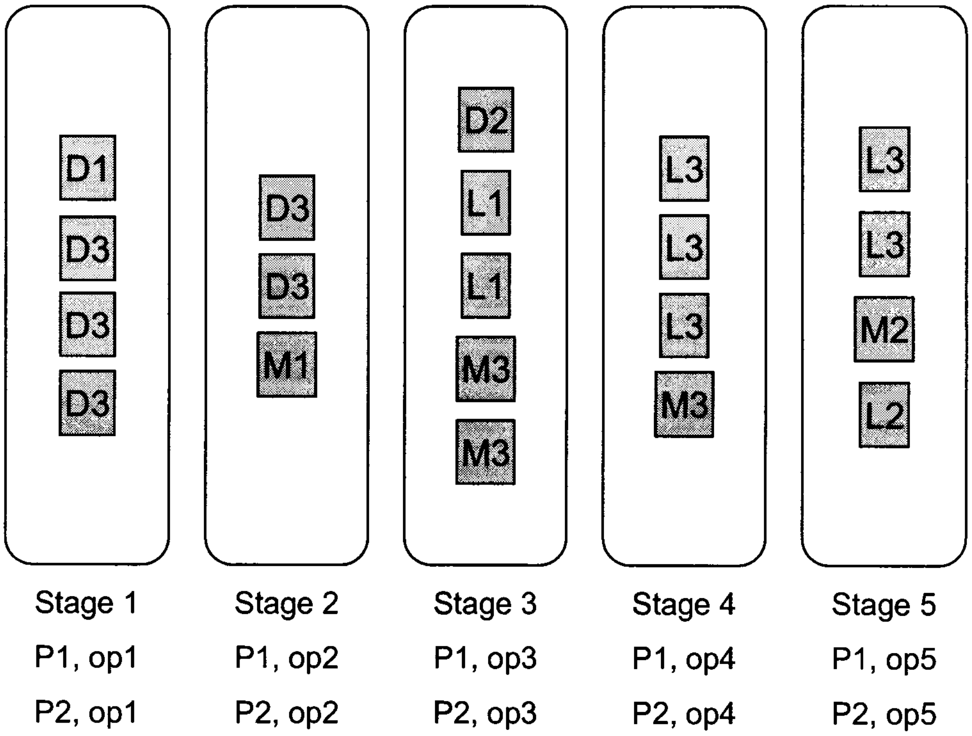


Figure 7.12 Scenario 1 / RMS Configuration / Year 5

The financial results of the FMS implementation for scenario 1 shows that it requires 118% more total investment compared to an RMS implementation to meet the demand requirements over the same system life span. However, the RMS system generates an NPV of $1.7M compared to an NPV of -$7.5M of an equivalent FMS implementation. This can be explained by high initial investment cost of FMS systems and the reconfigurability of RMS systems. The ability to reconfigure allows RMS systems to be efficiently used while FMS systems cope with variation by investing in slack capacity. Due to the investment cost of this extra capacity, FMS requires longer time to obtain return on the investment, and fails to return on its investment within the planning horizon.

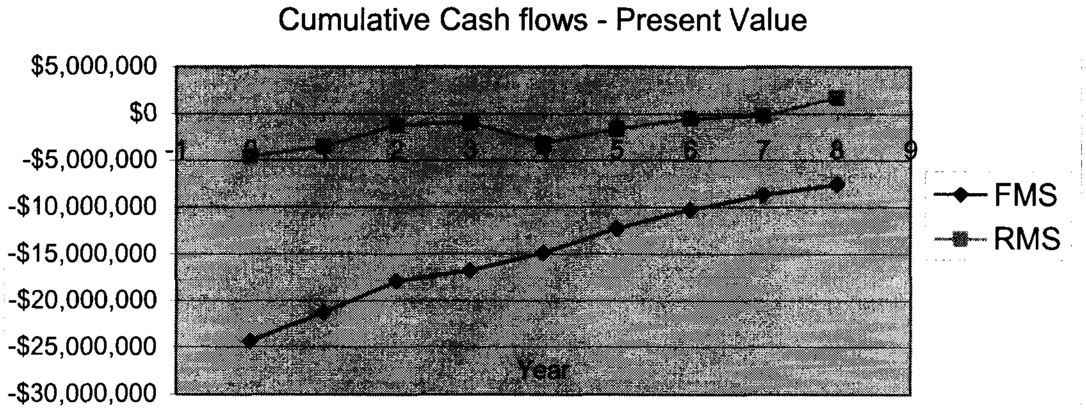


Figure 7.13 Scenario 1 / Cumulative Cash Flows / FMS vs. RMS

Table 7.8: Scenario 1 / FMS Performance Results

	0	1	2	3	4	5	6	7	8
Complexity		17.08	17.08	17.08	17.08	17.08	17.08	17.08	17.08
Responsiveness		13.05	13.05	13.05	13.05	12.63	12.55	12.51	12.44
Utilization		0.39	0.39	0.59	0.49	0.74	0.79	0.89	0.98
Outsourcing Level		1%	17%	0%	20%	20%	20%	20%	20%
Capital Outlays Actual value($K)	-24,360								
Cash Flows Actual value($K)	-24,360	3,470	4,222	1,595	2,968	4,520	4,057	3,346	2,883
Cumulative Cash flows Actual value($K)	-24,360	-20,889	-16,667	-15,071	-12,103	-$7,582	-3,524	-178	2,705
Cash Flows Present value($K)	-24,360	3,098	3,366	1,135	1,886	2,565	2,055	1,513	1,164
Cumulative Cash flows Present value($K)	-24,360	-21,261	-17,895	-16,759	-14,873	-12,307	-10,252	-8,738	-7,573
NPV(Cash Flows) ($K)	-7,573								

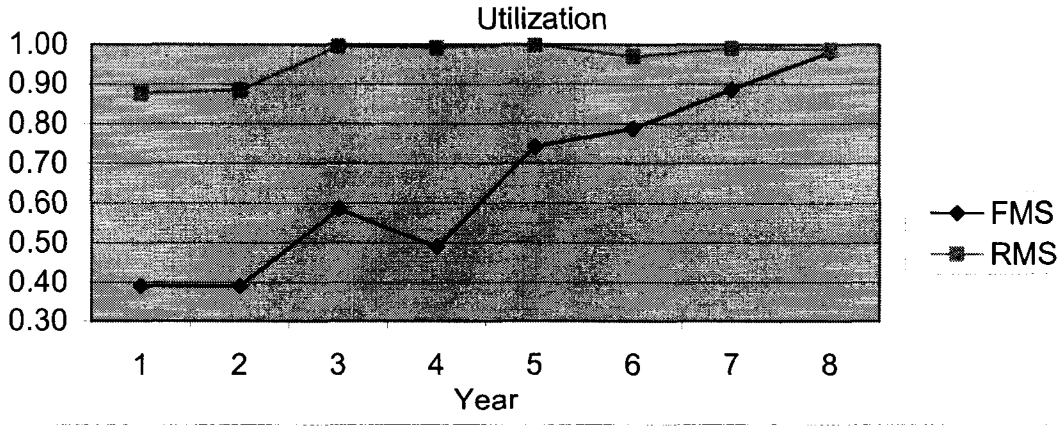


Figure 7.14 Scenario 1 / FMS vs RMS utilization

Figure 7.14 shows that FMS configuration is underutilized compared to RMS implementation throughout the planning horizon. While the built in capacity and capability allows better responsiveness in FMS, RMS configurations are used efficiently.

7.1.4.2 Demand scenario 2

Table 7.9 and Table 7.10 represent the results from FMS implementation for demand scenario 2. The satisfaction degrees for NPV, complexity, and responsiveness objectives are 0.953, 0.962, and 0.930 respectively. The complexity level of FMS configuration is at 19.51 bits, which is 98% more complex on average than the RMS implementation. The responsiveness level is 15.08/system or 0.47/machine for the FMS implementation. However, this higher level of responsiveness results in an average utilization level of 71% where the RMS is efficiently utilized with a 97% utilization rate.

Financial results of the FMS implementation for scenario 2 shows that it requires 44% more total investment compared to an RMS implementation to meet the demand requirements over the examined period. The FMS system generates an NPV of $8.8M compared to an NPV of $13.6M of an equivalent FMS implementation. This can be explained by the fewer outsourced products in the FMS case compared to the results of RMS implementation. The 15% average level of outsourcing in FMS case versus the 20% outsourcing level in RMS case is mainly due to the initial built-in excess capacity levels of FMS configuration.

Table 7.9: Scenario 2 / FMS Configurations

	1	2	3	4	5	6	7	8
CNC drill	9	9	9	9	9	9	9	9
CNC mill	19	19	19	19	19	19	19	19
CNC lathe	4	4	4	4	4	4	4	4
TOTAL	32	32	32	32	32	32	32	32

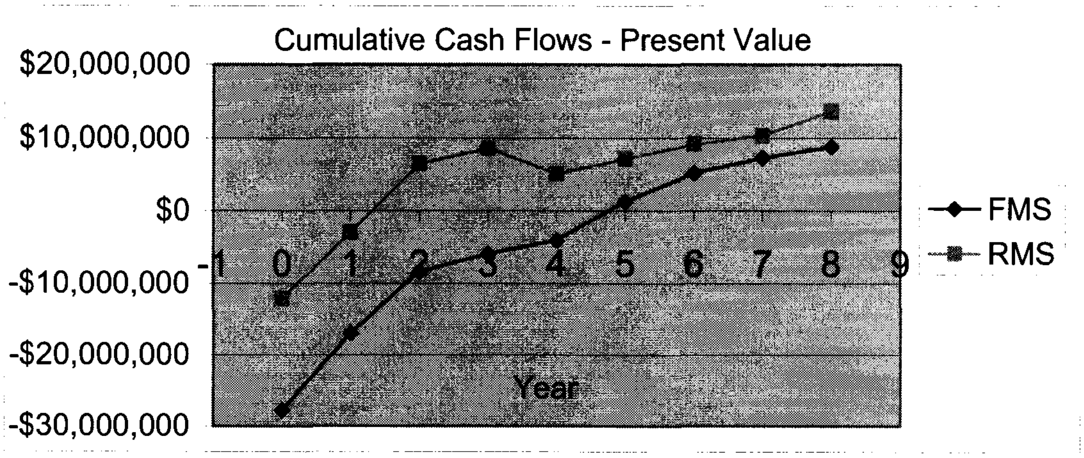


Figure 7.15 Scenario 2 / Cumulative Cash Flows / FMS vs RMS

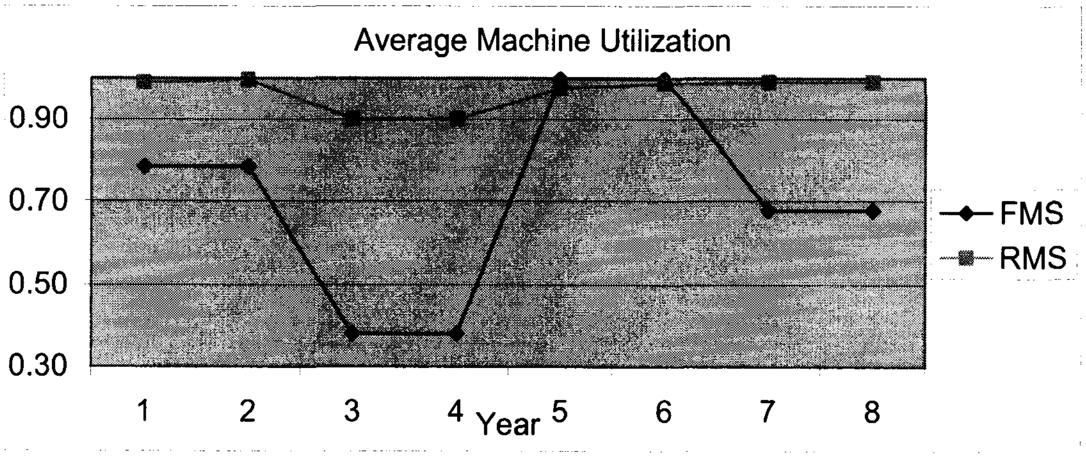


Figure 7.16 Scenario 2 / FMS vs. RMS utilization

Figure 7.16 shows that FMS investment is underutilized compared to RMS implementation throughout the planning horizon. Since FMS is designed to meet the anticipated demand increases, it will be underutilized in the periods where lower demand levels occur. While the built in capacity and capability allows better responsiveness in FMS, RMS configurations are used efficiently.

Table 7.10: Scenario 2 / FMS Performance Results

	0	1	2	3	4	5	6	7	8
Complexity		19.51	19.51	19.51	19.51	19.51	19.51	19.51	19.51
Responsiveness		15.52	15.52	15.52	15.52	14.80	14.67	14.60	14.49
Utilization		0.78	0.78	0.38	0.38	1.00	1.00	0.68	0.68
Outsourcing Level		20%	20%	1%	1%	20%	20%	20%	20%
Capital Outlays Actual value($K)	-27740								
Cash Flows Actual value ($K)	-27740	12137	10759	3461	2910	9373	7767	4570	3815
Cumulative Cash flows Actual value($K)	-27740	-15603	-4844	-1383	1528	10901	18668	23238	27052
Cash Flows Present value($K)	-27740	10837	8577	2464	1850	5319	3935	2067	1541
Cumulative Cash flows Present value($K)	-27740	-16903	-8326	-5863	-4013	1305	5240	7308	8848
NPV(ATCF) ($K)	8848								

7.1.5 Sensitivity analysis

In this section, the effect of reconfiguration task on RMS performance will be evaluated both in terms of financial and operational measures. Since the main operational characteristic of RMS is the reconfiguration activities, it is important to analyze how the duration of reconfiguration affects the RMS performance. In order to do this, the task time of one machine base installation/removal time, t_b, and one machine module installation/removal time, t_{MD}, is used. Initially, t_b, and t_{MD} is set to 5 hours and 2.5 hours respectively. At each step, machine base installation/removal time and machine module installation/removal time has been increased by 5 hours and 2.5 hours respectively.

The unit reconfiguration time changes have been applied to the fluctuating demand scenario 2. The following figure shows the effect of reconfiguration time on financial performance.

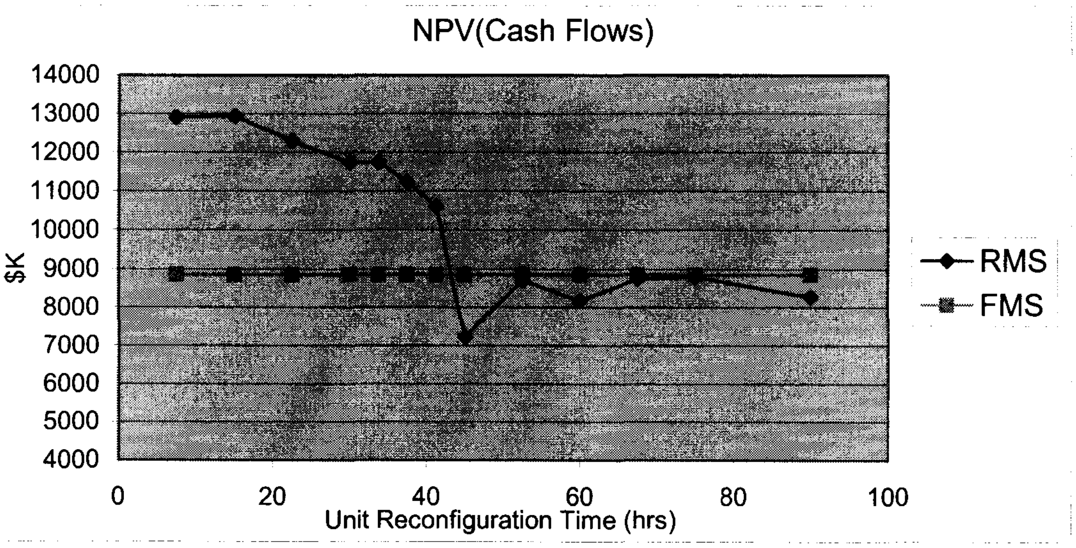


Figure 7.17 Effect of Reconfiguration Time on Financial Performance

Table 7.11: Effect of Reconfiguration time on Financial Performance

Reconfiguration Time (hrs.)	NPV (Cash Flows)	
	RMS	FMS
7.5	12,914	8,848
15	12,939	8,848
22.5	12,291	8,848
30	11,733	8,848
33.75	11,736	8,848
37.5	11,218	8,848
41.25	10,594	8,848
45	7,236	8,848
52.5	8,707	8,848
60	8,175	8,848
67.5	8,751	8,848
75	8,794	8,848
90	2,897	8,848

As illustrated in Figure 7.17, as the time to reconfigure a machine and a module increases, the financial performance decreases. This is due to the increasing cost of total reconfiguration and decreasing available time for actual production. The decrease in available time causes additional investment in machinery, which in turn lowers the NPV. It is also important to note that for a unit reconfiguration time greater than 42.8 hrs, the investment in FMS is more profitable.

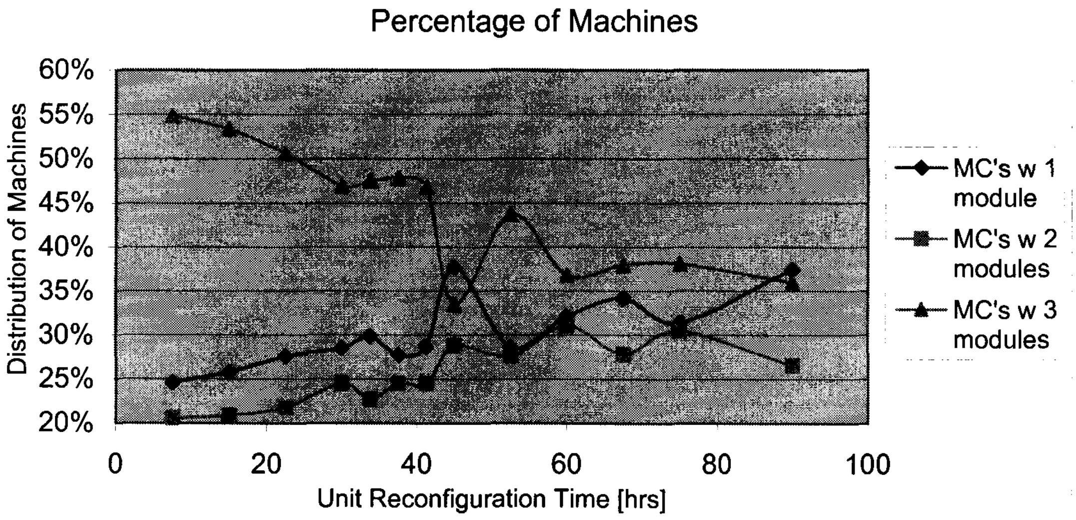


Figure 7.18 Distribution of Machines vs. Reconfiguration Time

Figure 7.18 shows that, as unit reconfiguration time increases, the frequency of machines that has only one module increases. This is due to the fact that machines with fewer modules require less reconfiguration time. In addition, the total average number of machines increases as the unit reconfiguration time increases, as shown in Figure 7.19.

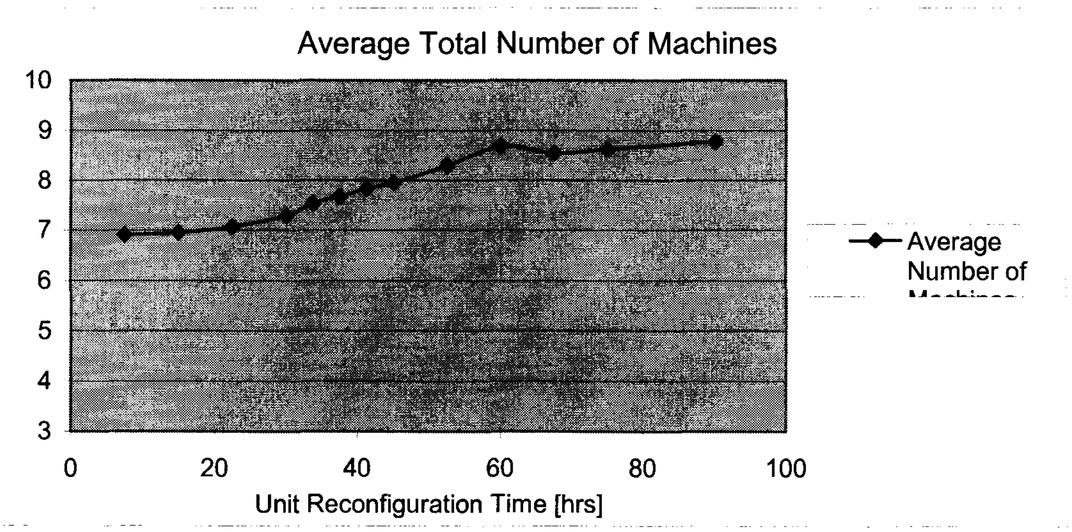


Figure 7.19 Effect of Reconfiguration Time on Total Number of Machines

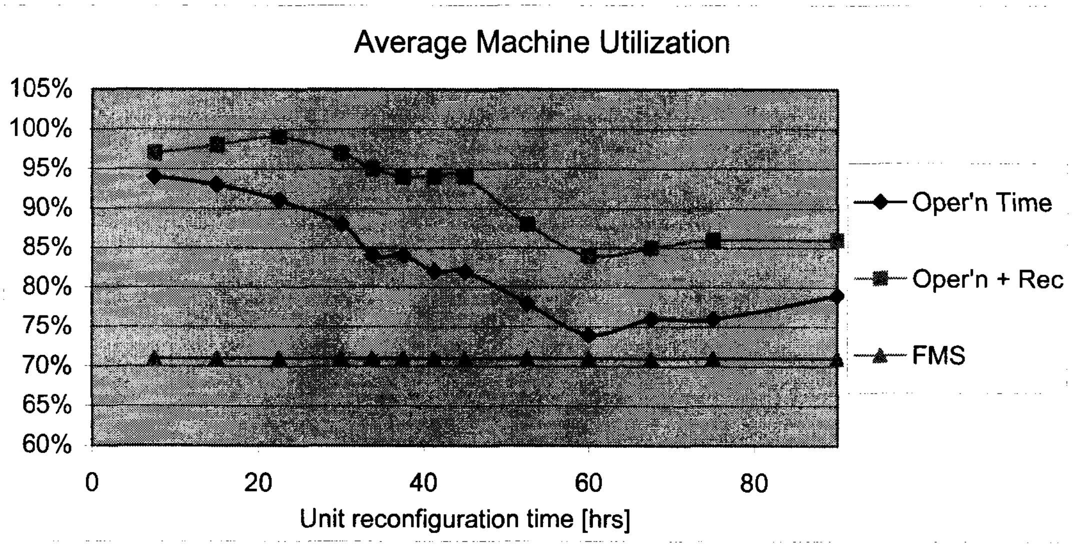


Figure 7.20 Effect of Reconfiguration Time on Utilization

Figure 7.20 shows the effect of unit reconfiguration time on average machine utilization. In this figure, the legend operation time represents the percentage of operation time to available time, which is the time during which the machine is capable of operating.

7.1.6 Simulation study

In order to examine at the performance of the generated configurations and validate the performance results of the developed model, each period's configuration are simulated using ARENA. The RMS configurations generated for demand scenario 1 are modeled to obtain the results on throughput, utilization and financial performance.

The following figure shows the actual value of cash flow results obtained from the simulation model.

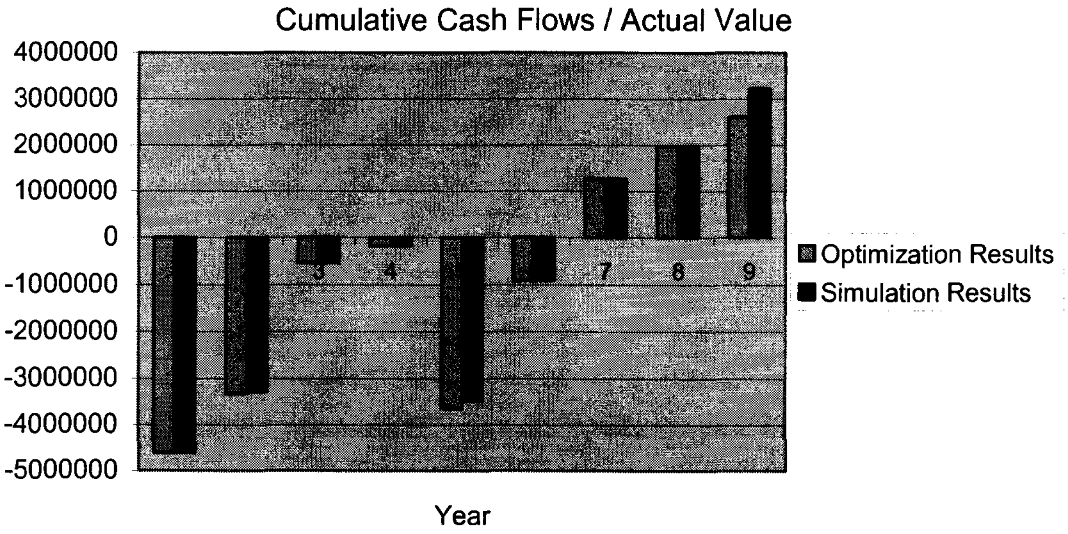


Figure 7.21 Actual Cash Flows / Simulation Results

Figure 7.21 show that the financial results is almost the same as the multiple objective optimization results. In addition, the demand requirements have been met at each period. The following figure represents the average utilization of machines, collected from the simulation model.

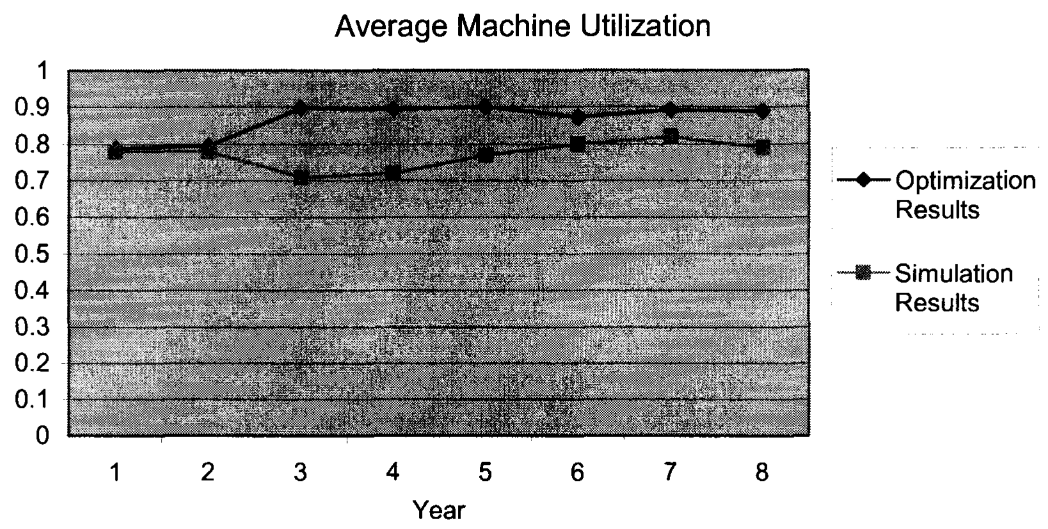


Figure 7.22 Average Machine Utilization

The results in Figure 7.22 show that the simulated utilization levels are lower than the optimization results. This can be explained by the fact that simulation model do not take the reconfiguration period in effect and considers this period as operational, therefore reduces the average machine utilization levels.

The simulation study has been applied to the FMS configuration generated for demand scenario 1, in order to compare the cost performance of FMS and RMS implementations. Figure 7.23 represents the average machine cost per part throughout the lifecycle. The average cost of RMS increases in periods where a reconfiguration task is performed, whereas FMS starts with higher average cost and decreases as the production increases. The difference between RMS and FMS's average cost is due to the high initial investment in FMS at the beginning of the lifecycle and efficient reconfiguration of RMS by only adding the necessary capacity and capability when needed. These results confirm the results obtained from the optimization tool proposed in this research work.

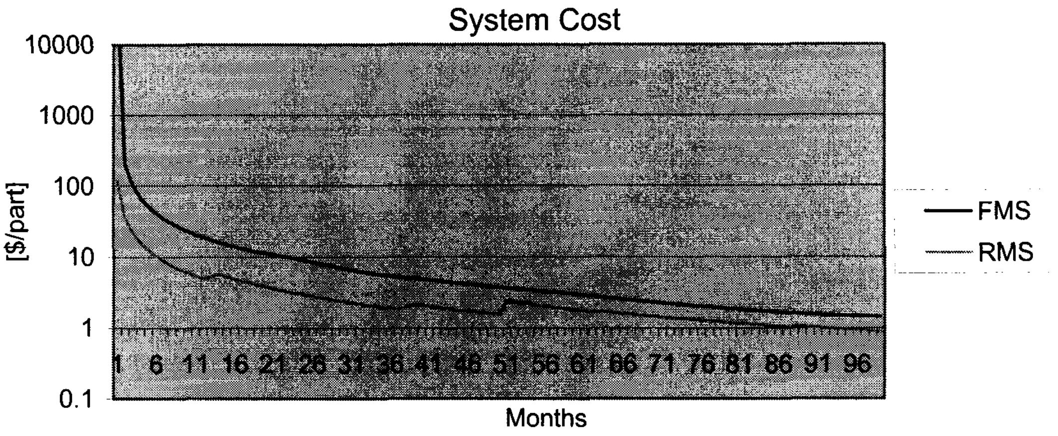


Figure 7.23 Average System Cost

7.2. Discussion

The proposed model takes into account both financial and strategic objectives simultaneously, in order to generate manufacturing systems configurations that meet the demand forecast. The model considers in-house production and outsourcing options, operational costs, reconfiguration costs and effective utilization of machines while minimizing the system complexity and maximizing the system responsiveness.

The use of the model has been illustrated with a case study of a reconfigurable manufacturing system under two different market conditions: increasing and fluctuating. Two sets of system configuration results are presented in order to highlight the difference between decisions made based on a multiple objective function and solely financial considerations. The results of this study showed the necessity of including the strategic benefits coupled with the financial objectives. In addition, the results indicate that reconfiguration provides the means to use the acquired equipment effectively.

In addition, the developed model has been used to compare investments in both RMS and FMS as potential alternatives for meeting the same demand requirements. The RMS implementation had the ability to reconfigure depending on the market conditions whereas the FMS configuration consisted of machines that were capable of carrying out various types of processes thanks to their built-in versatile capabilities. An increasing and a fluctuating demand scenario have been applied to both types of systems to generate two configurations. For this example, the results showed that the higher investment levels required for the FMS configuration could not be justified since RMS performed better in terms of utilization, complexity and financial performance levels. The developed model can help assess the trade-off between high initial capital investment in FMS vs. investment as needed for RMS. A reconfiguration period longer than one week decreases the financial performance of RMSs, and makes FMSs more profitable in such cases. The responsiveness metric performance results of FMS show that they respond better to demand changes within the same configuration, thanks to the built-in features of its machines. The model can support decisions by applying what-if scenarios when designing new systems and/or reconfiguring existing ones. Therefore, the developed multiple objective model can be used as a decision support tool to help system designers justify the investments in either FMS or RMS for given scenarios and market conditions.

CHAPTER EIGHT

CONCLUSIONS

Conventional manufacturing systems are designed in order to address the requirements once at the initial development phase; therefore the effect of changes in the configuration of a manufacturing system is not represented in lifecycle modeling of conventional manufacturing systems. The ability of RMSs to evolve over time according to changing market conditions requires a new technique to assess their investments. The objective of this research work was to develop a model that represents the lifecycle of an RMS in order to evaluate if such investments are economically and strategically justifiable. To achieve this objective the following issues has been dealt with:

- A fuzzy multi criteria decision making approach that simultaneously optimizes the net present value of after-tax cash flows, system configuration complexity, and the responsiveness of configurations to demand changes.

- First, a lifecycle cost model has been developed representing the various activities in RMS environment including the reconfiguration process. The cost model incorporates in-house production and outsourcing option of the demand, machine acquisition and disposal costs, operational costs, and reconfiguration cost and duration for modular machines.

- Second, a structural system complexity metric has been developed to ensure that the generated system configurations are easy to mange and simple. The proposed system complexity provides insight into the system components and structure, and the manageability of manufacturing systems configurations as well as assist in selecting a less complex system at the early design stages.

- Third, manufacturing system responsiveness metric has been developed in order to assess the configurations' ability to respond to the changes in demand mix within each period of the lifecycle.
- These objectives are then incorporated in fuzzy multiple objective optimization tool using fuzzy membership functions in order to incorporate the decision maker's preferences into the model.

The outcome of this tool is a system configuration for each period that satisfies the lifecycle cost, responsiveness, and complexity objectives within the targeted planning horizon. The resulting configurations are optimized simultaneously for lifecycle costs, responsiveness performance, and system structural complexity.

8.1. Conclusions

A case study is presented to demonstrate the use of the developed approach. A set of deterministic demand scenarios have been used to generate RMS configurations over a planning horizon of 8 periods. In addition, the same demand scenarios have been used to generate FMS configurations in order to compare the FMS versus RMS configurations. The following results can be pointed out from this research:

1. The results of this study showed the advantages of including the strategic benefits coupled with the financial objectives. Adding strategic criteria such as complexity and responsiveness generate configurations that are simple and responsive while maintaining acceptable financial performances.
2. The developed model can help assess the trade-off between high

initial capital investment in FMS vs. investment as needed for RMS.

3. Shorter reconfiguration periods are needed in order to obtain more profitable RMS configurations compared to FMS.

4. The reconfiguration ability of RMS provides faster return on investment by avoiding redundant initial investment and effectively readjusting the machine requirements at each period in the system lifecycle.

5. The reconfiguration time sensitivity analysis proved the need for easily reconfigurable machine structures in order to benefit from RMS investments.

6. Reconfiguration planning using the proposed multiple objectives leads to more effective utilization of equipment. The average utilization of RMS is better than equivalent FMS configurations.

7. The RMS configurations, generated using the developed tool, satisfied the demand requirements of various demand scenarios at different periods, which is a proof that RMS provides the required capacity needed when needed.

8. The results showed that RMS configurations perform better than FMS under the conditions where a new product is introduced to the system.

9. The responsiveness metric performance results of FMS show that it responds better to demand changes within the same configuration, due to the built-in features of its machines.

10. The results of the case studies show that using more capable machines in a manufacturing system reduces the overall complexity by decreasing the required number of machines.

The input data used in the proposed methodology is extensive and might be difficult to obtain the exact figures. In cases where there is uncertainty about the data, sensitivity analysis or representation of data with fuzzy numbers can be used to perform the analysis. In addition, the use of simulation tool to verify the generated results can also help to perform what-if scenarios and analyze the effect of changes in parameters. These various scenarios can also help decision makers to understand the behaviour of various candidate machines, and deduct generalizations about their performance. The same propositions are also valid for determining the ratio of outsourcing to total demand.

8.2. Research contributions

The reported research makes the following contributions to RMS research literature.

1. A decision support tool for planning RMS configurations and their justification has been developed. A fuzzy multiple objective lifecycle cost evaluation methodology has been developed, which includes several competing objectives such as:
    a. NPV of after tax cash flows,
    b. System complexity,
    c. Responsiveness
2. A cost model has been developed representing the various activities in RMS environment including the reconfiguration process. The cost model incorporates in-house production and outsourcing options of the demand, machine acquisition and disposal costs, operational costs, and reconfiguration cost and duration for modular machines. The tool generates a lifecycle cost performance profile of

reconfigurable manufacturing systems.

3. The lifecycle evaluation of RMS investments has been optimized for both financial and strategic criteria. The use of complexity and responsiveness metrics as performance criteria, allows strategically evaluating RMS investments along with the financial performance.
4. The use of fuzzy multiple objective optimization allows incorporating the decision maker's preferences on performance level of each criterion. In addition, it allows integrating various types of performance criteria with different unit scale (e.g bits for complexity, monetary unit for NPV).
5. While analyzing the economic justification of RMS investments, both production assignment and investment analysis are integrated within the developed optimization tool.
6. The machine structure is modeled assuming various types of base structures and module types, as opposed to one type of machine base and module.
7. A responsiveness metric has been developed that captures a manufacturing system's ability to respond to changes in demand within the same configuration. As the RMS' competitive advantage is being responsive to demand fluctuations, it is important to analyze the performance of responding to demand variations by investigating the two dimensions of manufacturing system responsiveness.
8. A System complexity metric has been developed that provides insight into the system components and structure, and the manageability of manufacturing systems configurations as well as assist in selecting a less complex system at the early design stages.

9. The reconfiguration cost is integrated to the lifecycle evaluation methodology, and all periods are optimized simultaneously rather than an individual analysis of each period.
10. The reconfiguration duration period is incorporated into the model. This also allowed analyzing the effect of the duration of reconfiguration period on utilization of the machines, and the financial performance of configurations.

8.3. Future research directions

The following topics can be further extension of the presented research work:

1. Using other strategic qualitative factors such as change in products quality level can be incorporated into the model using fuzzy linguistic expressions. The prediction of quality levels can play important role in selecting machine configurations.
2. Additional components of RMS such as buffers and material handling systems can be added to the model.
3. More detailed model, by adding alternative routes for processing sequence of products to be manufactured in the system.
4. Investigating the frequency of reconfigurations, the effect of unequal production periods on lifecycle performance.
5. Investigating the effect of system complexity on investment and reconfiguration cost, and accounting for the cost of complexity in manufacturing systems

6. Improve the responsiveness metric based on randomly changing schedule and analyzing its effects using simulation models.

8.4. Summary

In summary, the main contribution of this work is to increase knowledge in investment evaluation of manufacturing systems by incorporating economic and strategic objectives within a lifecycle analysis framework. A decision support tool for planning RMS configurations and their justification has been developed. The tool generates a lifecycle cost performance profile of reconfigurable manufacturing systems while incorporating strategic factors, and the decision makers' preferences. It can also be used for the comparison of Flexible Manufacturing Systems and RMSs.

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APPENDIX A: CASE STUDY DATA

Table 1. Part-Machine Incidence Matrix

Part	Operation	Z_{ijmk}								
		K=1			k=2			k=3		
i	J	D	M	L	D	M	L	D	M	L
1	1	1						1		
	2		1	1				1	1	
	3				1				1	
	4				1	1			1	1
	5					1	1			1
2	1	1	1					1		
	2		1					1	1	
	3			1					1	
	4				1	1			1	1
	5					1	1		1	1

Table 2. Processing and setup times of operation (i,j) on machine (m,k)

		p_{ijmk} , ST_{ijmk}								
Part	Operation	k=1			K=2			k=3		
i	J	D	M	L	D	M	L	D	M	L
1	1	0.15						0.18		
		2						0.5		
	2		0.2	0.22				0.18	0.19	
			3	4				0.5	0.25	
	3				0.18				0.16	
					2				0.5	
	4				0.22	0.22			0.19	0.19
					3	2			0.25	0.25
	5					0.2	0.2			0.17
						3	2.5			0.25
2	1	0.18	0.18					0.16		
		2.5	2.5					0.5		
	2		0.17					0.15	0.15	
			2.5					0.25	0.25	
	3			0.22					0.19	
				2					0.75	
	4				0.18	0.18			0.16	0.14
					3	4			0.5	0.25
	5					0.2	0.2		0.19	0.18
						2.5	2		0.25	0.5

Table 3. Setup cost, variable cost, and fixed cost of operation (i,j) on machine (m,k)

		SC_{ijmk} VC_{ijmk} FC_{ijmk}								
Part	Operation	k=1			k=2			k=3		
i	J	D	M	G	D	M	G	D	M	G
1	1	40						10		
		4						3		
		5						6		
	2		60	80				10	7.5	
			3.5	3.5				2.5	2.75	
			3	3				3.75	3.75	
	3				40				10	
					4.75				4.25	
					3.5				3.8	
	4				60	40			7.5	7.5
					6.1	6.05			4.85	5.1
					3	3			3.75	3.75
	5					60	50			7.5
						4	4.15			3.15
						3.75	4			4.5
2	1	50	50					10		
		3.5	3.75					3.1		
		3	3					3.5		
	2		50					8	8	
			4.2					3.8	3.7	
			3					3.4	3.6	
	3			40					15	
				2.9					2.4	
				3					3.76	

4			60	80			10	8
			3.75	3.8			3.2	3.15
			4.1	4.05			4.4	4.6
5				50	40		8	10
				3.6	3.3		3.1	3.05
				4	4		4.5	4.5

Table 4. Sales Price, Material Costs, and Outsourcing Costs

		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
In house profit	P1	22.36	21.91	21.48	21.05	20.63	20.21	19.81	19.41
	P2	18.44	17.15	15.95	14.83	13.79	12.82	11.93	11.09
Outsourcing Profit	P1	14.91	14.61	14.32	14.03	13.75	13.48	13.21	12.94
	P2	12.29	11.43	10.63	9.89	9.19	8.55	7.95	7.39

Table 5: Investment cost of machine type m at configuration k in period t ($ 000) ICmkt

Machine Type	Module instance	1	2	3	4	5	6	7	8
drill	1mod	150	150	150	150	150	150	150	150
mill	1mod	175	175	175	175	175	175	175	175
Lathe	1mod	120	120	120	120	120	120	120	120
drill	2mod	250	250	250	250	250	250	250	250
mill	2mod	250	250	250	250	250	250	250	250
lathe	2mod	200	200	200	200	200	200	200	200
drill	3mod	800	775	750	725	675	650	650	650
mill	3mod	900	875	850	825	800	750	750	750
lathe	3mod	860	850	825	800	775	750	725	700

Table 6. Salvage value of machine type m at configuration k in period t SV_{mkt}

Machine Type	Module instance	1	2	3	4	5	6	7	8
drill	1mod	131250	112500	93750	75000	56250	37500	18750	0
mill	1mod	153125	131250	109375	87500	65625	43750	21875	0
lathe	1mod	105000	90000	75000	60000	45000	30000	15000	0
drill	2mod	218750	187500	156250	125000	93750	62500	31250	0
mill	2mod	218750	187500	156250	125000	93750	62500	31250	0
lathe	2mod	175000	150000	125000	100000	75000	50000	25000	0
drill	3mod	700000	600000	500000	400000	300000	200000	100000	0
mill	3mod	787500	675000	562500	450000	337500	225000	112500	0
lathe	3mod	752500	645000	537500	430000	322500	215000	107500	0

APPENDIX B:SAMPLE GAMS MODEL

```
*Initial implementation for RMS investment evaluation
$inlinecom { }
$onsymxref

$gdxin suresh_case0.gdx


option limrow = 72;
Set
          t period index
          i product index
          j operation index
          m machine type index
          k configuration index
          s machine state index /1 2/;

Parameter Dit(i, t) demand of prod i in period t
          Pit(i, t) sale price
          OCit(i, t) outsourcing cost
          MCit(i, t) materials cost
          Hit(i, t) inventory holding cost
          Zijmk(i, j, m, k) process capability matrix
          Pijmk(i, j, m, k) operation process times
          STijmk(i, j, m, k) operation setup times
          ICmkt(m, k, t) machine investment cost
          SVmkt(m, k, t) machine salvage value
          SC(i, j, m, k) Setup cost of operation ij on machine mk
          VC(i, j, m, k) Variable cost of operation ij on machine mk
          FC(i, j, m, k) Fixed cost of operation (ij) on machine mk
          MINP(i, j) min processing time for operation (ij)
          MINST(i, j) min setup time for op ij
          EFF(i, j, m, k) efficiency matrix of op ij on mc mk
          RAimk(i, m, k) response ability of machine mk with respect to prod i;
$Load     i j m k t
$Load     Dit Pit Ocit MCit Hit Zijmk Pijmk STijmk ICmkt SVmkt SC VC FC
$gdxin
Display SC, VC, FC, Hit,ICmkt, SVmkt;

Set
          ifirst(i)   first product
          ilast(i)    last product
          jfirst(j)   first operation
          jlast(j)    last operation
          mfirst(m)   first machine
          mlast(m)    last machine
          kfirst(k)   first configuration
          klast(k)    last configuration
          tfirst(t)   first period
          tlast(t)    last period
          prod1(j)    prod1 process
          prod2(j)    prod2 process
          ij(i, j)    process plan definitions  /
          p1*p2.op1*op5/
          recp(t)     reconfiguration period;
alias     (k, kon);
alias     (i, i1);
alias     (j, j1);
```

```
alias     (m, m1);
alias     (t, ti);


Display ij;
ifirst(i) = yes$(ord(i) eq 1);
ilast(i)  = yes$(ord(i) eq card(i));
jfirst(j) = yes$(ord(j) eq 1);
jlast(j)  = yes$(ord(j) eq card(j));
mfirst(m) = yes$(ord(m) eq 1);
mlast(m)  = yes$(ord(m) eq card(m));
kfirst(k) = yes$(ord(k) eq 1);
klast(k)  = yes$(ord(k) eq card(k));
tfirst(t) = yes$(ord(t) eq 1);
tlast(t)  = yes$(ord(t) eq card(t));
recp(t) = yes;
recp(tlast(t))= no;
prod1(j)= yes$ij('p1',j);
prod2(j)= yes$ij('p2',j);
display prod1;
Scalar    interest "interest rate" /0.12/
          d        "CCA rate" /0.2/
          Tb "time to install/remove a base mins"  /300/
          Tmd "time to install/remove a machine module" /150/
          bigM "big M" /1000000/
          ;
Display recp;
Parameters CCTFnew(t)
          disc(t) discount factor
          TR(t) tax rate for period t
          CCTFold(t)
          LR hourly labour rate
          OLR(m, k, t) overtime labour rate on machine mk in period t
          Lt(t) number of setups in period t lot size
          Wt(t) number of available workforce
          rmk(m, k) reliability of machine mk
          AH(m, k) available hours of machine mk in one period
*         250 days 3 shifts 7 hours per shift 60 minutes per hour*
          dmk(m, k) straight line depreciation rate of machine mk
          ratio(i, t) demand ratio of product i in period t
          Passign(i, m, k, t) probability of assigining machine mk to prod i
                              in period t;
ratio(i, t) = (Dit(i, t)/sum(i1, Dit(i1, t)))$(sum(i1, Dit(i1, t))<>0);

MINP(i, j)$ij(i, j) = smin((m, k)$(Zijmk(i, j, m, k)=1), Pijmk(i, j, m, k));
MINST(i, j)$ij(i, j) = smin((m, k)$(Zijmk(i, j, m, k)=1), STijmk(i, j, m, k));
EFF(i, j, m, k)$(Zijmk(i, j, m, k)=1)=MINP(i, j)*MINST(i,j)/(Pijmk(i, j, m, k)
              $(Zijmk(i, j, m, k)=1)*STijmk(i, j, m, k)$(Zijmk(i, j, m, k)=1));
RAimk(i, m, k)= sum(j$(Zijmk(i, j, m, k)=1) , Zijmk(i, j, m, k)*EFF(i, j, m, k))
                /(card(prod1)$(ord(i) eq 1) + card(prod2)$(ord(i) eq 2)) ;
Passign(i, m, k, t) = ratio(i, t)*RAimk(i, m, k)
                      /smax((i1,m1,kon)$(ord(i1) eq ord(i)),RAimk(i1, m1, kon));
display ratio, passign;
disc(t)=1/(1+interest)**ord(t);
TR(t) = 0.40;
CCTFnew(t) = 1 - TR(t)*d*(1+0.5*interest)/((interest+d)*(1+interest));
CCTFold(t) = 1- TR(t)*d/(interest+d);
```

```
LR = 8;
OLR(m, k, t) = 12;
Lt(t) = 2000;
Wt(t) = 50;
rmk(m, k)$(ord(k)=1) = 0.92;
rmk(m, k)$(ord(k)=2) = 0.9;
rmk(m, k)$(ord(k)=3) = 0.88;
AH(m, k)=rmk(m, k)*250*7.5*60;
dmk(m, k) = 0.125;
Display MINP, MINST, EFF, RAimk;
*Create a gdxfile and unload data to that file
*$GDXout input_case1
*$unLoad     i j m k t
*$unLoad     Dit Pit Ocit MCit Hit Zijmk Pijmk STijmk ICmkt SVmkt SC VC FC EFF
*$GDXout


Variables
          intMit(i, t) "production quantity of product i in period t(integer)"
          intQit(i, t) "Quantity of products outsourced in period t(integer)"
          intYijmkt(i, j, m, k, t) "prod'n quantity of operation ij on machine
                                   mk inperiod t(integer)"
          reaProfit(t)
          intXmkt(m, k, t) "number of m/c type mk in period t(integer)"
          reaVXmkt(m, k, t) "absolute value of m/c difference..realnumber"
          intVXmktp(m, k, t) "positive side of absolute value"
          intVXmktn(m, k, t) "negative side of absolute value"
          binXsimkt(m, k, t) "Binary for m/c difference"

          intNSt(t) "Number of regular shifts in period t(integer .lo=1 .up=3"
          reaDPmkt(m, k, t) "depreciation charge for machine mk in period t"
          reaBVT(t) "Book value of the assets at the end of period t"

          intBmt(m, t) "number of machine bases from type m in period t"
          reaVBmt(m, t) "absolute value of bases difference..realnumber"
          intVBmtp(m, t) "positive side of absolute value (bases)"
          intVBmtn(m, t) "negative side of absolute value(bases)"
          binBetamt(m, t) "Binary for bases difference"

          intMDmkt(m, k, t) "numer of machine modules type m of configuration k
                            in period t"
          reaVMDmkt(m, k, t) "absolute value of modules difference..realnumber"
          intVMDmktp(m, k, t) "positive side of absolute value (modules)"
          intVMDmktn(m, k, t) "negative side of absolute value(modules)"
          binDeltamkt(m, k, t) "Binary for modules difference"

          intRTt(t) "Reconfiguration task in period t"
          reaRCt(t) "Reconfiguration cost in period t"
          reaRDt(t) "Reconfiguration duration in period t"
          reaCOt(t) "Opportunity cost for reconfiguration period t"
          reaCORUt(t) "Opportunity cost for rampup period t"
          reainvest "investment level"
          reaPresent "objective function"
          mureapresent "fuzzy satisfaction degree"
          cplxty(t) "complexity objective"
          mucplxty "fuzzy stais degree for cplxty"
          response(t)"responsiveness objective"
```

```
          muresp "fuzzy satis degree for responsiveness"
          cash(t) ;
positive variables reaBVT, reaRCt, reaRDt;
integer variables
          intMit, intYijmkt, intQit
          intXmkt, intVXmktp, intVXmktn
          intBmt, intVBmtp, intVBmtn, intMDmkt, intVMDmktp, intVMDmktn
          intRTt;
free variables    cash, reaprofit, reaVXmkt, reaVBmt, reaVMDmkt, reapresent,
                  reainvest, reaprofit, reatax, reacapital, reasalvage,reaopcos»
t
                  invest, mureapresent, cplxty, mucplxty, avecplxty, response,
                  muresp, averesp, lambda;



intMit.up(i,t) = 60000000;
intQit.up(i, t) = 60000000;
intYijmkt.up(i, j, m, k, t)= 100000000;
intXmkt.up(m, k, t) = 10;
reaVXmkt.up(m, k, t)= 20 ;
intVXmktp.up (m, k, t) = 20;
intVXmktn.up (m, k, t) = 20;
intNSt.up(t) = 3;
reaDPmkt.up(m, k, t)= 500000 ;
reaBVT.up(t) = 5000000000 ;
intBmt.up (m, t) = 500;
reaVBmt.up(m, t) = 1000;
intVBmtp.up(m, t) = 500;
intVBmtn.up(m, t) = 500;
reaVMDmkt.up(m, k, t) = 1000;
intMDmkt.up(m, k, t) = 500;
intVMDmktp.up(m, k, t) = 500;
intVMDmktn.up(m, k, t) = 500;
intRTt.up(t) = 100000;
reaRCt.up(t) = 100000;
reaRDt.up(t) = 100000;
reaPresent.up = 50000000000;
reainvest.up = 50000000000;
reaProfit.up(t)= 50000000000;
reatax.up(t)= 50000000000;
reaopcost.up(t)= 50000000000;
reacapital.up(t)= 50000000000;
reasalvage.up(t)=50000000000 ;

mureapresent.up = 1;
mucplxty.up =1;
muresp.up=1;
intMit.lo(i,t) = 0;
intQit.lo(i, t) = 0;
intYijmkt.lo(i, j, m, k, t)= 0;
intXmkt.lo(m, k, t) = 0;
reaVXmkt.lo(m, k, t)= -10 ;
intVXmktp.lo (m, k, t) = 0;
intVXmktn.lo (m, k, t) = 0;
intNSt.lo(t) = 1;
reaDPmkt.lo(m, k, t)= 0 ;
```

```
reaBVT.lo(t) = 0 ;
intBmt.lo (m, t) = 0;
reaVBmt.lo(m, t) = -1000;
intVBmtp.lo(m, t) = 0;
intVBmtn.lo(m, t) = 0;
reaVMDmkt.lo(m, k, t) = -1000;
intMDmkt.lo(m, k, t) = 0;
intVMDmktp.lo(m, k, t) = 0;
intVMDmktn.lo(m, k, t) = 0;
intRTt.lo(t) = 0;
reaRCt.lo(t) = 0;
reaRDt.lo(t) = 0;
reaPresent.lo = -5000000000;
reainvest.lo = 0;
reaProfit.lo(t)= 0;
reatax.lo(t)= 0;
reaopcost.lo(t)= 0;
reacapital.lo(t)= 0;
reasalvage.lo(t)=0;
mureapresent.lo = 0;
mucplxty.lo = 0;
muresp.lo=0;


binary variables  binXsimkt, binBetamt, binDeltamkt;

Equations
          NPV cash flow objective function (o1)
          NPV1(t) profit
          NPV2(t) operational costs
          NPV3(t) capital costs
          NPV4(t) tax savings
          NPV5(t) salvage of disposed mcs
          Cashflows(t)

          MU utility function for reapresent
          CPLX(t) system complexity objective function (o2)
          objective2 Conversion for complexity metric
          MU2 utility function for complexity
          Resp(t) responsiveness of period t objective function (o3)
          MU3 utility function for responsiveness
          objective3 Conversion for responsiveness metric
          o1
          o2
          o3
          outsourcing(i, t)
          initialinvest
          Demand(i, t) satisfy demand by outsourcing plus internal production (»
c1)
          Cap(i, j, m, k, t) only capable machines can perform ooperation ij (c»
2)
          Pquantity(i, j, t) Sum of production quantities of an operation shoul»
d be equal to the manufacturing order of product i (c3)
          Utilization(m, k, t) utilization of each machine
          Avail1(m, k, t) Required production time must be less than available »
time (c4)
          inidep(m, k, t) initial depreciation amount
```

```
          Depr(m, k, t) Depreciation amount of machine mk in period t (c6)
          inibookval(t)
          Bookval(t) Book value of the assets at the end of planning horizon (c7»
)
          Bases(m, t) Number of machine bases of type m in period t (c8)
          Modules(m, k, t) Number of modules of type mk in period t (c9)
          Rectask(t) Required reconfiguration task in period t (c10)
          Reccost(t) Reconfiguration cost in period t (c11)
          Recduration(t) Reconfiguration duration in period t (c12)

          Xmktconv1(m, k, t) difference in number of machines 1st conversion eq
          Xmktconv2(m, k, t) 2nd conversion eq
          Xmktconv3(m, k, t) 3rd
          Xmktconv4(m, k, t) 4th

          Bmtconv1(m, t) difference in number of machine bases 1st conversion eq
          Bmtconv2(m, t) 2nd conversion eq
          Bmtconv3(m, t) 3rd
          Bmtconv4(m, t) 4th

          MDmktconv1(m, k, t) difference in number of machine modules 1st conver»
sion eq
          MDmktconv2(m, k, t) 2nd conversion eq
          MDmktconv3(m, k, t) 3rd
          MDmktconv4(m, k, t) 4th;

MU.. mureapresent =e= reapresent/15737400;
MU2.. mucplxty =e= (14.15-avecplxty)/(14.15-9.17);
MU3.. muresp =e= (averesp-0.797)/(4.032-0.797);

Cashflows(t).. cash(t) =e=
                    + reaprofit(t){*disc(t)}*(1-TR(t))
                    +reatax(t){*disc(t)}*TR(t)
                    +reasalvage(t){*disc(t)}
                    -reacapital(t){*disc(t)}
                    -reaopcost(t){*disc(t)}*(1-TR(t))
                    -reaRCt(t){*disc(t)}{+reaCOt(t)}*(1-TR(t));

NPV..reapresent =e=  sum(t, reaprofit(t)*disc(t)*(1-TR(t)))
                    +sum(t, reatax(t)*disc(t)*TR(t))
                    +sum(t$recp(t), reasalvage(t)*disc(t))
                    +sum(t$(ord(t)eq 8), reaBVT(t)*disc(t))
                    -reainvest
                    -sum(t$recp(t), reacapital(t)*disc(t))
                    -Sum(t, reaopcost(t)*disc(t)*(1-TR(t)))
                    -Sum(t$recp(t), reaRCt(t){+reaCOt(t)}*disc(t)*(1-TR(t)))
;
initialinvest.. reainvest =e= Sum((m, k, t)$(ord(t) eq 1), ICmkt(m, k, t)*intXm»
kt(m, k, t))  {initial investment cost};
NPV1(t)..reaprofit(t)=e= +Sum(i, (MCit(i, t))*intMit(i, t))   {Profit from inte»
rnal production}
                         +Sum(i, (OCit(i, t))*intQit(i, t))   {Profit from outs»
ourcing} ;
NPV2(t)..reaopcost(t)=e= Sum((i, j, m, k)$ij(i, j), intYijmkt(i, j, m, k, t)*VC(»
i, j, m, k) + FC(i, j, m, k)*intXmkt(m, k, t))  {var + fix cost }
                        +Sum((i, j, m, k)$ij(i, j), SC(i, j, m, k){*intXmkt(m, k»
, t)}*intYijmkt(i, j, m, k, t)/Lt(t)) {Setup costs};
```

```

NPV3(t)$recp(t)..reacapital(t) =e= Sum((m, k), ICmkt(m, k, t)*intVXmktp(m, k, t)»
);
NPV4(t)..reatax(t) =e= +Sum((m, k), reaDPmkt(m, k, t)) ;
NPV5(t)$recp(t).. reasalvage(t) =e= Sum((m, k), intVXmktn(m, k, t)*SVmkt(m, k, »
t))      {Salvage value of disposed machines};

;
CPLX(t)..cplxty(t) =e= Sum((m, k), intXmkt(m, k, t)*(rmk(m, k)*log2(1/rmk(m, k)»
) + (1-rmk(m, k))*log2(1/(1-rmk(m, k)))));
objective2.. avecplxty=e= sum(t, cplxty(t))/8;
Resp(t).. response(t)=e= sum((i, m, k), Passign(i, m, k, t)*RAimk(i, m, k)*intXm»
kt(m, k, t));
objective3.. averesp=e= sum(t, response(t))/8;
o1.. mureapresent =g= lambda;
o2.. mucplxty =g= lambda;
o3.. muresp =g= lambda;

 Utilization(m, k, t).. Sum((i, j), (Pijmk(i, j, m, k)+STijmk(i, j, m, k)/Lt(t)»
)*intYijmkt(i, j, m, k, t))
                        + reaRDt(t)$recp(t) =g= 0.85*AH(m, k)*intXmkt(m, k, t);

 Demand(i,t).. intMit(i, t)  + intQit(i, t)  =e= Dit(i, t) ;
 outsourcing(i, t).. intQit(i, t) =l= 0.2*Dit(i, t);
 Cap(i, j, m, k, t)$(ij(i, j)and(Zijmk(i, j, m, k)=1)).. intYijmkt(i, j, m, k, t»
) =l= Zijmk(i, j, m, k)*intMit(i, t);
 Pquantity(i, j, t)$ij(i, j).. Sum((m, k)$(Zijmk(i, j, m, k)=1), intYijmkt(i,j,m»
,k,t)) =e= intMit(i,t);
 Avail1(m, k, t).. Sum((i, j)$ij(i, j), Pijmk(i, j, m, k)*intYijmkt(i,j,m,k,t)+ »
STijmk(i, j, m, k)/Lt(t)*intYijmkt(i,j,m,k,t))=l= AH(m, k)*intXmkt(m, k, t) -re»
aRDt(t)$recp(t) ;

 inidep(m, k, t)$(ord(t) = 1).. reaDPmkt(m, k, t) =e= intXmkt(m, k, t)*ICmkt(m,»
 k, t)*dmk(m, k);
 Depr(m, k, t)$recp(t).. reaDPmkt(m, k, t+1) =e=  reaDPmkt(m, k, t) + intVXmktp»
(m, k, t)*ICmkt(m, k, t+1)*dmk(m, k)-intVXmktn(m, k, t)*ICmkt(m, k, t+1)*dmk(m, »
k);
 inibookval(t)$(ord(t) = 1)..reaBVT(t)=e= Sum((m, k), ICmkt(m, k, t)*intXmkt(m, »
k, t)- reaDPmkt(m, k, t));
 Bookval(t)$recp(t).. reaBVT(t+1) =e= reaBVT(t) + Sum( (m, k), -reaDPmkt(m, k, »
t+1)+ intVXmktp(m, k, t)*ICmkt(m, k, t+1)-intVXmktn(m, k, t)*SVmkt(m, k, t+1));

 Bases(m, t).. intBmt(m, t) =e= Sum(k, intXmkt(m, k, t));
 Modules(m, k, t).. intMDmkt(m, k, t) =e= Sum( kon$(ord(kon)>=ord(k)), intXmkt(m»
, kon, t));
 Rectask(t)$recp(t).. intRTt(t) =e= Sum(m, Tb*(intVBmtp(m, t)+intVBmtn(m, t))) »
+ Sum((m, k),Tmd*(intVMDmktp(m, k, t)+intVMDmktn(m, k, t)));
 Reccost(t)$recp(t).. reaRCt(t) =e= LR*intRTt(t);

 Recduration(t)$recp(t).. reaRDt(t) =e= intRTt(t)/Wt(t);


 Xmktconv1(m, k, t)$recp(t).. reaVXmkt(m, k, t) =e= intXmkt(m, k, t+1)-intXmkt(m»
, k, t);
 Xmktconv2(m, k, t)$recp(t).. reaVXmkt(m, k, t) =e= intVXmktp(m, k, t)-intVXmktn»
(m, k, t);
 Xmktconv3(m, k, t)$recp(t).. intVXmktp(m, k, t) =l= binXsimkt(m, k,t)*bigM;
```

```
 Xmktconv4(m, k, t)$recp(t).. intVXmktn(m, k, t) =l= (1-binXsimkt(m, k,t))*bigM;

 Bmtconv1(m, t)$recp(t).. reaVBmt(m, t) =e= intBmt(m, t+1)-intBmt(m, t);
 Bmtconv2(m, t)$recp(t).. reaVBmt(m, t) =e= intVBmtp(m,t)-intVBmtn(m, t);
 Bmtconv3(m, t)$recp(t).. intVBmtp(m, t) =l= binBetamt(m, t)*bigM;
 Bmtconv4(m, t)$recp(t).. intVBmtn(m, t) =l= (1-binBetamt(m, t))*bigM;

 MDmktconv1(m, k, t)$recp(t).. reaVMDmkt(m, k, t) =e= intMDmkt(m, k, t+1)-intMDm»
kt(m, k, t);
 MDmktconv2(m, k, t)$recp(t).. reaVMDmkt(m, k, t) =e= intVMDmktp(m, k, t)-intVMD»
mktn(m, k, t);
 MDmktconv3(m, k, t)$recp(t).. intVMDmktp(m, k, t) =l= binDeltamkt(m, k,t)*bigM;
 MDmktconv4(m, k, t)$recp(t).. intVMDmktn(m, k, t) =l= (1-binDeltamkt(m, k,t))*b»
igM;


Model RMS "rms evaluation tool" /all/;


RMS.scaleopt = 1;
option iterlim = 500000;
*option minlp = sbb;
*option nlp = snopt;
option mip = cplex;
*RMS.optfile = 1;
OPTION SYSOUT=ON
option minlp = dicopt;
option nlp = minos;
*option mip = xpress;
RMS.OptFile=1;
$onecho > cplex.opt
reslim=10000000
mipemphasis 0
scaind 1
varsel 3
$offecho
*option iterlim = 2000;
$onecho > dicopt.opt
nlpiterlim 500000
$offecho
option reslim=10000;
RMS.OptCR=0.001;
$onecho > xpress.opt
RMS.OptCR=0.2;
$offecho

$onecho > suresh_case1_unix.gck
displaycr
advisory
$offecho


*Solve RMS using mip maximizing reapresent;
*Solve RMS using mip maximizing avecplxty ;
*Solve RMS using mip maximizing averesp;
Solve RMS using mip maximizing lambda;
execute_unload 'results_case0_final.gdx';
```

APPENDIX C: SAMPLE SIMULATION RESULTS REPORT

Unnamed Project

Replications: 1 Time Units: Hours

Key Performance Indicators

All Entities	Average
Non-Value Added Cost	0
Other Cost	0
Transfer Cost	0
Value Added Cost	0
Wait Cost	0
Total Cost	0

All Resources	Average
Busy Cost	0
Idle Cost	0
Usage Cost	0
Total Cost	0

System	Average
Total Cost	0
Number Out	16,676,871

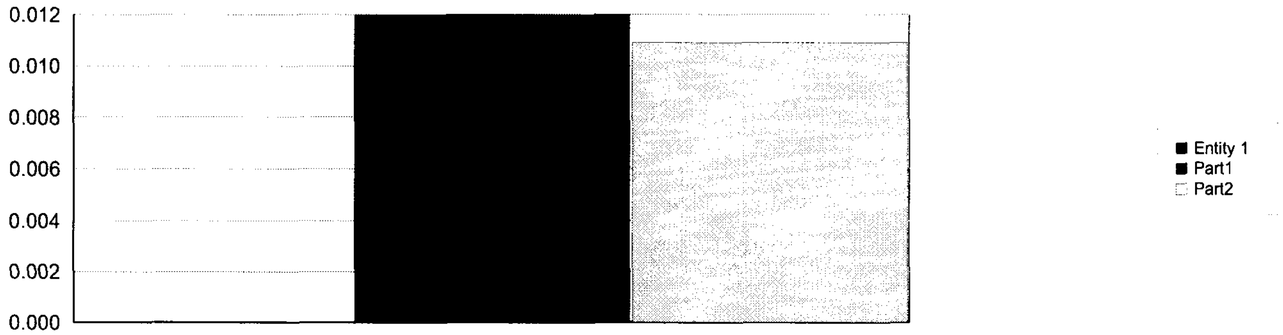
Unnamed Project

Replications: 1 Time Units: Hours

Entity

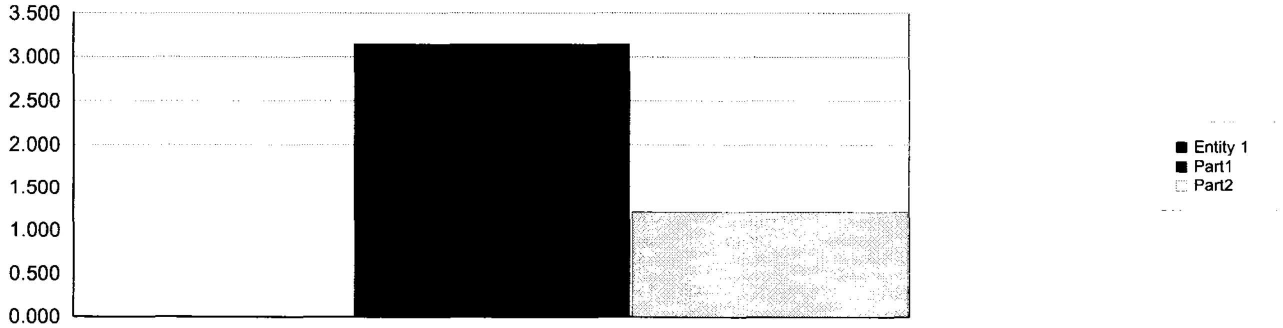
Time

VA Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00
Part1	0.01199660	(Correlated)	0.00933333	0.01200000
Part2	0.01089634	(Correlated)	0.00750000	0.01100000



NVA Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00
Part1	0.00	0.000000000	0.00	0.00
Part2	0.00	0.000000000	0.00	0.00

Wait Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00
Part1	3.1488	(Correlated)	0.00	40.7910
Part2	1.2038	(Correlated)	0.00	40.7921



Unnamed Project

Replications: 1 Time Units: Hours

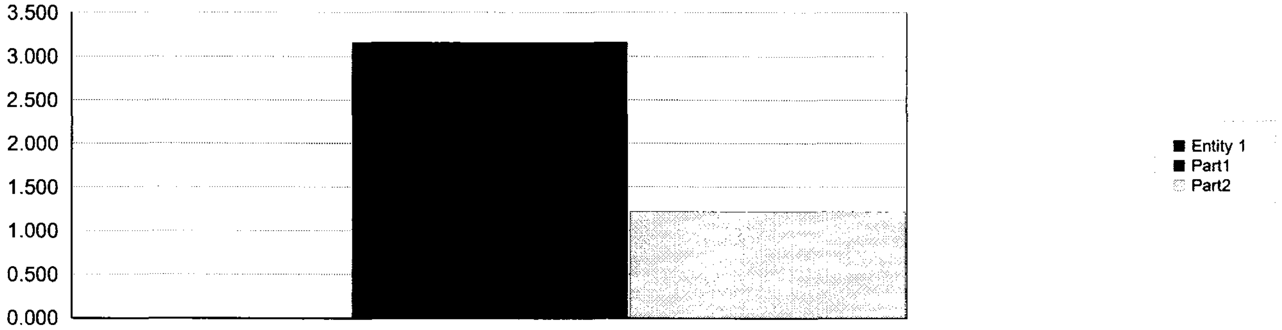
Entity

Time

Transfer Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00
Part1	0.00	0.000000000	0.00	0.00
Part2	0.00	0.000000000	0.00	0.00

Other Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00
Part1	0.00	0.000000000	0.00	0.00
Part2	0.00	0.000000000	0.00	0.00

Total Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00
Part1	3.1608	(Correlated)	0.01200000	40.8030
Part2	1.2147	(Correlated)	0.01100000	40.8031



Cost

VA Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00
Part1	0.00	0.000000000	0.00	0.00
Part2	0.00	0.000000000	0.00	0.00

NVA Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00
Part1	0.00	0.000000000	0.00	0.00
Part2	0.00	0.000000000	0.00	0.00

Unnamed Project

Replications: 1 Time Units: Hours

Entity

Cost

Wait Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00
Part1	0.00	0.000000000	0.00	0.00
Part2	0.00	0.000000000	0.00	0.00

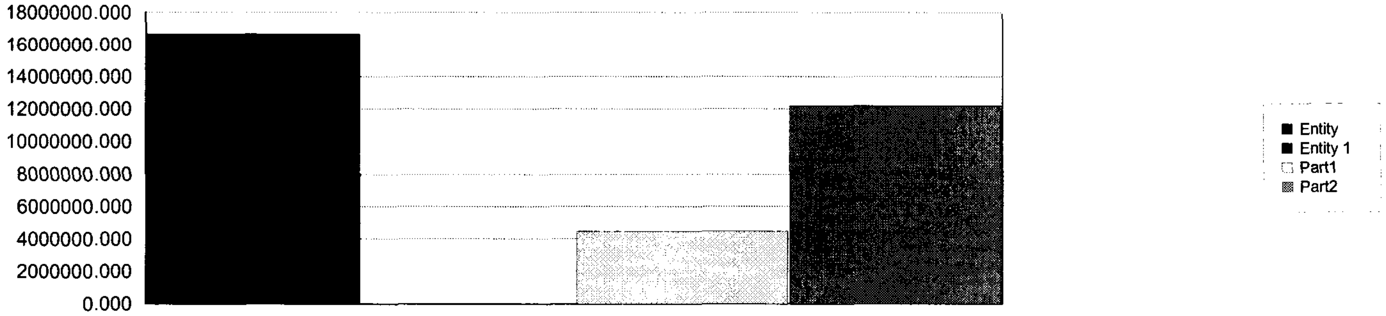
Other Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00
Part1	0.00	0.000000000	0.00	0.00
Part2	0.00	0.000000000	0.00	0.00

Transfer Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00
Part1	0.00	0.000000000	0.00	0.00
Part2	0.00	0.000000000	0.00	0.00

Total Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00
Part1	0.00	0.000000000	0.00	0.00
Part2	0.00	0.000000000	0.00	0.00

Other

Number In	Value
Entity	16676869
Entity 1	3.0000
Part1	4476869.00
Part2	12200000



Unnamed Project

Replications: 1 Time Units: Hours

Entity

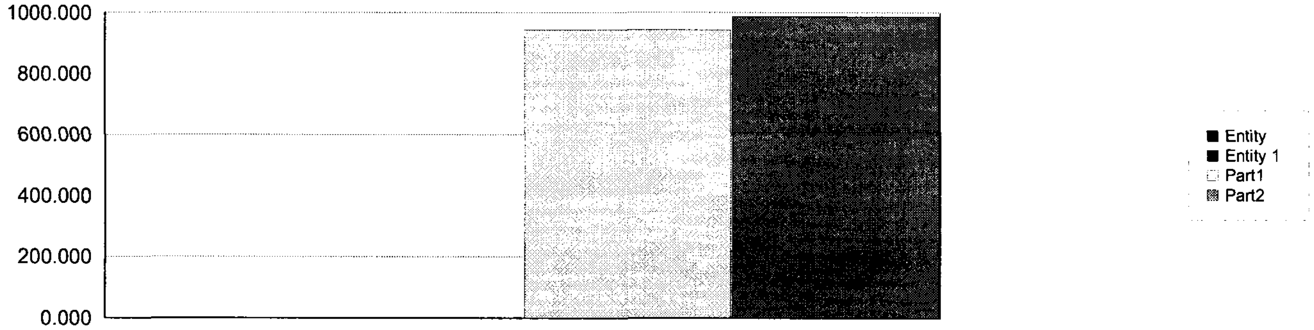
Other

Number Out

	Value
Entity	16676869
Entity 1	2.0000
Part1	4476869.00
Part2	12200000

WIP

	Average	Half Width	Minimum Value	Maximum Value
Entity	0.00	0.000000000	0.00	1.0000
Entity 1	1.0000	(Insufficient)	0.00	2.0000
Part1	943.35	1344.957	0.00	37876.00
Part2	987.96	1382.103	0.00	38499.00



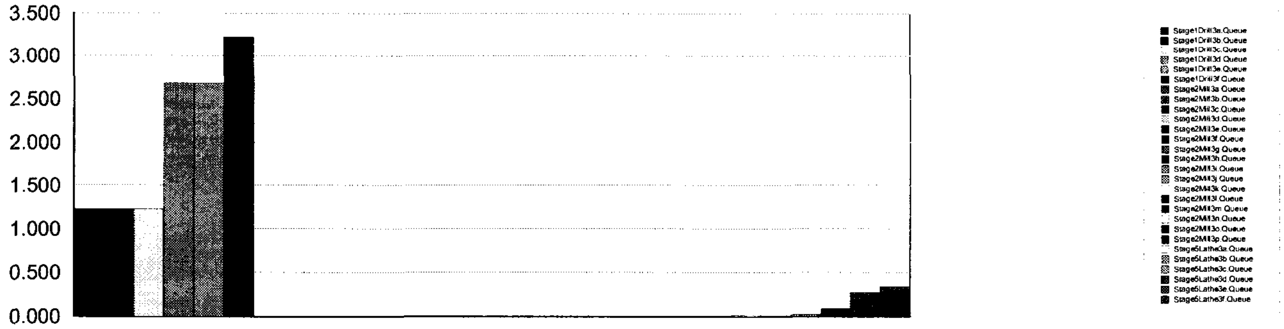
Unnamed Project

Replications: 1 Time Units: Hours

Queue

Time

Waiting Time	Average	Half Width	Minimum Value	Maximum Value
Stage1Drill3a.Queue	1.2221	(Correlated)	0.00	40.7828
Stage1Drill3b.Queue	1.2223	(Correlated)	0.00	40.7559
Stage1Drill3c.Queue	1.2217	(Correlated)	0.00	40.7619
Stage1Drill3d.Queue	2.6822	(Correlated)	0.00	40.7678
Stage1Drill3e.Queue	2.6845	(Correlated)	0.00	40.7576
Stage1Drill3f.Queue	3.2235	(Correlated)	0.00	40.7772
Stage2Mill3a.Queue	0.00349517	(Correlated)	0.00	1.1217
Stage2Mill3b.Queue	0.00341437	(Correlated)	0.00	1.1217
Stage2Mill3c.Queue	0.00334084	(Correlated)	0.00	1.1198
Stage2Mill3d.Queue	0.00324937	(Correlated)	0.00	1.1198
Stage2Mill3e.Queue	0.00315146	(Correlated)	0.00	1.1198
Stage2Mill3f.Queue	0.00299539	(Correlated)	0.00	1.1198
Stage2Mill3g.Queue	0.00278057	(Correlated)	0.00	1.1198
Stage2Mill3h.Queue	0.00308289	(Correlated)	0.00	1.1198
Stage2Mill3i.Queue	0.00286104	(Correlated)	0.00	1.1198
Stage2Mill3j.Queue	0.00359199	(Correlated)	0.00	1.1198
Stage2Mill3k.Queue	0.00341224	(Correlated)	0.00	1.1198
Stage2Mill3l.Queue	0.00320939	(Correlated)	0.00	1.1198
Stage2Mill3m.Queue	0.00316644	(Correlated)	0.00	1.1198
Stage2Mill3n.Queue	0.00316771	(Correlated)	0.00	1.1198
Stage2Mill3o.Queue	0.00291897	(Correlated)	0.00	1.1197
Stage2Mill3p.Queue	0.00260236	(Correlated)	0.00	1.1195
Stage5Lathe3a.Queue	0.01249010	0.019403558	0.00	3.3733
Stage5Lathe3b.Queue	0.01417961	0.024311379	0.00	3.3723
Stage5Lathe3c.Queue	0.02283499	0.039084937	0.00	3.3713
Stage5Lathe3d.Queue	0.08622705	0.128145078	0.00	3.3713
Stage5Lathe3e.Queue	0.2747	(Correlated)	0.00	3.3705
Stage5Lathe3f.Queue	0.3388	(Correlated)	0.00	3.3702



Unnamed Project

Replications: 1 Time Units: Hours

Queue

Cost

Waiting Cost	Average	Half Width	Minimum Value	Maximum Value
Stage1Drill3a.Queue	0.00	0.000000000	0.00	0.00
Stage1Drill3b.Queue	0.00	0.000000000	0.00	0.00
Stage1Drill3c.Queue	0.00	0.000000000	0.00	0.00
Stage1Drill3d.Queue	0.00	0.000000000	0.00	0.00
Stage1Drill3e.Queue	0.00	0.000000000	0.00	0.00
Stage1Drill3f.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3a.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3b.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3c.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3d.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3e.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3f.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3g.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3h.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3i.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3j.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3k.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3l.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3m.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3n.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3o.Queue	0.00	0.000000000	0.00	0.00
Stage2Mill3p.Queue	0.00	0.000000000	0.00	0.00
Stage5Lathe3a.Queue	0.00	0.000000000	0.00	0.00
Stage5Lathe3b.Queue	0.00	0.000000000	0.00	0.00
Stage5Lathe3c.Queue	0.00	0.000000000	0.00	0.00
Stage5Lathe3d.Queue	0.00	0.000000000	0.00	0.00
Stage5Lathe3e.Queue	0.00	0.000000000	0.00	0.00
Stage5Lathe3f.Queue	0.00	0.000000000	0.00	0.00

Other

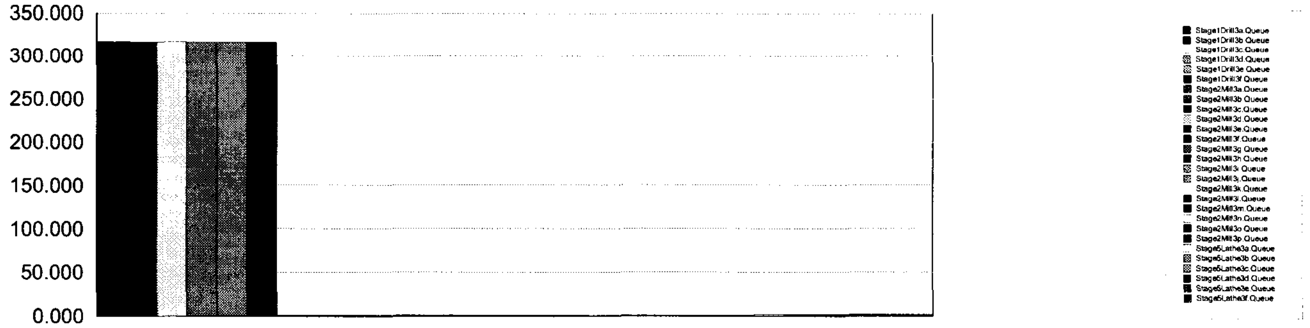
Unnamed Project

Replications: 1 Time Units: Hours

Queue

Other

Number Waiting	Average	Half Width	Minimum Value	Maximum Value
Stage1Drill3a.Queue	316.83	451.526	0.00	12346.00
Stage1Drill3b.Queue	316.77	451.518	0.00	12346.00
Stage1Drill3c.Queue	316.70	451.511	0.00	12345.00
Stage1Drill3d.Queue	316.63	451.503	0.00	12345.00
Stage1Drill3e.Queue	316.57	451.495	0.00	12345.00
Stage1Drill3f.Queue	316.50	451.487	0.00	12345.00
Stage2Mill3a.Queue	0.9924	(Correlated)	0.00	2.0000
Stage2Mill3b.Queue	0.9690	(Correlated)	0.00	2.0000
Stage2Mill3c.Queue	0.9475	(Correlated)	0.00	2.0000
Stage2Mill3d.Queue	0.9204	(Correlated)	0.00	2.0000
Stage2Mill3e.Queue	0.8894	(Correlated)	0.00	2.0000
Stage2Mill3f.Queue	0.8140	(Correlated)	0.00	2.0000
Stage2Mill3g.Queue	0.6542	(Correlated)	0.00	2.0000
Stage2Mill3h.Queue	0.6173	(Correlated)	0.00	2.0000
Stage2Mill3i.Queue	0.4834	(Correlated)	0.00	2.0000
Stage2Mill3j.Queue	0.4416	(Correlated)	0.00	2.0000
Stage2Mill3k.Queue	0.4166	(Correlated)	0.00	2.0000
Stage2Mill3l.Queue	0.3653	(Correlated)	0.00	2.0000
Stage2Mill3m.Queue	0.3054	(Correlated)	0.00	2.0000
Stage2Mill3n.Queue	0.2767	(Correlated)	0.00	1.0000
Stage2Mill3o.Queue	0.2428	(Correlated)	0.00	1.0000
Stage2Mill3p.Queue	0.1671	(Correlated)	0.00	1.0000
Stage5Lathe3a.Queue	1.7642	2.84543	0.00	734.00
Stage5Lathe3b.Queue	1.6552	2.84240	0.00	733.00
Stage5Lathe3c.Queue	1.5414	2.82904	0.00	733.00
Stage5Lathe3d.Queue	1.4821	2.81609	0.00	733.00
Stage5Lathe3e.Queue	1.4685	2.81039	0.00	733.00
Stage5Lathe3f.Queue	1.4594	2.80651	0.00	733.00



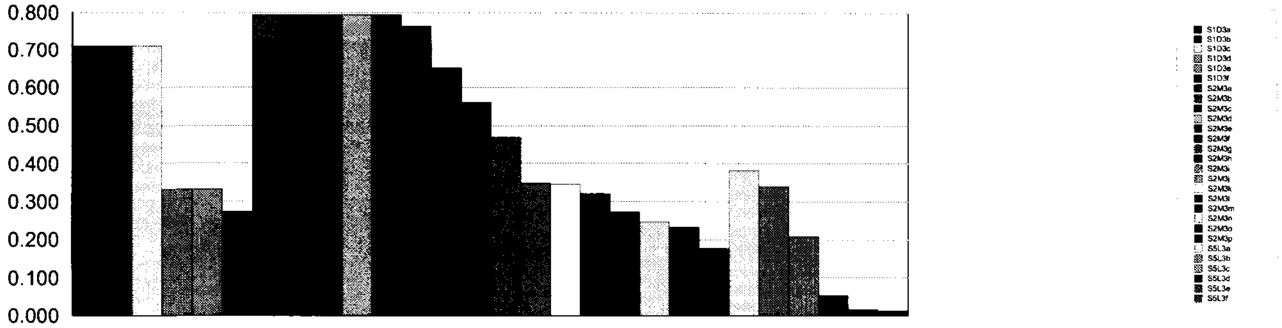
Unnamed Project

Replications: 1 Time Units: Hours

Resource

Usage

Instantaneous Utilization	Average	Half Width	Minimum Value	Maximum Value
S1D3a	0.7090	(Correlated)	0.00	1.0000
S1D3b	0.7090	(Correlated)	0.00	1.0000
S1D3c	0.7089	(Correlated)	0.00	1.0000
S1D3d	0.3321	(Correlated)	0.00	1.0000
S1D3e	0.3319	(Correlated)	0.00	1.0000
S1D3f	0.2734	(Correlated)	0.00	1.0000
S2M3a	0.7946	(Correlated)	0.00	1.0000
S2M3b	0.7946	(Correlated)	0.00	1.0000
S2M3c	0.7946	(Correlated)	0.00	1.0000
S2M3d	0.7946	(Correlated)	0.00	1.0000
S2M3e	0.7944	(Correlated)	0.00	1.0000
S2M3f	0.7639	(Correlated)	0.00	1.0000
S2M3g	0.6518	(Correlated)	0.00	1.0000
S2M3h	0.5614	(Correlated)	0.00	1.0000
S2M3i	0.4692	(Correlated)	0.00	1.0000
S2M3j	0.3482	(Correlated)	0.00	1.0000
S2M3k	0.3455	(Correlated)	0.00	1.0000
S2M3l	0.3215	(Correlated)	0.00	1.0000
S2M3m	0.2723	(Correlated)	0.00	1.0000
S2M3n	0.2463	(Correlated)	0.00	1.0000
S2M3o	0.2332	(Correlated)	0.00	1.0000
S2M3p	0.1774	(Correlated)	0.00	1.0000
S5L3a	0.3828	(Correlated)	0.00	1.0000
S5L3b	0.3395	(Correlated)	0.00	1.0000
S5L3c	0.2082	(Correlated)	0.00	1.0000
S5L3d	0.05419228	(Correlated)	0.00	1.0000
S5L3e	0.01684880	(Correlated)	0.00	1.0000
S5L3f	0.01356413	(Correlated)	0.00	1.0000



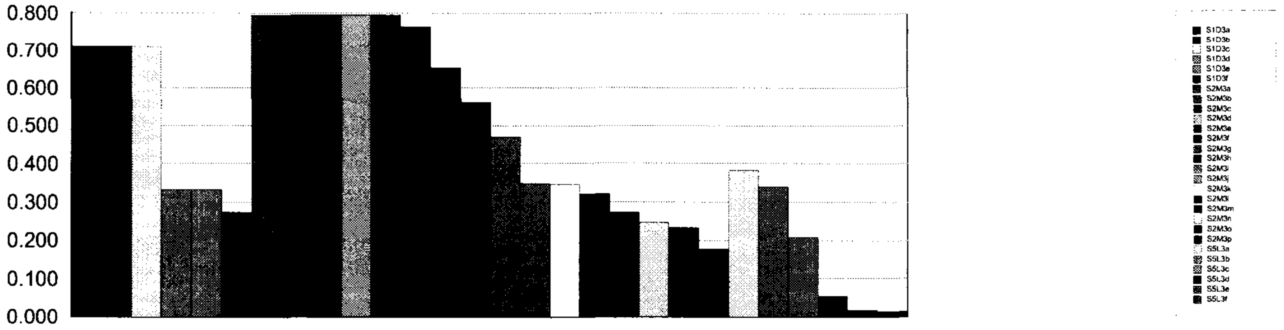
Unnamed Project

Replications: 1 Time Units: Hours

Resource

Usage

Number Busy	Average	Half Width	Minimum Value	Maximum Value
S1D3a	0.7090	(Correlated)	0.00	1.0000
S1D3b	0.7090	(Correlated)	0.00	1.0000
S1D3c	0.7089	(Correlated)	0.00	1.0000
S1D3d	0.3321	(Correlated)	0.00	1.0000
S1D3e	0.3319	(Correlated)	0.00	1.0000
S1D3f	0.2734	(Correlated)	0.00	1.0000
S2M3a	0.7946	(Correlated)	0.00	1.0000
S2M3b	0.7946	(Correlated)	0.00	1.0000
S2M3c	0.7946	(Correlated)	0.00	1.0000
S2M3d	0.7946	(Correlated)	0.00	1.0000
S2M3e	0.7944	(Correlated)	0.00	1.0000
S2M3f	0.7639	(Correlated)	0.00	1.0000
S2M3g	0.6518	(Correlated)	0.00	1.0000
S2M3h	0.5614	(Correlated)	0.00	1.0000
S2M3i	0.4692	(Correlated)	0.00	1.0000
S2M3j	0.3482	(Correlated)	0.00	1.0000
S2M3k	0.3455	(Correlated)	0.00	1.0000
S2M3l	0.3215	(Correlated)	0.00	1.0000
S2M3m	0.2723	(Correlated)	0.00	1.0000
S2M3n	0.2463	(Correlated)	0.00	1.0000
S2M3o	0.2332	(Correlated)	0.00	1.0000
S2M3p	0.1774	(Correlated)	0.00	1.0000
S5L3a	0.3828	(Correlated)	0.00	1.0000
S5L3b	0.3395	(Correlated)	0.00	1.0000
S5L3c	0.2082	(Correlated)	0.00	1.0000
S5L3d	0.05419228	(Correlated)	0.00	1.0000
S5L3e	0.01684880	(Correlated)	0.00	1.0000
S5L3f	0.01356413	(Correlated)	0.00	1.0000



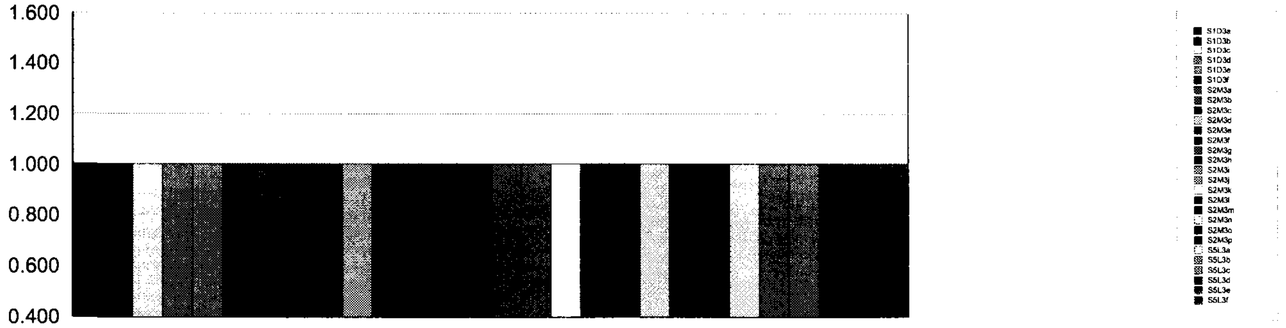
Unnamed Project

Replications: 1 Time Units: Hours

Resource

Usage

Number Scheduled	Average	Half Width	Minimum Value	Maximum Value
S1D3a	1.0000	(Insufficient)	1.0000	1.0000
S1D3b	1.0000	(Insufficient)	1.0000	1.0000
S1D3c	1.0000	(Insufficient)	1.0000	1.0000
S1D3d	1.0000	(Insufficient)	1.0000	1.0000
S1D3e	1.0000	(Insufficient)	1.0000	1.0000
S1D3f	1.0000	(Insufficient)	1.0000	1.0000
S2M3a	1.0000	(Insufficient)	1.0000	1.0000
S2M3b	1.0000	(Insufficient)	1.0000	1.0000
S2M3c	1.0000	(Insufficient)	1.0000	1.0000
S2M3d	1.0000	(Insufficient)	1.0000	1.0000
S2M3e	1.0000	(Insufficient)	1.0000	1.0000
S2M3f	1.0000	(Insufficient)	1.0000	1.0000
S2M3g	1.0000	(Insufficient)	1.0000	1.0000
S2M3h	1.0000	(Insufficient)	1.0000	1.0000
S2M3i	1.0000	(Insufficient)	1.0000	1.0000
S2M3j	1.0000	(Insufficient)	1.0000	1.0000
S2M3k	1.0000	(Insufficient)	1.0000	1.0000
S2M3l	1.0000	(Insufficient)	1.0000	1.0000
S2M3m	1.0000	(Insufficient)	1.0000	1.0000
S2M3n	1.0000	(Insufficient)	1.0000	1.0000
S2M3o	1.0000	(Insufficient)	1.0000	1.0000
S2M3p	1.0000	(Insufficient)	1.0000	1.0000
S5L3a	1.0000	(Insufficient)	1.0000	1.0000
S5L3b	1.0000	(Insufficient)	1.0000	1.0000
S5L3c	1.0000	(Insufficient)	1.0000	1.0000
S5L3d	1.0000	(Insufficient)	1.0000	1.0000
S5L3e	1.0000	(Insufficient)	1.0000	1.0000
S5L3f	1.0000	(Insufficient)	1.0000	1.0000



Unnamed Project

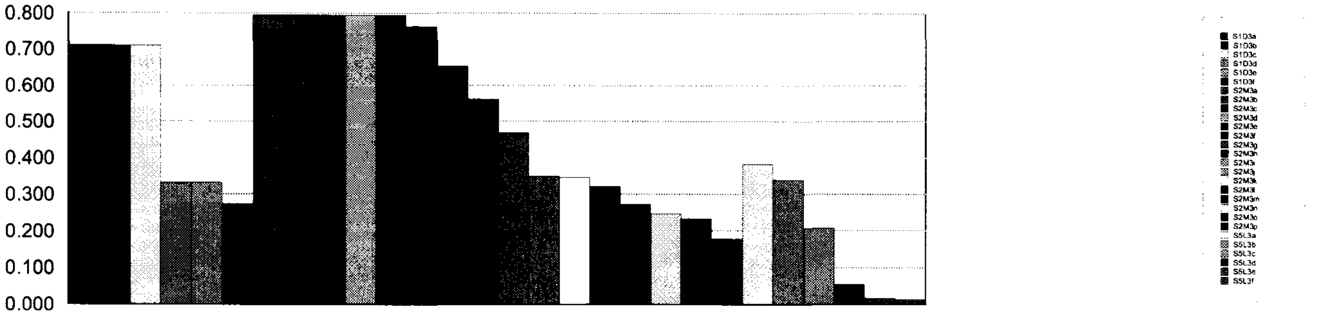
Replications: 1 Time Units: Hours

Resource

Usage

Scheduled Utilization

	Value
S1D3a	0.7090
S1D3b	0.7090
S1D3c	0.7089
S1D3d	0.3321
S1D3e	0.3319
S1D3f	0.2734
S2M3a	0.7946
S2M3b	0.7946
S2M3c	0.7946
S2M3d	0.7946
S2M3e	0.7944
S2M3f	0.7639
S2M3g	0.6518
S2M3h	0.5614
S2M3i	0.4692
S2M3j	0.3482
S2M3k	0.3455
S2M3l	0.3215
S2M3m	0.2723
S2M3n	0.2463
S2M3o	0.2332
S2M3p	0.1774
S5L3a	0.3828
S5L3b	0.3395
S5L3c	0.2082
S5L3d	0.05419228
S5L3e	0.01684880
S5L3f	0.01356413



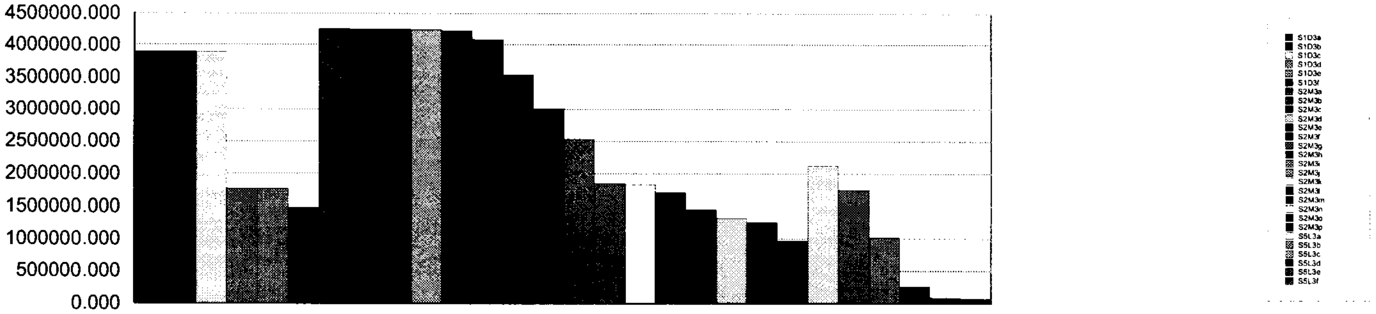
Unnamed Project

Replications: 1 Time Units: Hours

Resource

Usage

Total Number Seized	Value
S1D3a	3888763.00
S1D3b	3887331.00
S1D3c	3888411.00
S1D3d	1770731.00
S1D3e	1768882.00
S1D3f	1472751.00
S2M3a	4258838.00
S2M3b	4256803.00
S2M3c	4254037.00
S2M3d	4249005.00
S2M3e	4233218.00
S2M3f	4076187.00
S2M3g	3529143.00
S2M3h	3003629.00
S2M3i	2534217.00
S2M3j	1843908.00
S2M3k	1831496.00
S2M3l	1707200.00
S2M3m	1446558.00
S2M3n	1310300.00
S2M3o	1247843.00
S2M3p	963345.00
S5L3a	2118700.00
S5L3b	1750996.00
S5L3c	1012553.00
S5L3d	257829.00
S5L3e	80193.00
S5L3f	64609.00



Unnamed Project

Replications: 1 Time Units: Hours

Resource

Cost

Busy Cost

	Value
S1D3a	0.00
S1D3b	0.00
S1D3c	0.00
S1D3d	0.00
S1D3e	0.00
S1D3f	0.00
S2M3a	0.00
S2M3b	0.00
S2M3c	0.00
S2M3d	0.00
S2M3e	0.00
S2M3f	0.00
S2M3g	0.00
S2M3h	0.00
S2M3i	0.00
S2M3j	0.00
S2M3k	0.00
S2M3l	0.00
S2M3m	0.00
S2M3n	0.00
S2M3o	0.00
S2M3p	0.00
S5L3a	0.00
S5L3b	0.00
S5L3c	0.00
S5L3d	0.00
S5L3e	0.00
S5L3f	0.00

Unnamed Project

Replications: 1 Time Units: Hours

Resource

Cost

Idle Cost

	Value
S1D3a	0.00
S1D3b	0.00
S1D3c	0.00
S1D3d	0.00
S1D3e	0.00
S1D3f	0.00
S2M3a	0.00
S2M3b	0.00
S2M3c	0.00
S2M3d	0.00
S2M3e	0.00
S2M3f	0.00
S2M3g	0.00
S2M3h	0.00
S2M3i	0.00
S2M3j	0.00
S2M3k	0.00
S2M3l	0.00
S2M3m	0.00
S2M3n	0.00
S2M3o	0.00
S2M3p	0.00
S5L3a	0.00
S5L3b	0.00
S5L3c	0.00
S5L3d	0.00
S5L3e	0.00
S5L3f	0.00

Unnamed Project

Replications: 1 Time Units: Hours

Resource

Cost

Usage Cost

	Value
S1D3a	0.00
S1D3b	0.00
S1D3c	0.00
S1D3d	0.00
S1D3e	0.00
S1D3f	0.00
S2M3a	0.00
S2M3b	0.00
S2M3c	0.00
S2M3d	0.00
S2M3e	0.00
S2M3f	0.00
S2M3g	0.00
S2M3h	0.00
S2M3i	0.00
S2M3j	0.00
S2M3k	0.00
S2M3l	0.00
S2M3m	0.00
S2M3n	0.00
S2M3o	0.00
S2M3p	0.00
S5L3a	0.00
S5L3b	0.00
S5L3c	0.00
S5L3d	0.00
S5L3e	0.00
S5L3f	0.00

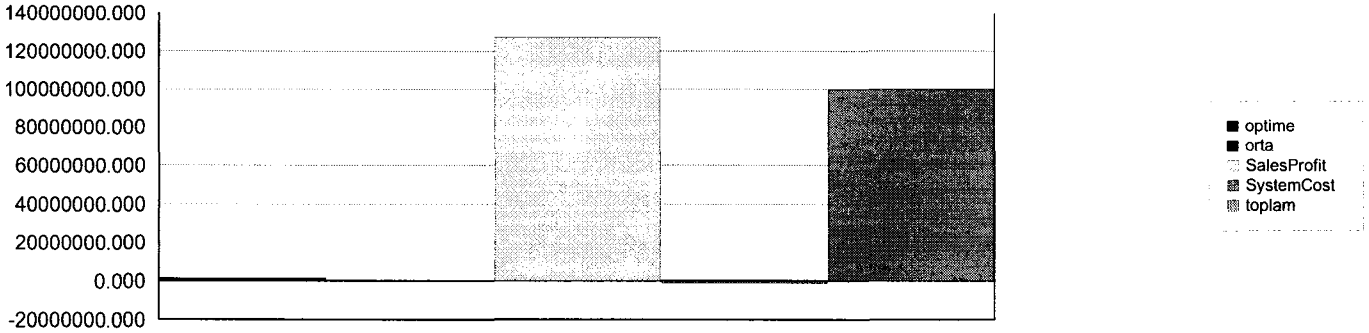
Unnamed Project

Replications: 1 Time Units: Hours

User Specified

Time Persistent

Variable	Average	Half Width	Minimum Value	Maximum Value
optime	1279188.79	(Correlated)	0.00	2757836
orta	12.5382	(Correlated)	0.00	13.7695
SalesProfit	127233896	(Correlated)	0.00	267288283
SystemCost	-1049653	(Correlated)	-24360000	21459869
toplam	99954317	(Correlated)	0.00	218326835



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