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Evaluation of machining systems from a complexity and cost perspectives

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EVALUATION OF MACHINING SYSTEMS FROM A COMPLEXITY AND COST PERSPECTIVES

By

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ABSTRACT

Manufacturing systems, specifically machining, are typically designed as either dedicated or flexible; representing two very different paradigms. Measures for manufacturing flexibility have been proposed; generally, according to behaviour of system or product mix. Attempts have also been made to relate flexibility to subsequent costs.

In this thesis, System Design is presented as a property of inherent attributes determined at the design stage. This provides the 'Flexibility Level' and its measurement is based on physical-functional attributes. Hence, System Design is viewed as a continuous quality, which describes both the level of flexibility and/or dedicated nature of a system.

This metric is related to cost in a model which describes system design in its entirety; including manufacturing complexity in relation to cost as a tool to minimize manufacturing costs. Consequently, system behaviour is investigated given alternate manufacturing conditions such as varying product mix and production volume requirements. Industrial examples are used.

DEDICATION

This thesis has been a major investment of time and effort but it is also a major accomplishment. Support and encouragement has always been a critical driver necessary especially through some difficult times.

I dedicated this work to two very important people in my life. First, my soon to be wife, Kerri Charron, who has been patient to support all the time I have invested in this effort. She has decided to stand by my side, provided strength and happiness; these are the foundations for success.

I also dedicated this work to my mother, Deborah Gillis de Gonzalez. She has always supported and pushed education upon her children. She has made it a priority for us to strive to excel and I believe this work is culmination of her forming.

Lastly, some very important mentions of very important people that, even though they are no longer with us, would have been extremely happy to share this moment and the accomplishment. These are my aunt Lorie Cox, my grandmother Maria Luisa Roman Diaz, and my aunt Silvia Cristina Gonzalez Roman.

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Dr. Andrzej Sobiesiak was instrumental in given advice about starting this program as well as for approaching potential program advisors. He has also provided great advice as a member of my thesis committee. Dr. Baki has also been an active participant in my committee meetings from where I have acquired great advice.

I will also like to express my appreciation to Aunt Ann for assisting in formatting my work and Samin Shroki who has been a great friend and resource to discuss ideas and where I always found support.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1 Introduction

Manufacturing systems have been developed from their initial introduction in the industrial revolution and through the mass production systems in the last century. The development is characterized by the desire to push the limits of productivity and manufacturing economy; this is still true to this day. The next challenge is presented by ever increasing demanding customers and increase in market niches due to globalization. Consumers have grown over past decades not only to expect affordable prices but also to demand a level of quality and performance previously not achievable. In short, this means that manufacturing systems now have three expectations: mass production prices, competitive quality, and desirable and comprehensive product catalog. This is in contrast to only cost being important to consumers as in the early 1900's.

Manufacturing technology has been developed from dedicated equipment to the flexible C.N.C. (Computer Numerically Controlled) machining centers; both used today. Nevertheless, either type of design presents its unique challenges for cost management of high volume manufacturing. Transfer systems consist of highly non-responsive systems composed of many dissimilar stations unique only to the individual process step. Machining centers avoid this problem, hence making the system highly responsive to changes. However, this type of system is usually expensive to operate and maintain.

The intention of this thesis is to address the comparison of both the dedicated and flexible machining systems. It is discussed that either of these systems are extreme cases of manufacturing system design. It is desired to understand which system is most economically beneficial for midrange to high volume manufacturing production. This is while establishing as the basis for analysis the attributes for individual station-system design.

It is presumed that manufacturing systems design can be compared by their level of flexibility; this level is inherent to their initial design and is measured by a scale of manufacturing flexibility. A simple methodology for measuring this flexibility is required. Each design alternative has a cost burden set by its designed flexibility and is estimated with the manufacturing system's cost function. This establishes a relation between flexibility and cost.

Furthermore, cost and manufacturing system complexity estimations are compared in a proportionality relation. This is related by manufacturing system behaviour and operational challenges, and it is useful as a tool for minimizing cost. All together, a design model is assembled from these manufacturing system properties on a scale for flexibility level. Assertions are made and a design strategy is developed for search of economical designs.

The development of a unified model which describes a manufacturing system based on total cost versus flexibility level is of extreme importance. It sets the stage for minimization of cost for a varying level of flexibility. Thus, allowing trade-off of flexible system designs and cost. It is believed that a refinement of the outlook of manufacturing flexibility deployment, as proposed in this paper, will maximize its observed benefits. It will drive economical design.

Therefore, objectives of this thesis are summarized as follows:

- Determine method to measure flexibility of a manufacturing system
- Develop unified system model to be used to described performance of manufacturing systems in general and make assertions
- Use developed model to measure performance of sample manufacturing systems with varying levels of flexibility design
- Incorporate Complexity Analysis into proposed design strategy
- Investigate behaviour of model after design and implementation

A fundamental development of the proposed design model is first introduced in Section 1.2. All the definitions, relations, and rules required to build the model are brought together. It is the foundation of the research. The design of a flexible manufacturing system is viewed as a range of alternative system options designed for an application but varying only in the level of flexibility implementation. That is, application remains constant while the level of flexibility of the manufacturing system is changed. Then, it is presumed that cost implication is a function related to the flexibility of the system. The scale for measuring system flexibility is discussed in Chapter 3.

Chapter 4 discusses definitions of Complexity and its formulation to be used in the design model. The design strategy is concluded in Chapter 5 with the introduction of a 'product size' axis; furthermore, properties of system range, reconfigurability, and design optimality are also discussed as applicable to the strategy.

Chapter 6 develops the manufacturing cost function. It is a practical description of all the components of cost which are applicable from initial design, installation, operation, possible reconfigurations and through final disposal of system. Thus, it infers to total manufacturing costs. It is developed using Axiomatic Design. A cost report card is developed and used for comparison of manufacturing system design alternatives. Applications are given in Chapter 7, results and discussion in Chapter 8, and conclusions in Chapter 9.

1.1 Flexible Manufacturing System Design Alternatives

Figure 1-1 and Figure 1-2 are examples of the extremes of dedicated and flexible technology. Both system alternatives are used to process cylinder blocks but in two completely different manners; each has its own advantages and disadvantages. Therefore, developing a means of comparing and evaluating them is the intent. The discussion can be enlightened by making the following questions. How would the cost distribution look if the ninety six holes boring station of Figure 1-1 is replaced by a machining center as the one in Figure 1-2? How would production schedules and required reconfigurations affect this?

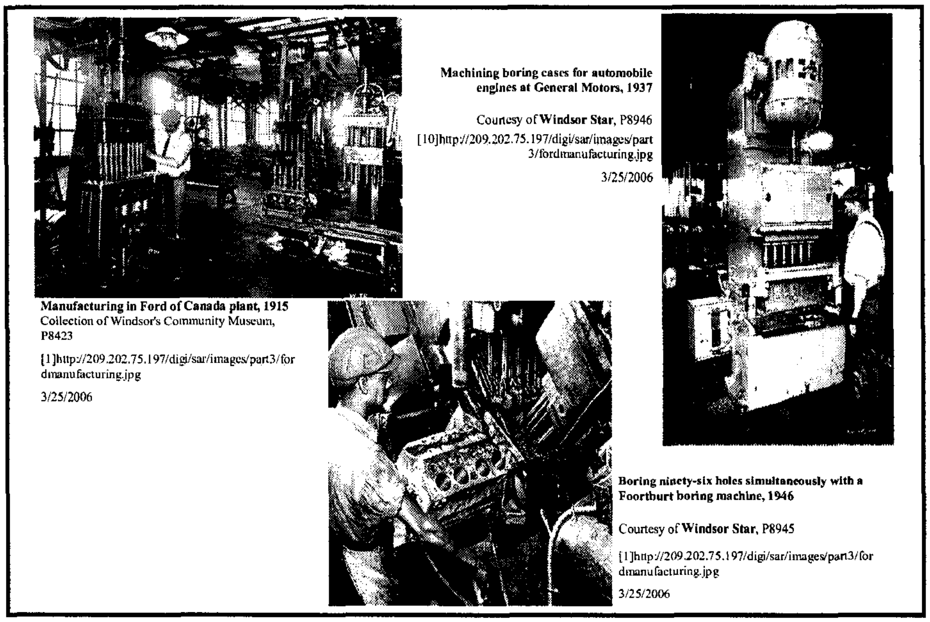


Figure 1-1: Examples of vintage dedicated equipment.

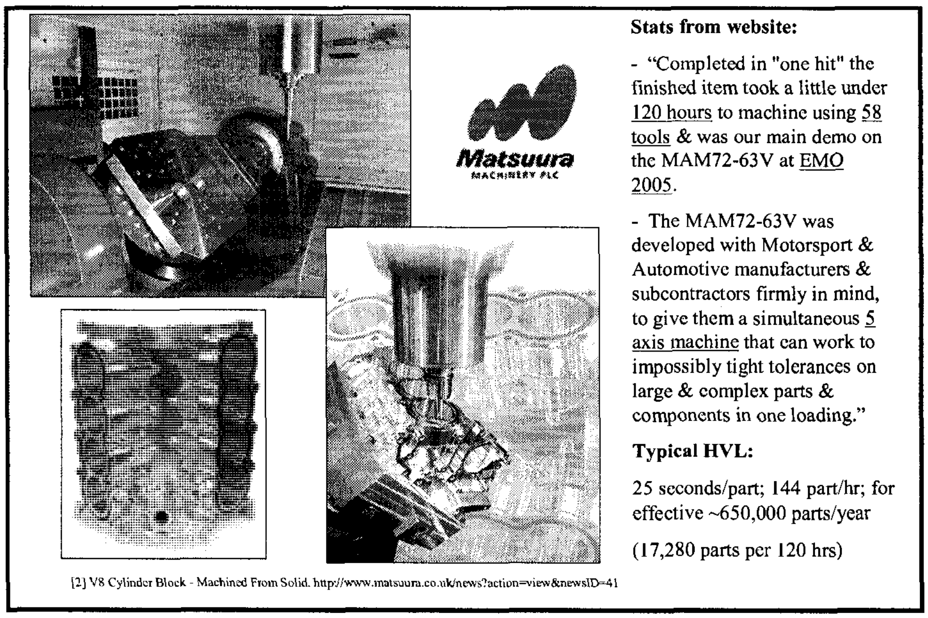


Figure 1-2: Examples of most advanced flexible technology in use to date.

1.2 Model for Manufacturing Flexibility Performance

Discussion in Chapter 3 will show how flexibility is not a single entity which describes a quality of manufacturing system. Instead, it is understood as a property applicable to many levels of manufacturing from the shop floor and up to the strategic structure of a firm. Nevertheless, it is the combined effect of the application of flexible policies at all levels which makes or breaks the advantage acquired by its application. For example, consider two alternatives of poor application:

(1) Flexibility not used or when a system is well designed but by choice of management only used for one product and marginal reconfiguration, and

(2) Flexibility limited by its design or when a system is only capable of operating within a fraction of the total products in a family.

In contrast, a flexible system application can be of great benefit to the firm when a successful flexible manufacturing system design is supported by a corresponding supply chain capable of handling this flexibility. Furthermore, a product and release engineering capable of following demands by marketing is essential.

This research is concentrated at the base level of a manufacturing firm: the shop floor. This is not only where capital expenditure is most extensive but also where great effort must be invested for changeover to new products. Here, a designer must work within work-planes to design a manufacturing line. Individual stations are designed to produce features in one work-plane. Further stations are added serially until all features within a work-plane and all work-planes which make the product are covered.

The focus is to develop a method and/or guidelines for analysis at the station level. It is to combine knowledge and experience with research to propose a structure for 'flexible manufacturing' machining systems. In addition, this report will also propose guidelines which must be met for good implementation. The reader should keep in mind that the proposed methodology is meant to be used for analysis of any industry application.

This section addresses the design model to serve as unifying-theory for all applicable concepts. This is started by making reference to an important concept: productivity. The following paragraph taken from the Accel-Team.com (2005) gives an enlightening business perspective of this term.

> *"Essentially, productivity is the ratio to measure how well an organization (or individual, industry, country) converts input resources (labour, materials, machines, etc.) into goods and services.*
>
> *This is usually expressed in ratios of inputs to outputs. That is (input) cost per (output) good/service. It is not on its own a measure of how efficient the conversion process is."*

Therefore, the following assembly 'A' is extracted from previous reference:

[1]A = Productivity

A1 = applicable to an organization

A2 = Measure of performance

A3 = Ration of input (cost) per output (good/service)

A4 = Not measure of efficiency (of conversion process)

A similar statement should be inferred for manufacturing flexibility. Flexibility will reach its full value when its effect can be related to a cost function. Thus, as productivity relates to costs incurred by the production per unit produced, a scale of flexibility must also relate cost to its extent of implementation. The future is the ability to distinguish applications which are most cost effective and maximize strategic advantage. This is in an attempt to avoid expensive practices. Therefore, from assembly 'B', Flexible Manufacturing System (FMS) can be defined for intent of this thesis as follows:

---

[1] For development of demonstrations I referenced first two chapters of "Theory of Sets" by (Bourbaki, 2004) for constructing logical assemblies.

*A **Flexible Manufacturing System (FMS)** is a quality, or alternative, of a manufacturing system where it is designed to have some amount of flexibility (flexibility level); system has quality of being flexible. The system is then said it can react in case of changes whether predictable or unpredictable. Also, its application is done at many levels.*

Definition extracted from following assembly 'B' of definitions for Flexible Manufacturing System (wikipedia.org, "flexible manufacturing system", 2007), Flexible and Flexibility (Lexicon, 1988). See APPENDIX A(a) quoted statements.

B = Flexible Manufacturing System (FMS)

B1 = quality of a Manufacturing System

B2 = has some amount of flexibility (quality of being flexible)

B2, 1 = system can react in the case of changes

B2, 2 = predicted or unpredicted changes

B3 = has levels of application (i.e. machine, routing, etc.)

***Cost of a Manufacturing System**, from assembly 'C', is the aggregated costs throughout the system's life cycle. Typical components of costs are installation or capital cost, operation (human, computing, etc), conversions or product upgrades, maintenance, and losses through inherent downtime.*

C = Cost of manufacturing system

C1 = aggregated cost

C2 = through system life cycle

C3 = of all components

C3, 1 = installation, capital cost

C3, 2 = operation (human)

C3, 3 = conversions, product upgrades

C3, 4 = maintenance

C4, 4 = losses, downtime (inherent)

Also, it can be argued that, C depends on B, since manufacturing cost is dependent on the design of the system. This is true in all manufacturing systems since incurred cost always is greatly influenced by design options such as equipment type and numbers, arrangements, distances, etc. This will also affect future operation burden. It said that,

C is a relation of B, C |B|,

Therefore,

Since it can be argued that when cost is considered for the entire life cycle of the system, it depends on the type of flexibility designed into the manufacturing system (flexibility level). Therefore,

Equation 1 *Cost = f (Flexibility Level)*

Chapter 3 will provide the required clarification on relating Manufacturing System design and Flexibility Level. Briefly, Flexibility Level is proposed as a measure of design of a manufacturing system based on its abilities. This distinguishes between alternative levels of flexibility but does not make dedicated and flexible system paradigms independent. It describes both; this gives any system the ability to be dedicated or flexible as a continuous flow of design levels. Hence, design depends on flexibility level. It is measured on a scale from '0' for dedicated equipment to '1' for maximum flexibility ability.

Figure 1-3 illustrates the theoretical view of Equation 1. Here the system design range is on the x-axis with dedicated to fully flexible systems at its extremes. Also plotted in Figure 1-3 is a conceptual cost curve; it is an assumed approximation applicable to high volume manufacturing. Arguably, cost maxima will occur at the dedicated extreme since reconfiguration cost is high. Investment cost might also be high. The low installation and reconfiguration cost in a flexible system is replaced by a high operation cost. Investment can also be high; thus, this gives the second cost maxima.

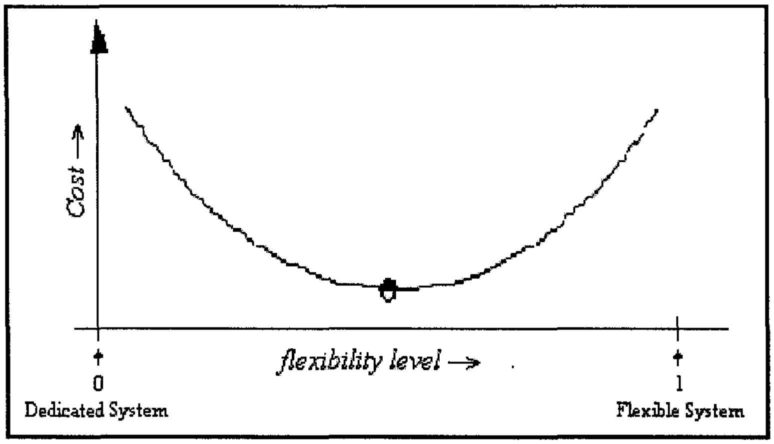


Figure 1-3: Cost vs. System Design.

A complete model which describes total manufacturing cost is required. It is desirable to find one that copes with alternate products (A, B, or C). Effectively, an understanding of the behaviour of the cost optima according to flexibility level and product changes is required. Furthermore, a manufacturing complexity variable is introduced to illustrate the effects of increased complexity of both products and machines. All this is illustrated in the updated model of Figure 1-4.

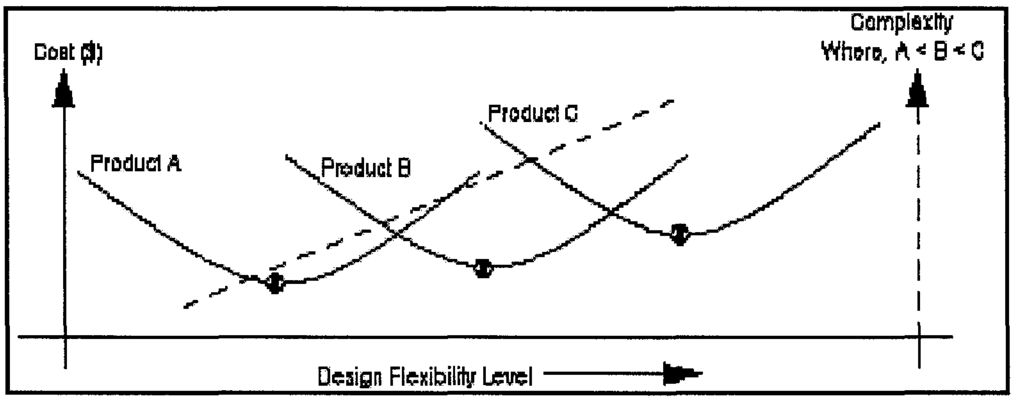


Figure 1-4: Objective: *Cost vs. System Design* applied on a complexity.

In context, Figure 1-4 implies that there exists proportionality between cost and complexity of a system. This is illustrated in Assumption 1 which is the important tool for finding minimum inherent cost of manufacturing system. The following definitions regarding manufacturing system behaviour are necessary to establish this relation. Before, behaviour of a real manufacturing system is defined.

Manufacturing System Behaviour *is the way in which a manufacturing system behaves with respect to its original design intent and parameters. It is also the way it responds to its environmental influences: human operation, maintenance, tooling / materials, temperature-humidity, etc.*

Ideal Manufacturing System Behaviour *is deterministic. It refers to a system which is predictable and controlled with certainty. It behaves according to its design and does not react to environmental influences.*

Therefore, ***Manufacturing System Behaviour*** *is an ensemble of elements or information; therefore, it* ***depends*** *on Physical Information, Effective Complexity, and Environmental Information, or Real or Imaginary Complexity. It directly affects performance.*

In analogy to an ensemble, Manufacturing System Behaviour can be thought of as an ensemble made up by random elements which contribute to the overall performance. Consequently,

D[2] = Manufacturing System Behaviour

D1 = Ensemble of elements (information)

D2 = Output is system performance

D3 = Elements (Information)

D3, 1 = Physical = Effective Complexity

D3, 2 = Environmental = Uncertainty and Ignorance

Behaviour is n. manners, deportment || moral conduct || the way in which a machine, organ or organism works with respect to its efficiency || the way in which something reacts to environment ... (Lexicon, 1988).

[2] See APPENDIX A(b) for applicable definitions for D and E.

Where,

E = Performance

E1 = property of something, system (applicable to task)

E2 = state of action; execution. Representation by action (completion)

E3 = what is accomplished, contrasted with capability (level of success)

E3, 1 = accomplish

= to bring to a successful conclusion, fulfill

***Performance** is a property of a system or task which is being executed. It is a representation of the action and how well it is completed contrasted with capability. Thus, for a manufacturing system, the representation of how well the task of producing a product is measured by cost. Therefore, it is inferred that:*

$$\sum \textbf{\textit{Cost}} \sim \sum \textbf{\textit{Complexity}}$$

Since Manufacturing System Behavior affects performance; complexity affects cost.

Assumption 1: Complexity-Cost Proportionality Relation

For any system of 'i' sub-units made up by 'j' components, the sum of Cost and the sum of Complexity components are proportional such that:

Equation 2 $$\sum \text{Cost}_{ij} \sim \sum \text{Complexity}_{ij}$$

Furthermore, breaking into subcategories we obtain:

Equation 3

$$(\text{Cost}_{ij})_1 + (\text{Cost}_{ij})_2 + \ldots = (k_{ij} * \text{Complexity}_{ij})_1 + (k_{ij} * \text{Complexity}_{ij})_2 + \ldots$$

Assumption 1: is important because it provides the means to bind Complexity theory to Manufacturing Cost. Chapter 4 is a discussion of the knowledge necessary for understanding of Complexity for practical purposes. It is a proficient tool for analysis where other methods are limiting or might require great investment. Therefore, Complexity can be used to increase understanding and control of systems. This is done by means of managing information content of those variables which are unknown or not very well understood.

Equation 2 may be modified by rearranging variables. Terms from either the cost or complexity side are interchanged with their reciprocals. Thus, a complexity term can replace a not well understood cost term. This will aid in the overall understanding and manipulation of the final cost. The following assumption states this argument.

Assumption 2: Variable Interchange
Interchange reciprocal terms from cost or complexity sides of equation.

Equation 4:

$$(\text{Cost}_{ij})_1 + (k_{ij} * \text{Complexity}_{ij})_2 + \ldots = (k_{ij} * \text{Complexity}_{ij})_1 + (\text{Cost}_{ij})_2 + \ldots$$

Then, all that is left is the application of this tool. This is made clear with Assumption 3.

Assumption 3: Minimization of replaced variable
The effects of the replaced cost component are minimized by minimization of the complexity term. Thus,

Equation 5:

$$\min \{(\text{Cost}_{ij})_1\} = \min \{(k_{ij} * \text{Complexity}_{ij})_1\}$$

In summary, the proposed approach is to use axiomatic design to generate a cost function for all components of a flexible manufacturing system. Then, one can replace cost variables with complexity terms, which can have their effects minimized.

Chapter 2 Literature Search

The task of establishing a relation between costs and manufacturing flexibility is available in literature in varying degrees. Different aspects of flexible manufacturing are approached; ranging from product mix, equipment layout, and product design among others. Much evidence exists published in literature. Furthermore, several different computation schemes for both cost and flexibility are available. However, a unification model as one proposed in this thesis can serve to enhance research; great effort is spent in this model to gather the necessary description to relate machining station design to strategic plan of manufacturing firm. Some related articles are mentioned.

Complexity in General

Aldaihani (*et al.*, 2005) provide an important example commonly present in flexible systems in particular when common material handling systems is available between stations. This is an example strongly related to scheduling complexity discussion of Section 4.3.5. They present "a stochastic model to determine the performance of a flexible manufacturing cell (FMC) under variable operational conditions, including random machining times, random loading and unloading times, and random pallet transfer times. The FMC under study consists of two machines, pallet handling system, and a loading/unloading robot. After delivering the blanks by the pallet to the cell, the robot loads the first machine followed by the second. Unloading of a part starts with the machine that finishes its part first, followed by the next machine. When the machining of all parts on the pallet is completed, the handling system moves the pallet with finished parts out and brings in a new pallet with blanks."

Phukan (*et al.*, 2005) propose complexity metrics for manufacturing control architectures. "There is a need to develop metrics that quantify the complexity of a system that can serve as a means for comparing alternative architecture at the design stage. In this paper, we propose metrics used in software engineering to characterize the complexity of manufacturing systems. These metrics have been applied for measuring the Complexity of two software systems: material delivery system and distributed scheduling." This is an interesting alternative to the discussions of Chapter 4.

An important concept which will be examined in later sections is the necessity and importance of understanding product family and the effects this has on manufacturing cost and flexibility agility. Suh E.S. (*et al.*, 2007) expanded on this. "In this paper, a multidisciplinary process for designing flexible product platform components is introduced, assuming the platform component is decided a priori. The design process starts with identification of uncertainties and generation of multiple design alternatives for embedding flexibility into the component. Design alternatives are then optimized for minimum cost, while satisfying the component performance requirements. The flexible designs are then evaluated for economic profitability under identified uncertainty."

Measure of Flexibility

Groote (1994) sets on finding a general framework for the modeling an analysis of flexibility. It is based on the identification of three elements: the set of technologies whose flexibility is to be compared, the sets of environments in which those technologies might operate, and the performance criterion for the evaluation of the technologies. For purpose of the discussion, Groote (1994) defines flexibility as:

"DEFINITION (flexibility as a complement to diversity). Technology $t_1 \in T$ is said to be more flexible than technology $t_2 \in T\,(t_1 \geq_f t_2)$ if for any pair of environments $e_1, e_2 \in E$ such that $e_1 \geq_d e_2$, the following inequality holds:

$$\pi(t_1, e_1) - \pi(t_1, e_2) \geq \pi(t_2, e_1) - \pi(t_2, e_2)."$$

This definition relates flexibility with an environmental response. Effectiveness is measured by cost implications.

Aksin (*et al.*, 2007) review the flexibility question. “The objective is to identify preferred flexibility structures in service or manufacturing systems, when demand is random and capacity is finite. Considering a network flow type model as the basis of the analysis, general structural properties of flexibility design pertaining to the marginal values of flexibility and capacity are identified.”

Equipment Design (flexibility) and Cost

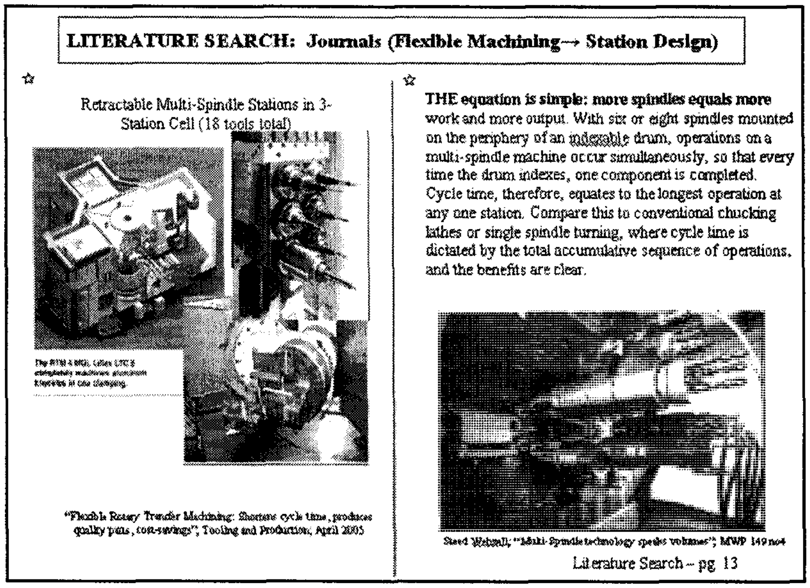


Figure 2-1: Station Design – Flexible, Dedicated (LiCON MT L.P., 2006) and Webzell (Apr 2005).

Akturk (*et al.*, 2006) propose a cellular manufacturing system design model to manage product variety by integrating with the technology selection decision. The proposed model determines the product families and machine groups while deciding the technology of each cell individually. In order to integrate the market characteristics in their model, they proposed a new cost function. The design process introduced is based on two matrices one to describe ‘machine capability, MCM’, and a second to describe ‘part requirements, PRM’ for processing. Both are identity matrices composed of 0’s and 1’s to indicate required or not.

The effort then consists of comparing between predetermine flexible and dedicated operations to find best selection and arrangement. Flexibility of an entire cell is varied by selecting between either alternative for each step. Selection of most economical cell is made by ranking the totals for all pre-calculated cost indices. Ability to handle all available products is also considered. Both, Akturk (*et al.*, 2006) and this thesis are inline for identifying a relationship between flexibility vs. cost. However, Akturk (*et al.*, 2006) is focused on a higher level, cell design, than this report is, station design.

Freiheit (*et al.*, 2007) investigate the investment and operational cost differences between high volume serial and parallel C.N.C.-based machining lines. This study provides insight into the cost-benefit tradeoff of implementing parallelism; that is, effects of production line layout of flexible systems on machine reliability, line balance, configuration throughput, and cost yields.

Kurtoglu (2004) explores a method for modeling and comparing between alternatives of flexible assembly stations. A 'Total Cost, TC' function is the basis of comparison. It depends on matrices describing Flexibility of Workstation, FW' (one for setup cost and a second for resetting costs), Productivity, Operation Needs, Setup (current state), etc. The values in these matrices are pre-calculated and either denotes time or cost considerations.

Comparison is possible once the Total Cost function is determined for each system variant. Production rate vs. cost plots from TC are then used to find optimum production rate and costs for each system variant. This reference does not consider the detailed behaviour of a station. The method for distinguishing flexibility is limited.

"It is important to determine an appropriate level of flexibility in the reconfiguration of production systems while considering the tradeoffs between its costs and benefits. This paper develops a real-option theoretical model that provides insights into flexibility planning in an RMS (Reconfigurable Manufacturing System). A practical method is presented to assist the justification of an RMS in deciding how to influence its operating environment and choose right reconfiguration technologies in order to maximize the performance measure of profitability." (Du, *et al.*, 2006)

The analysis in Du (*et al.*, 2006) is based on the following. "According to de Groote (1994) general framework, in planning flexibility strategy with an RMS involves two types of decisions:

1. Let G= {e|e = 1, . . . , E} be the set of all environmental factors upon which the RMS is operated and which in turn influence the RMS.
2. Let F = { f | f= 1, . . . , F} be the set of all possible reconfiguration technologies from which an RMS can be implemented.

The implementation of an RMS involves both a production environment and reconfiguration technologies. Let C(e) and C(f) represent the cost associated with implementing an environment and a reconfiguration technology, respectively.

Further let p(e, f) be the performance criterion (called profit function), where p(e, f) can be any real-valued function, i.e., $p : G \times F \rightarrow R$. Therefore, the flexibility planning problem can be stated as:

$$\max_{G,F} \; p(e, f),$$

Though the profit function, p(e, f), can in principle be empirically estimated, the implications about the profit function are not as straightforward as suggested by the properties of these functions (Jordan, et al., 1995). This paper proceeds with the development of a real-option method to estimate the profit function for given environment and reconfiguration technologies."

Evans (*et al.*, 2004) proposed comparison of competing flexible manufacturing systems by the development of an Investment Analysis to review cost implications. This is done for capital investment, variable cost structure and fixed costs on a net present value over a five-year term and for each system option. The most profitable option is then weighted over its profitability.

Further development of investment analysis is proposed by Palmer (*et al.*, 2005). "The proposed model better enables rational analysis of Flexible Computer-Integrated Manufacturing (FCIM) system investment options, resulting in a more accurate prediction of income and product line profitability attributable to FCIM system investment."

Boyer (*et al.*, 1996) focuses on increased flexibility as a tool to address the challenges posed by variable demand. This is done by examining two types of flexibility: process and machine flexibility. The first is defined as the ability of a single manufacturing plant to make more than a single type of product. Machine flexibility is defined in terms of changeover cost (capacity or production loss). Further development consists of relating product mix, plants, capacity at plants, and average demands. Example: Table 3 from Boyer (*et al.*, 1996). This research does not sufficiently detail individual station parameters.

Turkcan (*et al.*, 2007) review system design question with a dual objective: minimization of cost and total weighted tardiness. "In this study, we consider flexible manufacturing system loading, scheduling and tool management problems simultaneously. Our aim is to determine relevant tool management decisions, which are machining conditions selection and tool allocation and to load and schedule parts on non-identical parallel C.N.C. machines."

Spicer (*et al.*, 2007) "Investigates how to determine the optimal configuration path of a scalable-RMS that minimizes investment and reconfiguration costs over a finite horizon with known demand.

- First, a practical cost model is presented to compute the reconfiguration cost between two scalable-RMS configurations. This model comprehends labor costs, lost capacity costs, and investment/salvage costs due to system reconfiguration and ramp up.

- Second, the paper presents an optimal solution model for the multi-period scalable-RMS using dynamic programming (DP).
- Third, a combined integer programming/dynamic programming (IP-DP) heuristic is presented that allows the user to control the number of system configurations considered by the DP in order to reduce the solution time while still providing a reasonable solution."

Lau (*et al.*, 2004) propose a framework to be used for manufacturing system design. "This framework aims at providing a unified platform for complex manufacturing systems with enhanced formality. Features include procedures for requirement analysis, simulation of system behaviour, and formal verification of abstract implementation. The proposed framework helps to shorten lifecycle for system design and helps engineers to produce manufacturing systems that conform better to original specifications to better quality".

Furthermore, Boyle (2004) suggests a management strategy for implementation of flexible manufacturing. "The purpose of this research is to develop a framework and an initial list of best management practices for implementing manufacturing flexibility. To identify these practices, recent frameworks (i.e. 1988 and onward) for implementing manufacturing flexibility in organizations are reviewed. Based on this review, the major management practices for implementing flexibility are identified and synthesized into a new framework.

This framework suggests that manufacturing flexibility should be implemented using a three-stage approach, labeled: *identifying required flexibility* (i.e. *identifying and justifying the flexibility types*, measurements and tools needed to achieve the required manufacturing flexibility), achieving required flexibility (i.e. acquiring and implementing the organizational and technological tools needed to achieve the required manufacturing flexibility) and *managing required flexibility* (i.e. monitoring and changing the required flexibility types and levels, in light of changing uncertainty and competitive, manufacturing and marketing strategies). Based on this framework, a number of potential best management practices are identified." This paper is of interest since it mirrors the efforts proposed in this thesis but from a management perspective rather than system design.

Van Biesebroeck (2007) presents an overview of cost of flexibility. It "provides evidence that while flexibility has an advantage to cope with increasing variety, there are non-negligible costs as well".

Flexible-dedicated equipment design

Examples of creative equipment design and which are also directionally related to ideas proposed in this thesis are found in literature. That is, the use of flexible-dedicated design as an alternative to pure flexible or dedicated systems. Some examples are Lorincz (2006), LiCON MT L.P. (2006) and Webzell (Apr 2005). The last two are reviewed earlier in this section. Furthermore, the review by Webzell (Feb 2005) also provides flexible cell designs which have flexible-dedicated attributes. Thus, providing further prove that the technology described in this thesis is already under development. This makes an excellent case for the necessity of model presented. That is, to provide a roadmap for future implementation and research that speeds development and minimizes risk of failure. The last example of equipment design to be mentioned is presented by Katz (2007) which is an overview of reconfigurable equipment design.

Chapter 3 Dimensions of Manufacturing Flexibility

A method for distinguishing between flexible manufacturing system designs must be establish first before attempting to compare among alternatives. This must consist of a qualitative metric, which describes system design from flexible to dedicated arrangements. Thus, discussion in this Chapter begins with a summary of researched material into the meaning of flexibility in manufacturing.

Manufacturing flexibility implementation varies at different levels of the firm but each is important. For example, plant level design is a characteristic which contributes to flexibility. In turn, it is independent of logistics planning but both are critical and must be designed together. Both must meet the high level strategic plan of the firm. Therefore, a firm's Flexible Manufacturing System (FMS) strategic implementation plan must consider the 'top-to-bottom' structure of the organization. In brief, we must consider these characteristics as the *'dimensions of manufacturing flexibility'* as discussed by Koste and Malhorta (1999). In their discussion, an exhaustive research is conducted among the available literature to distinguish what are considered as dimensions of flexibility and the extent of research among each. Table 3-1 summarizes their findings. Included are the tiers of a manufacturing firm at which each dimension is applicable.

Table 3-1: Definition and hierarchy of flexibility (Koste, *et al.*, 1999).

	Dimensions		Description
1	Individual Resource	Machine Flexibility	The number and heterogeneity (variety) of operations a machine can execute without high transition penalties or large changes in performance outcomes.
2	**[Tier 1]**	Labour Flexibility	The number and heterogeneity (variety) of tasks/operations a worker can execute without incurring high transition penalties or large changes in performance outcomes.

3		Material Handling Flexibility	The number of existing paths between processing centers and the heterogeneity (variety) of material which can be transported along those paths without incurring high transition penalties or large changes in performance outcomes.
4	Shop Floor **[Tier 2]**	Routing Flexibility	The number of products which have alternate routes and the extent of variation among the routes used without incurring high transition penalties or large changes in performance outcomes.
5		Operation Flexibility	The number of products which have alternate sequencing plans and the heterogeneity (variety) of the plans used without incurring high transition penalties or large changes in performance.
6	Plant **[Tier 3]**	Expansion Flexibility	The number and heterogeneity (variety) of expansion which can be accommodated without incurring high transition penalties or large changes in performance outcomes.
7		Volume Flexibility	The extent of change and the degree of fluctuation in aggregate output level which the system can accommodate without incurring high transition penalties or large changes in performance outcomes.
8		Mix Flexibility	The number and variety (heterogeneity) of products which can be produced without incurring high transition penalties or large changes in performance outcomes.
9		New Product Flexibility	The number and heterogeneity (variety) of new products which are introduced into production without incurring high transition penalties or large changes in performance outcomes.
10		Modificati on Flexibility	The number and heterogeneity (variety) of product modification which are accomplished without incurring high transition penalties or large changes in performance

			outcomes.
	Functional **[Tier 4]**	R&D Flexibility	
		System Flexibility	
		Organizational Flexibility	
		Manufacturing Flexibility	
		Marketing Flexibility	
	Strategic Business Unit **[Tier 5]**	Strategic Flexibility	

It is still necessary to find a scale for each dimension to be used in future design of industrial applications. Koste (*et al.*, 1999) also set to find a framework for analyzing the dimensions of manufacturing flexibility. They defined critical characteristics, or elements, that must be applied to each dimension if one intends to completely describe flexibility. Table 3-2 describes the four elements that comprise the domain of any flexibility dimension. These elements are Range-Number (R-N), Range-Homogeneity (R-H), Mobility (M), and Uniformity (U).

Table 3-2: Elements of flexibility and potential indicators (Koste, et al., 1999).

Elements	Indicators
Range-number (R-N)	Number of options (operations, tasks, products, etc.)
Range-heterogeneity (R-H)	Heterogeneity of options (difference between operations, tasks, products, etc.)
Mobility (M)	Transition penalties – time, cost, effort of transition
Uniformity (U)	Similarity of performance outcomes – quality, costs, time, etc.

Koste (*et al.*, 1999) discuss, *'Range'* is described as the number of different positions, or flexible options, that can be achieved for a given flexibility dimension. This is designed as R-N (range-number). They also argued range may not be as objective as a numerical count; thus, *'Heterogeneity'* is also necessary to capture the full extent of the range and create a richer measurement of range (designate as R-H or range-heterogeneity).

'Mobility' is the third element and it represents the ease with which the organization moves from one state to another. It corresponds to the 'ease of movement' which uses both time and cost to assess its impact (Koste, *et al.*, 1999). (The term agility is sometimes used instead of mobility.) The last element is *'Uniformity'*. Given the similarity of performance outcomes, the less flexible system will exhibit losses in performance outcomes.

3.1 Proposed Flexibility Scale Methodology

Figure 3-1 describes the inner workings of the proposed Flexibility Scale. In short, it is a bi-axis development that starts at the Firm's Catalog of Offerings where a product family is extracted as a complete set. An idealized system which is capable of handling all products within this family is built as the Industry Application.

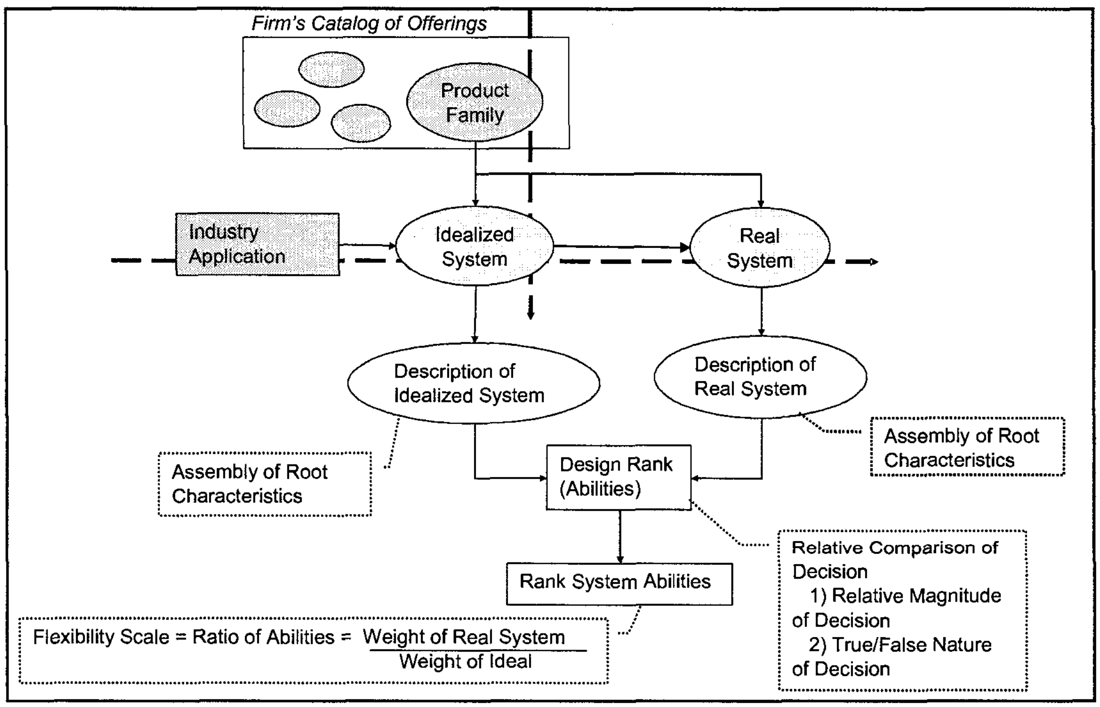


Figure 3-1: Structure of Flexibility Scale.

A set of real system alternatives to be compared are also produced. A description for both the Idealized and Real systems are developed using proposed methodology of Root Characteristics. Finally, each real system alternative is ranked compared to the idealized industry application. This is the Flexibility Level expressed as the Ratio of Abilities.

The methodology proposed as follows is applied at the lowest level (dimension) as represented in Table 3-1; *machine flexibility*[3]. The ***first step*** for set-up of this analysis of system flexibility is to make a determination on the 'product family' to be reviewed.

A[4] = family

A1 = group of elements

A2 = grouped by a common characteristic

B = Product

B1 = good which can be bought or sold (has value)

B2 = purchased as materials and sold as good (is produced)

Assembly C = Product Family, or Range Product Range

= given by assembly of characteristics A and B

= Characteristic of any one or group of object x

= AB(x)

Product Family, or Product Range, *is a single or group of objects 'x' characterized by a common* ***characteristic, utility****. Each having both commercial value or existing need, and is an item produced as result of a manufacturing activity*[5].

D = Utility

D1 = State or act of using or being used (useful)

[3] Method can be extended to provide scale for the remaining dimension of FMS.

[4] Definitions utilized can be found in APPENDIX B(a)

[5] Example: Cylinder Blocks, Crankshafts, or Transmission Cases are three alternative Product Families.

D2 = function, the purpose for which is something is used (has function).

E = Property

E1 = is an attribute

E2 = common to elements of a group

E3 = cannot be used to distinguish between elements of a class

Therefore, from assembly of D and E; we consider utility as of set of objects x,

Utility *of object, or group of objects x is first the state or act of having usefulness, which satisfies purpose and/or function. Secondly, group of products must be related by a common attribute(s) but which cannot be used for distinguishing between them.*

This means, for example, that we might group elements of the family of cylinder blocks having "counter-weighted cranks", "cylinder head(s)", and "piston-connecting rod" as common characteristics. The distinguishing characteristics are size and arrangement (V or I). These limitations are not applicable to Wankel rotary engines since crank is replaced by a rotor, head by cover, and piston is non existent.

Note that a second terminology is used in this report as the 'catalog of offerings'; it is the catalog which includes all product families offered by the firm (cranks, blocks, etc). Not to be confused with product family.

The ***second step*** defines the guidelines for comparison. This is based on comparing competing systems with respect to one another; relative comparison.

F[6] = Decision

F1 = a definite selection

F2 = select one choice from set of alternatives

F3 = designated for an application (has related application)

G = Comparison

[6] Applicable references are found in APPENDIX B(b)

G1 = must have at least two elements or characteristics

G2 = must have expression of objects or characteristics (direct or transformation) which allows determination of like/unlike comparison (must be comparable)

H = Relative

H1 = is object or characteristic of something (quantity, quality, truth, idea, etc.)

H2 = is known only with respect to a second object or characteristic

H3 = is not absolute statement

Therefore, from assembly FGH and for this thesis,

Relative Comparison of Decision *(or Relative Comparison) is a definite statement or assertion which selects one alternative among many; these are related and satisfy a need.*

These alternatives are expressions of objects or characteristics such as quantity, quality, truth, idea, etc., which assists in making determinations between them. However, no absolute statement exist and all is known is with respect to a second object or characteristic.

Two concepts of choice-decision are applicable:

1) Relative Magnitude of decision *– This type of comparison is used to describe features of flexibility having magnitudes of abilities. This is accomplished by using factors. These could be numbers such as 0, 1, 2, etc. Zero is for non-desirable and higher numbers for increasingly advantageous systems.*

This addresses the comparison question such as, for example, one system which is of impeding changeover cost (0), while the second is 2 times less cost; making it the leader. A third system could top both for a cost factor of 3 times less cost. Given by, J = Relative Magnitude Comparison

J1 = set of comparables

J1, 1 = is object or characteristic of something

J1, 2 = is a magnitude measurable

J1, 3 = there exists two or more objects

J2 = relation is non-absolute rather it is know with respect to a base of comparison. (Use of factors)

2) True or False nature of decision *– Objects or characteristic that are of existence type. That is, they either exist or not; are available or not. The designation for this comparison is of binary type; values are (True = 1, False = 0). This addresses the general ability question: can the system cope with such: yes/no?* Given by,

I = T / F Decision

I1 = is a decision (as per previous discussion)

I2 = is an existence characteristic

(It either exists or not; available or not)

The ***third step*** is to identify and list all available characteristics for a system/industry application. The task is to achieve all ***root characteristics*** of a manufacturing system. Care must be taken to avoid mixing similar options; thus, achieving range-(number, heterogeneity) as per previous discussion

K[7] = Root

K1 = is a statement of object or characteristic

K2 = is fundamental or essential

L = Characteristic

L1 = quality of object

L2 = is distinguishable from other descriptions

[7] Applicable references are found n APPENDIX B(c)

M = Manufacturing System

M1 = Equipment

M1, 1 = Production Equipment

M1, 1, 1 = Operation Equipment

M1, 1, 1, 1 = Station equipment

M1, 1, 1, 1, 1 = Spindle

M1, 1, 1, 1, 1 = Slide(s) System

M1, 1, 1, 1, 1 = Tooling

M1, 1, 2 = Work Holding-Fixturing

M1, 2 = Material Handling Equipment

M1, 3 = Test Systems

M2 = Management Strategy (Flex., Quality System, etc)

M3 = Human Factors

Therefore, from assembly of KLM,

Root Characteristic *of Manufacturing Systems is a statement of an object or characteristics which is an essential element of a description. It describes a quality which is unique and fundamental. It is the functional elements which make a manufacturing system. The alternatives in arrangements make the alternatives in manufacturing systems (flexible, dedicated).*

For example, functional components of a machining application are: spindles, transfers, slides, tools, etc. Once identification of all options is complete, it is time to set-up evaluation. The basis for the proposed measure of manufacturing flexibility is given by the measure of Total Abilities of an Industry Application. The description of an industrial application is given by the assembly KLM applied to the manufacturing equipment. That is, it is the set of 'root characteristics' which complete a description of a system.

N = Industry Application

N1 = set of manufacturing equipment (system)

N2 = has intent of addressing a need

(Low/High Volume, Product Type, Size, etc)

N3 = inherent type (machining, assembly, stamping, etc)

*An **Industry Application** is a set of manufacturing equipment of inherent type (machining, assembly, stamping, etc.) arranged to address a manufacturing need (Low/High Volume, Work Size, etc). A **Description of Industry Application** is the set of root characteristics without specifying arrangement.*

Description of an industry application' is the assembly of KLM and N (KLMN(x)); where x is any equipment. Then, Total Abilities of an Industry Application are the sum of the weights of all root characteristics identified in the description of industry application. It is given by rankings I, J applied to assembly KLMN(x); it is assembly (IJ) KLMN(x). That is,

O= Weight of Root Characteristic

O1 = Root Characteristic (1 through n); KLMN(x)

O2 = Elements of Comparison

O2, 1 = Range-Homogeneity

O2, 2 = Range-Heterogeneity

O2, 3 = Uniformity

O2, 4 = Mobility

O3 = Comparison Ranking; IJ

O3, 1 = T/F Comparison (Binary 0 or 1)

O3, 2 = Magnitude Comparison (Factors 0, 1, 2 ...)

O4 = Max possible weight

*The **Weight of a Root Characteristic** is calculated for each root independently. It is based on ranking each with respect to the elements of a scale for flexible manufacturing dimension (*Table 3-1*). The **rank** will be given from the comparators T/F and Magnitude (I and J Comparators). The **weight** is the sum of ranks for a given system.*

Then, ***Total Abilities*** *of an Industry Application is the weight taking the highest possible value for all ranks of all the root characteristics which make the entire description.*

The ***fourth step*** is the final comparison of the system in question and the industry application. Hereafter all is left is to unite all concepts introduced thus far and explain how they form the ***scale for manufacturing flexibility***. This is introduced as the ***Ratio of Abilities***; this is the scale.

Recalling the assembly KLMN(x) is a description of equipment x by assembly of all root characteristics. Also, the rank is given by assembly (IJ) applied to KLMN(x) following condition O2. The weight is then the sum of all ranks for all characteristics.

Ratio of Abilities *- Total Abilities is the weight calculated by summing all maximum possible ranks; this can be considered as the number options available in an Industry Application. However, not all systems have the same abilities. They will have varying weights. Therefore, the actual weight of a system is defined as the 'Weight of a System'. Then, arguably, it is possible to deduce the comparison of a given system with the Industry Application as:*

$$\textbf{Flexibility Scale} = \textit{Ratio of Abilities} = \frac{\textit{Weight of a System}}{\textit{Total Abilities}}$$

Total Abilities is also understood as the weight of the system with maximum possible options which describes a given product family. That is, the ***idealized manufacturing system for a given product family,*** or Industry application, which contains all possible system arrangements.

3.2 Example of Computation of Flexibility Scale

Table 3-3 is a sample applied to dimension 1: *machine*. This is for machining a prismatic product family with six work-planes perpendicular to each other making a cube. Four system options are presented for the example as follows:

A) Option 'A' is the classical dedicated machine with fixed multi-spindle head on a unidirectional slide (extremely limited flexibility).

B) Option 'B' is the application of a multi-axis spindle head with additional work-table axis. This gives the most flexibility but it will be shown in later Chapter how there is a price attached to this benefit (due long cycles, high wear, and high number of equipment required).

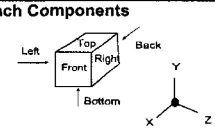
C) Option 'C' is the flexible-dedicated alternative to be introduced. It still assumes multi-axis spindles and work-table axis as in Option B but a limit on flexibility is introduced; it is made less flexible. It is accomplished through the use of spindle head adapters.

D) The exercise in Table 3-3 is extended using this methodology to find Option D. Considerations are taken to maximize machine flexibility given cube-like product family. It is noted that the addition of a 90 degree reposition of the product allows maximum flexibility.

Table 3-3: Scale of Flexibility.

Range (number, heterogeneity) options	Max Score	Applied factor	Dedicated Line Option A	CNC (single spindle tool) Option B	CNC with dedicated spindle adapters Option C	Fully Flexible Machine (single-spindle tool) Option D
1) Tool Component						
i) size of tool changeable (Yes/No)	1	1	1	1	1	1
(M) - Transitional Penalty (0,1,2,3)	3		1	3	2	3
(U) - Uniformity in performance (0,1,2)	2		2	2	2	2
ii) Speed/rpm variable (Yes/No)	1	1	1	1	1	1
(M) - Transitiional Penalty (0,1,2)	2		0	2	2	2
(U) - Uniformity in performance (0,1,2)	2		2	2	2	2
iii) Machine Tool Capability						
Normal Operations (drill, bore, ream, tap, mill/facing, endmill/plunge)	6	1	2	6	5	6
Axial Operations (turning, ID/OD milling, turn broach)	3	1	0	0	0	0
2) Internal Fixture Component						
iv) Axial Accesibility (Total Planes = 6)	6					
Rotation about Axis Y - Abilitated?	1		0	1	1	1
Planes Accesible? (Initial)			0	4	4	4
Rotation about Axis X - Abilitated?	1		0	0	0	1
Planes Accesible? (remaining)			0	0	0	2
Rotation about Axis Z - Abilitated?	1		0	0	0	0
Planes Accesible? (remaining)			0	0	0	0
			Dedicated line with transfer-bar style system does not have ability to reposition other than specialized in-line stations	Only 4 planes available at any one time. External intervention needed for reposition to view 2 remaining planes	Same as 'B' since this ability is not related to tooling adaptions	The simple addition of a repositioning axis 'X' allows full viewing of remaining axis with minimum effort.

2) Approach Components



Details by Approach

Approach	Max Score	Applied factor	A: F	A: B	A: L	A: R	A: T	A: B	B: F	B: B	B: L	B: R	B: T	B: B	C: F	C: B	C: L	C: R	C: T	C: B	D: F	D: B	D: L	D: R	D: T	D: B
Approachable? (Yes/No)	1	6	1	0	0	0	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	1	1
(M) - transitional Penalty (0,1,2)	2		2	0	0	0	0	0	2	2	2	2	0	0	2	2	2	2	0	0	2	2	2	2	2	2
(U) - Uniformity in performance (0,1,2)	2		2	0	0	0	0	0	2	2	2	2	0	0	2	2	2	2	0	0	2	2	2	2	2	2
Variable feed along approach? (Yes/No)	1	6	1	0	0	0	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	1	1
(M) - transitional Penalty (0,1,2)	2		2	0	0	0	0	0	2	2	2	2	0	0	2	2	2	2	0	0	2	2	2	2	2	2
(U) - Uniformity in performance (0,1,2)	2		2	0	0	0	0	0	2	2	2	2	0	0	2	2	2	2	0	0	2	2	2	2	2	2
Horizontal motion on plain normal to approach allowable? (Yes/No)	1	6	0	0	0	0	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	1	1
(M) - transitional Penalty (0,1,2)	2		0	0	0	0	0	0	2	2	2	2	0	0	2	2	2	2	0	0	2	2	2	2	2	2
(U) - Uniformity in performance (0,1,2)	2		0	0	0	0	0	0	2	2	2	2	0	0	2	2	2	2	0	0	2	2	2	2	2	2
Vertical motion on plain normal to approach allowable? (Yes/No)	1	6	0	0	0	0	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	1	1
(M) - transitional Penalty (0,1,2)	2		0	0	0	0	0	0	2	2	2	2	0	0	2	2	2	2	0	0	2	2	2	2	2	2
(U) - Uniformity in performance (0,1,2)	2		0	0	0	0	0	0	2	2	2	2	0	0	2	2	2	2	0	0	2	2	2	2	2	2
Stiching capability? (Yes/No)	1	6	1	0	0	0	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	1	1
Stiching Sizeable (a-dir)? (Yes/No)	1	6	1	0	0	0	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	1	1
(M) - transitional Penalty (0,1,2)	2		0	0	0	0	0	0	2	2	2	2	0	0	0	0	0	0	0	0	2	2	2	2	2	2
(U) - Uniformity in performance (0,1,2)	2		2	0	0	0	0	0	2	2	2	2	0	0	2	2	2	2	0	0	2	2	2	2	2	2
Stiching Sizeable (b-dir)? (Yes/No)	1	6	1	0	0	0	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	1	1
(M) - transitional Penalty (0,1,2)	2		-1	0	0	0	0	0	2	2	2	2	0	0	0	0	0	0	0	0	2	2	2	2	2	2
(U) - Uniformity in performance (0,1,2)	2		2	0	0	0	0	0	2	2	2	2	0	0	2	2	2	2	0	0	2	2	2	2	2	2
Stiching Multiplicable? (Yes/No)	1	6	1	0	0	0	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	1	1
(M) - transitional Penalty (0,1,2)	2		-1	0	0	0	0	0	2	2	2	2	0	0	0	0	0	0	0	0	2	2	2	2	2	2
(U) - Uniformity in performance (0,1,2)	2		2	0	0	0	0	0	2	2	2	2	0	0	2	2	2	2	0	0	2	2	2	2	2	2
Total Allowable points:		***245***																								
Subtotals (1):			9						22						20						25					
Subtotals (2):			18	0	0	0	0	0	36	36	36	36	0	0	30	30	30	30	0	0	36	36	36	36	36	36
Total Score:			27						166						140						241					
Flexibility Factor:			**0.11**						**0.68**						**0.57**						**0.98**					

3.3 Next Dimension of Flexibility: Product Flexibility

The method for evaluation flexibility of a system was introduced thus far. This looked at the problem from equipment perspective. However, product was mentioned in the 'first step' of the methodology; most notably, it is important for finding the Idealized Manufacturing System. Its use is illustrated in example of Table 3-3. This Chapter discusses the importance of 'Product Flexibility' in further detail. The concept is vital for identifying root characteristics.

This next dimension connects the shop to the strategic plan of the firm. It details requirements for machines and machine applications. The agenda is to address product family by dividing it into two concepts: the 'opposing-demand products' or the strategic value and the 'generic composite model'. This later one serves as the blueprint for the plant level design.

i) Opposing-demands Products

The concept of **'opposing-demand products'** is introduced as a relation between the strategic levels of a firm with the shop floor. It assists in giving a guideline for effective implementation of a flexible manufacturing system. It represents comprehension and coverage.

*Two products y and z are **Opposing-demands products** if demands Y and Z are related under relation **R**, are representation of entire set of customer demand, and are opposite. That is, for last condition, Y depends on need 'a' which is prevalent when need 'b' of demand Z is not. Vice versa is true.*

*Therefore, Flexible System is said to be **Comprehensive** if it is designed for Product Family (Y, Z).*

From assembly A:

A = Comprehensive

A1 = about group of terms

A2 = inclusion

A3 = extent

Comprehensive is adj. including much || all-inclusive || able to understand much (Lexicon, 1988).

For example, larger V8/V10 engines are expensive items which are attractive for producing increased revenues; this is true only when economics are permitting. Nevertheless, shifts in economics can significantly hamper the market's ability to purchase such vehicles. In turn, demand for such opposing-demands products as 4 or 6 cylinder engines increases. Significant excess costs are observed since firms have to make commitments to not only larger engine manufacturing but also for small ones. Thus, firm requires excess capacity. Therefore, flexibility design for opposing-demands products allows for shared capacity and subsequent savings.

Capacity planning for a high volume manufacturing firms is done to be able to fulfill all possible market demands; that is, minimizing missed sales opportunities due to under capacity during peak demands. This implies that manufacturing capacities are designed to fulfill forecasted high demand volumes; with some flexibility due to handling of inventories.

Catalog of product offerings is designed to fulfill all possible variations of product types which might need to be offered. Manufacturing capacities are then assigned for the entire catalog; thus, establishing the firm's catalog into producible goods. Production schedules then vary with time depending on market demands.

The concept of Opposing-demands products is a relation between product catalog, market demand variations, and equipment mix capability. It first requires identifying relations between products that have dependent demands, and then further groups them into those able to share capacity since peak demands are likely to be out of face. The selection of these relations depends on demand cycles. This is significant because it sets the condition that a good flexible system design must be comprehensive; thus, able to adapt to likely future requirements.

Product demand cycles might be five, ten or even twenty years but pre-designing for these allows for avoiding starting over every so many years. Instead, process for product families are broken down into processing steps. Each one can be designed for a 'general composite product model', as discussed next, which covers the entire product family. Flexibility of equipment is then used to support volume flexibility of fluctuating demands. Improvement plans can be focused over time at improving individual steps.

ii) General Composite Product Model

Definitions and guidelines for product family and root characteristics have been discussed; these are both necessary for making a descriptive assembly of the system in question. Scale for flexibility was also presented. An additional concept is necessary to facilitate this process. It is introduces as the ***'general composite product model'***.

Groover (2001, pp. 434-435) defines a composite part as follows. "The composite part concept takes this part family definition to its logical conclusion. It conceives of a hypothetical part, a composite part for a given family which includes all of the design and manufacturing attributes of the family. A machine cell to produce this part family would be designed with the capability to accomplish all operations required to produce the composite part."

This also facilitates calculation of the flexibility scale. It describes a generic model which describes a product family formed by grouping similarities of product and manufacturing processes.

B[8] = Model

B1 = representation

B1, 1 = conceptual (facts, inferences, etc.)

B1, 2 = mathematical

B1, 3 = physical (scale, sample, etc.)

B2 = of object(s), term(s)

B3 = made by set of variables and of logical and quantitative relationships

C = Composite

C1 = refers to an object(s), term(s)

C2 = made up of parts, or components

C2, 1 = each itself a hole or taken from another hole

D = General

D1 = refers to an object(s) or term(s) in a set

D2 = pertaining to a whole or to most of its parts, objects, terms

From assembly BCD,

General Composite Model *is a representation of object(s) or term(s) made up by variables or logical relationships. These refer to individual elements and their assembly completely describes the object(s) or term(s). It is a representation referring to all objects or terms in a set (general); for this discussion, it refers to all products in the product family.*

For this discussion of flexible manufacturing in machining systems, elements which make up a product-system are ***'work-planes'****.*

'Work-planes' is an industry terminology used to describe features which can be processed simultaneously. This is because they share a common tool work-axis (or feed-axis). That is for example, drills, reamers, taps, and end mills share a common work-axis along the length of the tool so they might be processed in a common head; they lay

[8] Applicable definitions listed in APPENDIX C.

within common work plane. Therefore, when we look at designing a composite model, we are really looking at grouping common work planes. Examples of types of Work-Planes are categorized in Table 3-4.

Table 3-4: Product general flexibility work planes.

Approach Plane Type	***Description***	***Machining Application***
Normal Work Plane Operations	Work planes with normal axis parallel to each work direction for every feature on plane.	Drilling Reaming Boring Tapping Milling/facing End-mill/plunge mill
Axial Work Plane Operations	Working operations occurring perpendicular normal to a particular axis of a product rather than to a plane.	Turning ID/OD milling Turn broaching

The last concept required for completion of the description is one relating location of work planes, or ***accessibility axis***.

Accessibility Axis *is the axis about which a product needs to be rotated in order to obtain access to a work plane(s). This axis does not coincide with any of the planes it inscribes (no intersection). A* ***'primary accessibility axis'*** *is the first axis which inscribes most of the work planes, or the one that must be moved first. A* ***'secondary accessibility axis'*** *is all additional axis required to inscribe remaining work planes.*

An accessibility axis rotates a product's work plane to a position normal to the spindle axis. It gives access for processing. Therefore, to fully describe a product family, we must identify all work planes which make up the general composite model. All these characteristics also describe the requirements for the system. This is described in Chapter 2 as approach components of Table 3-3.

Table 3-5 is the 'Generic Composite Model' for the family of Cylinder Blocks. It can be inferred that it joins 'Machine Flexibility' to 'Product Flexibility. It is a simple characterization of all possibilities within a cylinder block family (for any In-line, V-engine, etc). The strategy is to divide applications in features found in all engines by means of work planes.

It was previously discussed that 'root characteristics' are those which make up a description for product family. However, these cannot be used to differentiate within a set. Then, the descriptors required are ***general characteristics*** or ***'gc'***.

> ***General Characteristics*** *are descriptions required to make distinction between elements of a product family. They differ from root characteristics in that these describe an entire set and general characteristics do so for subsets.*

For example, for the cylinder block example, the "head deck" work plane has no functional difference between V and I-engines. Then, the characteristics required for distinguishing are:

a) ***gc = length***; this accounts for the length/height of the work plain; for example, head deck can have 3, 4, 5, or 6 cylinders. The features to cut will be multiples.

b) ***gc = size***; this refers to the size of actual features. We can have 2, 5 or even 50 cm bores; the activity to be done in the work plane will be the same; what changes is the dimension of the required tooling.

c) ***gc = orientation***; this refers to the normal orientation of the work plane distinguishing between 90°-V or 60°-V or even In-line.

Accordingly, other product features will have additional gc's; but in all, a product family will only have a limited amount. This is also included in Table 3-5.

Table 3-5: Composite Product Model - Cylinder Block.

Product gc's: gc_1 = length : base length plus addition of repetitions of middle bore
gc_2 = height : height position of head deck
gc_3 = bore size : size of bore also sets with of engine
gc_4 = Head deck No. : number of head decks

Axes of rotation → need two axis for cylinder block : (y and z-y combination)

WorkPlane	Characteristic Features	gc's	Engine Type Application	Axis Accesibility
A) Head Deck	Head bolt holes	gc_1 = L - Length gc_2 = Deck Height	V-Engine I - Engine	z-y axis rotation
	Cylinder Bores	gc_3 = B - bore dia gc_2 = Deck Height		
	Return Oil Holes	gc_1 = L - Length gc_2 = Deck Height		
	Head Oil Feed Hole	gc_2 = Deck Height		
	Water Jacket Access	NA		
B) Bottom Face	Pan Rail Flat	gc_1 = L - Length gc_3 = B - bore dia	V-Engine I - Engine	z-y axis rotation
	Pan Rail Bolts			
	MBC Flate/Width			
	Bulk Heads			
	MBC Bolts			
	Oil Return Holes			
C) Front Face	Front Face	gc_2 - deck height, gc_4 - No of decks	V-Engine I - Engine	y axis rotation
	Water Pump			
	Oil Filter/Pump System			
	Front Cover Bolts			
	Frost Plugs			
	General Pads/Bolts			
	Oil Gallery	and, gc_1 = L - Length		
	Crank Bores			
D) Rear Face	Rear Face	gc_2 - deck height, gc_4 - No of decks	V-Engine I - Engine	y axis rotation
	Frost Plugs			
	Thrust Face/Dia			
	General Pads/Bolts			
	Transmission Mounts			
E) Right/Left Hand Skirt Face	Side MBC Bolts	gc_1 = L - Length	V-Engine I - Engine	y axis rotation
	Oil Pump Mounting and dirty/clean oil holes	Optional on side depends on engine type		
	Dip-Stick Access	Optional on side or engine type		
	Mountings: engine, A/C, steerting pump, general	Optional on side or engine type		
G) Right/Left Block Wall	Frost Plugs	gc_1 = L - Length	V-Engine I - Engine	x axis rotation
	Mountings: engine, general	Optional on side or engine type		
	Water Jacket Drain			
I) Top Face	Intake Mounts	Optional on side or engine type	V-Engine	x axis rotation
	Charger mounts			
	General Sensors			
	General mounts			

Chapter 4 Complexity

Gell-Mann (*et al.*, 1996) defines *Total Information* as the tradeoff between knowledge and ignorance: measure knowledge using AIC of an ensemble and measure ignorance using Shannon's information. Therefore, two approaches re explored: Entropy approach in Section 4.1 and the Effective Complexity in Section 4.2.

4.1 Entropy approach or Shannon's Information

Suh (2005, pp. 4-5) states that "complexity must be defined in the 'functional domain' rather than the 'physical domain.' When we try to achieve a certain function within a desired accuracy (or equivalently, if we want to predict certain behaviour of natural systems within a desired accuracy), our ability to achieve the desired function determines the complexity. Hence, ***complexity*** is defined as a measure of uncertainty in understanding what it is we want to know or in achieving a functional requirement, FR. When we try to fulfill the FR, there is an uncertainty, thus complexity, of satisfying it within the specified accuracy or tolerance."

In addition, Suh (1999) also states that "in many past works, complexity was treated in terms of an absolute measure. In axiomatic design, information and complexity are defined only relative to what we are trying to achieve and/or want to know, in the functional domain. Information was defined as a logarithmic function of the probability of achieving the specified Functional Requirements (FR), where the probability of achieving a specified FR (complexity) was determined by computing the area under the system probability density function (pdf) within the common range. Thus, complexity is related to information." The types of complexities described by Suh are discussed next.

Complexity (Suh, 2005, pp. 7-11) can be *Time Independent Real Complexity*, which is the measure of uncertainty when the probability of achieving the FR is less than 1 and is the area under the probability density function common to both the design and system ranges, and is expressed as in Equation 6.

Equation 6: $C_R = \{\text{Information Content}\} = I = \sum \log_2 (1/P_i)$

Time Independent Imaginary Complexity (Equation 7) is the uncertainty that is not real but it arises because of the designer's lack of knowledge and understanding of a specific design itself.

Equation 7: $C_I = \{\text{Imaginary Uncertainty}\} = \log (1/P) = \log n!$

Time Dependent Combinatorial Complexity is a function of decisions made over the designs past history. *Time Dependent Periodic Complexity* is complexities that are dependent on the combinatorial effect of its past history but only within certain periods; although, these are irrelevant and have no effect on the following period.

The idea of complexity as a measure of information arises from Shannon C. E. (1964) where he attempts to describe information sources in terms of 'channel capacity' and message composition for discrete, continuous, and mixed messages. The solution was the E*ntropy Approach* which is used for definition of information content and complexity. This is commonly referred to as Shannon's Complexity.

4.2 Effective Complexity

Gell-Mann and Lloyd (1996) propose an *Effective Complexity* measure as the amount of information needed to describe the set of identified regularities of an entity. It is specified by the length of a message or the 'Algorithmic Information Content', AIC. That is, the length of the most concise program that instructs a given Universal Computer, 'U', to produce a message of a string of symbols, 's', and then halt – $K_U(s)$.

AIC makes formally precise the intuitive notion that information is the length of a compact description, where it requires no probabilities over an ensemble of messages to define the information content. Rather, it is a property of each individual message. Thus, for a set of messages which do make up an ensemble, Equation 8 sets an inequality relation for the different measures of complexity.

$$\underbrace{\sum p_r \log p_r}_{\text{Shannon's entropy}} = \underbrace{\sum p_r K_u(r \mid E)}_{\text{AIC – Ideal}} = \underbrace{\sum p_r \log p_r + C_u(E)}_{\text{Shannon's + Actual}}$$

Equation 8:

Where,

$K_u(r \mid E)$ = the length of shortest program for U which specifies individual message ‘r’, given a description of ensemble E.

$C_u(E)$ = the length of a program that instructs U to create a code for the members of R minimizing the expected value $\sum p_r l_r$ of the code word lengths.

Furthermore, Gell-Mann (*et al.*, 1996) also proposes a variation of their argument which consists of when estimations of AIC are capable of describing ensembles. For this case, one can modify the universal computer in such a way that the average AIC over the ensemble is essentially equal to the information over the ensemble:

$$\sum p_r \log p_r \sim \sum pr K_u(r \mid E)$$

Therefore, we can assign AIC to the entity, e, by equating it to the AIC of the string, s_e; thus, $K_u(e) = K_u(S_e)$ and {Effective Complexity, e}= {AIC of ensemble in which entity is embedded, $K_u(\tilde{E})$}. The AIC of an ensemble is the length of the shortest program required to specify the members of the ensemble together with their probabilities (for ensembles whose membership and probabilities are computable). Furthermore, for entity, e, embedded in a coarse-grained ensemble $\tilde{E} = \{(r, p)\}$, the total information or argument entropy is,

$$\sum = e + s = K_u(\tilde{E}) - \sum p_r \log p_r$$

It is stated in Theorem 1 of Gell-Mann (*et al.,* 1996) that Total Information, $\sum$, achieves an approximate absolute minimum when, $K_{u'}(e) \sim K_{u'}(\tilde{E})$.

Algorithm Information Content, AIC, is defined as Kolmogorov Complexity (Cover, et al., 2006). AIC for manufacturing systems is discussed in Section 4.2.1. For this we discuss,

Def **ⁿ:** The Kolmogorov complexity, $K_U(x)$ of a string x with respect to a universal computer U is defined as,

$$K_U(x) = \min_{p:\, U(p)=x} l(p)$$

It is the minimum length over all programs that print x and halt. Thus, $K_U(x)$ is the shortest description length of x over all descriptions interpreted by computer U. Furthermore, the *'Universality of Kolmogorov Complexity'* states that if U is a universal computer, for any other computer A there exists a constant C_A such that

$$K_U(x) = K_A(x) + C_A$$

for all strings $x \in \{0, 1\}^*$, and constant C_A does not depend on x.

It follows a definition of the universal computer which will describe the process. It refers to the **'*Universal Turing Machines*'**; Hennie (1977, pp. 57-89) presents a concise discussion on general Turing machines, but in principle they "can be thought of as embodying an algorithm for converting one string of symbols into another".

4.2.1 Computing Effective Complexity, $K_u(\tilde{E})$, for Manufacturing Systems

ElMaraghy H.A. (2006) defined levels, or sources, of a manufacturing complexity as Machine Type, Control, Programming, and Operation. If it is assumed that these are functional characteristics of a system, it is possible to model machine types and components as functions. This is as for program-units in a Universal Turing machine. Then, it is possible to subdivide into ***functional components*** which can be approximated into respective quintuples.

In Turing machines, programs have three basic characteristics as convention for quintuples: changes in type of symbols, motions, and states. Therefore, a similar convention is needed to satisfy a description of the general components of a manufacturing machine. Thus, a proposed convention is:

- ***Motions*** = this characteristic should describe motions available to the functional unit or assembly; it can be translation in T_x, T_y, or T_z directions and or rotation about R_x, R_y, or R_z.

- ***Number of parts or components*** = entails the number of components required to accomplish the task.

- ***Geometry*** = this is needed to provide information which describes the level of complexity of the functional unit or assembly. It should provide us with the information required to make a comparison between two functional similar units which are different only by the level of complexity of their design. Using convention for '$c_{j, product}$' from ElMaraghy W. H. (*et al.*, 2004).

The convention uses a tree similar to that used to describe C.N.C. equipment. Thus, for the example of the fixtures for crankshaft inside pin grinder, we have Figure 4-2. Thus, the required quintuple convention having characteristics required above is:

$$(T_x = Y/N, T_y = Y/N, T_z = Y/N, R_x = Y/N, R_y = Y/N, R_z = Y/N, P, \sum_{j=1}^{N} (n_j + c_{j, product}))$$

Where,

- P → Number of components which make an assembly. Assigned bit value is N+ 1 bit. That is 0 parts → 1, 1 bit; 1 part → 11, 2 bits; 2 parts → 111, 3bits; …; p parts → p + 1 bits.
- n → Quantity of component j which exist in assembly
- $c_{j, product}$ → Product Complexity Coefficient for component j. Range is from 0 to 1. Thus, we assign 1 to 21 bits respectively and every additional bit given for every increase by 0.05.
- Motions identifier is of existence type. Then, bit length is Y ('Yes' for available) → 11; length 2 bit, and N ('No' for not available) → 1; length 1 bits
- Separation between each characteristic within a function is '0' → 1 bit and separation within functions is '00' → 2 bits.

Note that in term $\sum_{j=1}^{N} (n_j + c_{j, product}))$ components which are identical can be grouped by common $(n_j + c_{j, product})$ terms. This is because to make the shortest description possible of components which make an assembly it is necessary to list the quantity of the item first and the item itself secondly. It means that common characteristics have a complexity which equals the number of items plus complexity of the common item. Furthermore, distinct characteristics have a bit length description equal to the addition of each individual description. Same principle is used for calculating effective complexity of an entire system.

The length of the description, l_U, is given by the total number of binary digits in the description; total number of zeros and ones. The quintuple describes machine abilities or motions of individual functional components. The ***total length of description*** of a machine or system is the addition of lengths of description of all individual components functioning either in series or parallel.

In short, a standard convention for describing any manufacturing equipment is established based on a quintuple system in analogy to the Universal Turing Machine. This is to allow comparison between different equipments given that the length of description is measured using same methodology. The length of the shortest description given this universal methodology, l_U, is the measure of Effective Complexity (or Algorithm Information Content, AIC).

The relation for comparison of systems, or machines, is given by the length obtained used the same 'universal description standard'. Assume following assemblies (1), (2), and (3) are complete functional descriptions of real non-identical systems,

A	B	C	D	E	F	G	System (1)
A'	B'	C'	D'	E'	F'	G'	System (2)
A"	B"	C"	D"	E"	F"	G"	System (3)

The assembly of shortest possible description, U{1}, U{2} and U{3}, which captures initial state, A, final product, G, and transform process, CE, while keeping functionality intact is given by,

U{1}	→	A C E G	System (1)'
U{2}	→	A' C' E' G'	System (2)'
U{3}	→	A" C" E" G"	System (3)'

That is, shortest description does not contain sub-process or sub-steps 'B D F' since these are non-essential and are not required for basic functional description. Descriptions U{1}, U{2} and U{3} are given by computer U. If lengths of descriptions are not equal (not identical systems), the following relation is established:

Equation 9: $l_{U(1)} \neq l_{U(2)} \neq l_{U(3)}$

The systems are compared using a relative relation of Effective Complexity. Estimating the actual effective complexity in a real system is extremely difficult. It is sufficient to understand how one system performs based on some other system which is used as the base. Therefore, relative comparison for purpose of proposed methodology is defined as the ratio of length of descriptions of systems being compared using the min $\{l_{U(1)}, l_{U(2)}, l_{U(3)} \ldots\}$ as the base. That is, from Equation 10:

Equation 10: If $l_{U(1)} < l_{U(2)} < l_{U(3)}$

$$\frac{l_{U(1)}}{l_{U(1)}} < \frac{l_{U(2)}}{l_{U(1)}} < \frac{l_{U(3)}}{l_{U(1)}}$$

Or $L_{U(1)} < L_{U(2)} < L_{U(3)}$

The relation for ***Effective Complexity Comparison Ratio***, $L_{U(n)}$, is defined as $l_{U(n)} / l_{U(min)}$ for a set of systems being compared. This is also the suggested indices to be used to refine Complexity Code proposed by ElMaraghy H.A. (2006). This method greatly simplifies the effort. However, the use of a method such as that proposed by the calculation of Effective Complexity and the Comparison Ratio could improve its sensitivity to typical variations found in manufacturing. Section 4.2.3 discusses some examples to support this argument.

4.2.2 Importance of Effective Complexity

It is arguable that there exists a relation between the three types of complexity previously discussed; Table 3-1 illustrates this and groups them into ignorance, uncertainty, and physical complexities.

It is important to understand and measure the effective or physical complexity since it plays a primary role in our perception and our ability to understand phenomena. The writer presumes this drives uncertainty, alongside other factors. The second type of complexity discussed is uncertainty and this, as noted by Suh (2005), is the probability of achieving the functional requirements; the functional realm. The last is ignorance.

Table 4-1: Summary of Complexity.

ElMaraghy H.A. (*et al.*, 2005), ElMaraghy H.A. (2006), Suh N.P. (2005)				Suh N. P. (1999)	Gellman & Lloyd (1996)
Time Independent Complexity		**Time Dependent Complexity**		**Shannon's Entropy Approach**	**Effective Complexity**
Imaginary, CI	Real, CR	Combinatorial	Periodic		
{Imaginary Uncertainty} $CI = \log \{1/P\} = \log n!$	{Information Content} $I=\sum \log_2 \{1/P_i\}$	{Real Complexity} → Worsens as time progresses	{Real Complexity} → Worsens as time progresses only in periods	Measure of Information Content	Algorithm Information Content, AIC
Uncertainty that arises because of designer's lack of understanding a specific design itself.	Measure of uncertainty when the probability of achieving FR is are under pdf common to design and system range	Is a function of the decision made over the design's past history	Dependent on combinatorial effect but only within certain periods. No effect carried to next period	Entropy approach to measure information content.	Length of shortest program which instruct a Universal machine to produce message and then halt – Ku(s)
Ignorance	**Uncertainty**				**Physical World**

Then, the task is to use this knowledge into a manufacturing application. This is introduced by Urbanic (2002) where a methodology for determining 'Operational

Complexity (Effort)' is developed for human involvement in manufacturing systems. In her research, Urbanic uses application of Hick's Law (Wikipedia.org, Hick's law, 2007) as follows:

> "Hick's law, or the Hick-Hyman law, is a human-computer interaction model that describes the time it takes for a user to make a decision as a function of the possible choices he or she has. Given n equally probable choices, the average reaction time T required to choose among them is approximately
>
> $$T = b \log_2 (n + 1)$$
>
> where b is a constant that can be determined empirically by fitting a line to measured data. According to Card, Moran, and Newell (1983), the +1 is "because there is uncertainty about whether to respond or not, as well as about which response to make." The law can be generalized in the case of choices with unequal probabilities p_i of occurring, to
>
> $$T = b H$$
>
> Where,
>
> H is the information-theoretic entropy of the decision, defined as
>
> $$H = \sum_{i}^{n} p_i \log_2(1/p_i + 1)$$
>
> Intuitively, one can reason that Hick's law has a logarithmic form because people subdivide the total collection of choices into categories, eliminating about half of the remaining choices at each step, rather than considering each and every choice one-by-one, requiring linear time.
>
> Hick's law is sometimes cited to justify menu design decisions. However, applying the model to menus must be done with care. For example, to find a given word (e.g. the name of a command) in a randomly ordered word list (e.g. a menu), scanning of each word in the list is required, consuming linear time, so Hick's law does not apply. However, if the list is alphabetical, the user will likely be able to use a subdividing strategy that may well require logarithmic time. The user must also know the name of the command. Of course, well-designed submenus can allow for automatic subdivision". (Wikipedia.com, "Hick's Law", 2007)

This gives us an approximation of entropy given we have a number of choices. Note the condition sited: Hick's Law applies to organized data where grouping is possible for faster search. The alternate to this is given by the case where choices are randomly positioned and where grouping is not possible.

Landauer (et al., 1985) investigates human performance in selection of alternatives in touch screens. They discussed the workings of response times. "The psychological laws at issue are the Hick-Hymen law, which governs choice time as a function of number of alternatives, and Fitt's law, which governs movement time as a function of target size and distance (Landauer, et al., 1985)." Therefore, response time is related to entropy relation because of number of choices as derived from Hick's law, and because of the physical entailments as illustrated by Fitt's law which is expressed as follows from (Wikipedia.org, Fitt's Law, 2007):

$$T = a + b \log_2 \left(\frac{D}{W} + 1 \right)$$

Where,

T = the average time taken to complete the movement, a and b are empirical constants,

D = the distance from the starting point to the center of the target, and

W = the width of the target measured along the axis of motion.

An additional situation which will also affect response time is the case similar to that of Hick's Law where selection is taken from an arrangement of items but rather than having some type of order it is random. "The main question with respect to the application of the Hick-Hyman law to menu choice is whether the response time for menu selection is determined by a choice among responses or by the time for visual scan-and-match processes. The time for visual scanning of a list for a target is generally a linear rather than log function of the number of items in the display, at least if the items are randomly ordered (Landauer, et al., 1985)" An example of this linear effect is the doubling of response time as the number of options increases. A substantial increase will be observed as 'N' increases for this case when compared to the log-linear relation discussed in both Hick and Fitt's laws.

Effective complexity can be a relation in entropy and complexity measures. Hence, relating physical information to drive stochastic response. This gives the amount of physical information in the system (machine-machine motions). It will have an effect on the ability of achieving the desired goal. For example, having several machines or having one machine to accomplish the same task will have a significant effect on the effort required to achieve the same goal.

4.2.3 Effective Complexity Application Example

<u>Scenario I: Gravity Roller Conveyor</u>

The first scenario to be discussed is a common type of material conveyance system. The Gravity Roller Conveyor consists of rollers typically fixed on the conveyor armature by means of bearing-pillow blocks on either side; thus, rollers are free to rotate. The conveyance energy is gravity acting on the product. Installation of conveyor is on a gradient in direction of travel.

The identified essential functional components are the roller and two pillow blocks. These are mounted as a unit and as many times as required to cover the required length. The effective complexity for a single roller is estimated using standard methodology developed from Section 4.2.1 as follows:

Quintuple for Shaft-roller:	(N, N, N, Y, N, N; 1; 1 + 0.05[9])
Unary description is:	(1 0 1 0 1 0 11 0 1 0 1 00 11 00 1 1)
Length of description is:	l_U {shaft} = 20.

Quintuple for Pillow Block:	(N,N,N, Y, N, N; 1; 1 + 0.10)
Unary description is:	(1 0 1 0 1 0 11 0 1 0 1 00 1 00 1 11)
Length of description is:	l_U {pillow block} = 20

Therefore, length for one complete roller assembly given one shaft and two common pillow blocks is:

$$l_U \{\text{shaft}\} + (2 + l_U \{\text{pillow block}\}) = 42$$

[9] This is an assumed number. It is to be developed as per methodology in (ElMaraghy W.H., *et al.*, 2003) for Product Complexity. Details not relevant for example.

This enlightens the reason of 'refining' complexity indices (ElMaraghy H.A., 2006) with propose method. Minor differences in complexity can be measured. The difference is since the conveyor is made from common components at varying multiples which set the total length; that is,

- Gravity Roller Conveyor with 10 roller assemblies:

  l_U {Conveyor of 10} = 10 + 42 = 52

- Gravity Roller Conveyor with 15 roller assemblies:

  l_U {Conveyor of 15} = 15 + 42 = 57

However the similarities, this simple change is enough to introduced variation in performance of designed system. The chance of product hang-ups increases with the total length. More ramps, turns or stops will also affect the difficulty to operate the system.

Scenario II: Motorized Chain Roller Conveyor

Using similar development one can analyze a chain driven conveyor, which is also common in a manufacturing environment. For sake of simplicity it is assumed the information stored in the motorized conveyor of 15 rollers is 5 times that of the gravity conveyor of same length. Thus,

$$l_U \text{ \{Motorized Chain Conveyor of 15 rollers\}} = 5 * 57 = 285$$

Then, the indices for the comparison of 10 and 15 roller gravity conveyors and the motorized conveyor of 15 rollers are:

$L_{u\{Grav.,\ 10\ rollers\}} = 52 / 52 = 1.000$

$L_{u\{Grav.,\ 15\ rollers\}} = 57 / 52 = 1.096$

$Lu_{\{Mot.,\ 15\ rollers\}} = 285 / 52 = 5.481$

Scenario III: Pin Grinder

A basic example in industry is that of the pin grinder application for a crankshaft finish-end machining line. The alternative which caught my attention is as in Figure 4-1. Here, dedicated grinders are in-line to grind one-pin-at-a-time in a consecutive order.

These grinders are fed by a common overhead gantry which has two arms: one for retrieval and the second for insertion of work-piece.

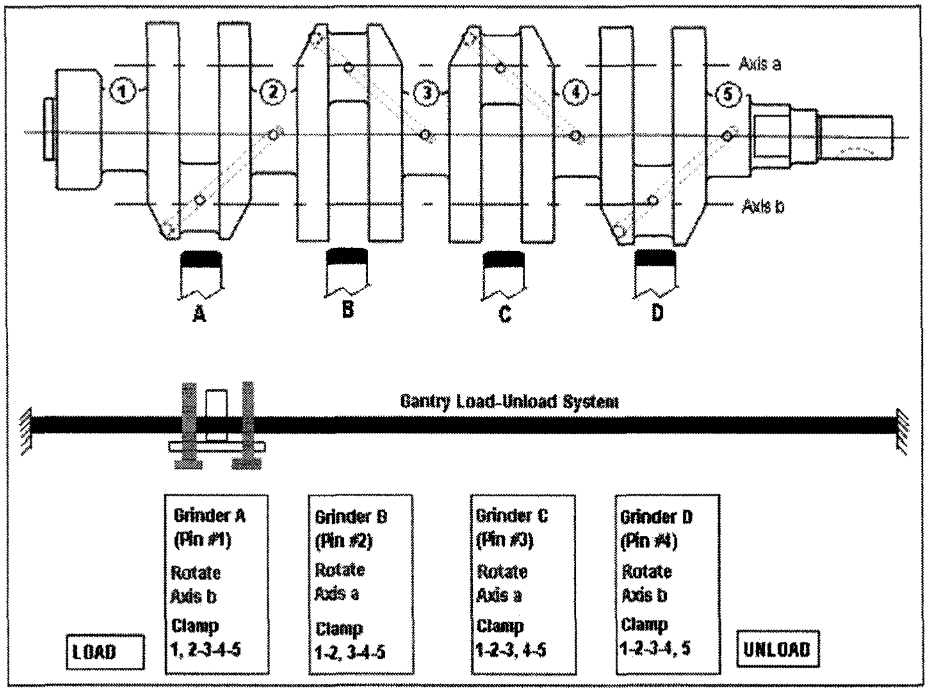


Figure 4-1: Crankshaft pin-grinding machining application.

The fixture is a counter-balance rotating unit which clamps on pins and mains in sequence as illustrated in Figure 4-1. For grinding, the fixture rotates about the pin-center-axis. The grinding wheel finishes the part in a counter motion rotation to that of the pin. Once the first pin is finished in 'Grinder A', the gantry moves the crankshaft to the following grinder, 'B', for processing of the following pin; this is repeated sequentially for all pins.

The investigation done between a fellow student and myself is an alternative design where flexibility level of individual grinders is increased. The modified grinders still have a counter-balance rotating fixture but, rather than having fixed clamps as the previous design, adjustable ones are considered. Furthermore, an additional axis of motion is introduced for the grinding wheel. This is to allow reposition along the length of the crankshaft; thus, allowing ability to grind all crankshaft pins within one grinder. Complexity of machine is increased.

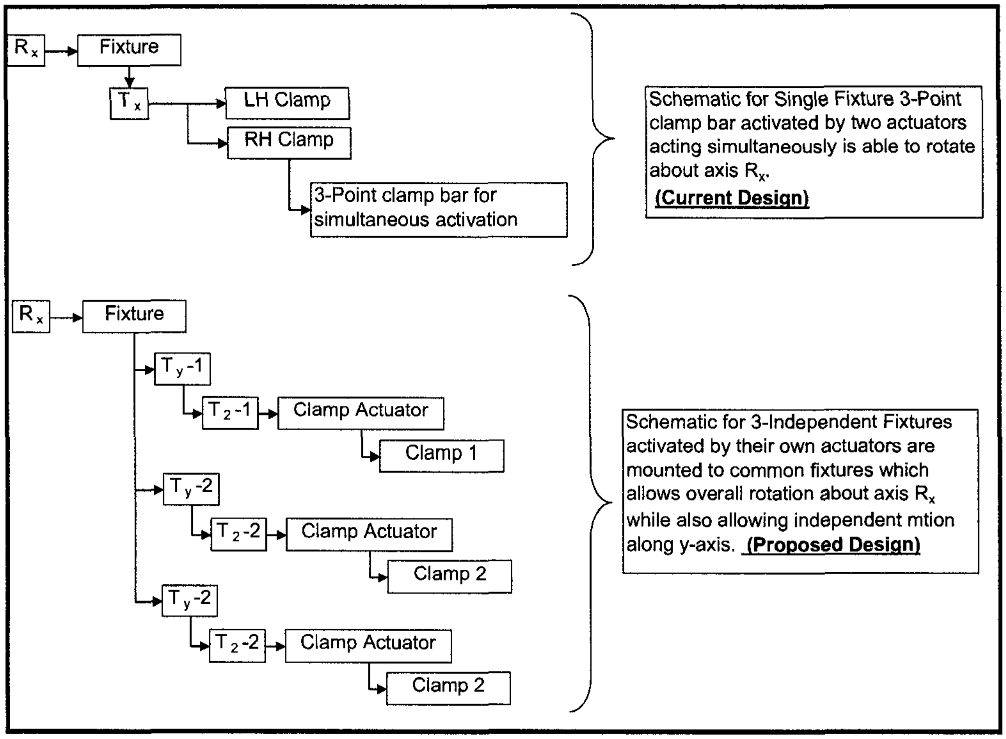


Figure 4-2: Fixture System Structure.

Figure 4-2 illustrates the basic machine diagram for this application. This time this type of diagram is taken from machine programming applications, specifically, C.N.C. control coding methodology.

The task on hand is to use the effective complexity according to the convention adopted for theoretical Turing machine approximation for both current and improved fixture designs. The first step is to determine the length of description of motions for current design. Important to specify is that the descriptor of available motions is '11' with length of 2 bits and for non-available is '1' or 0 bits. This is per convention defined in Section 4.2.1. Furthermore, note that descriptors are separated by a one bit identifier. Therefore, for current design:

a) Description of motions available (Yes/No) with subsequent bit length are summarized as follows:

$T_x = Y$	$Rx = Y$
$T_y = N$	$Ry = N$
$T_z = N$	$Rz = N$
110 1010	110101
Translation Sub-Total = 7	Rotation Sub total = 6

Motions Total = 13 bits

b) The second member of the quintuple designation is number of parts. That is, for our example, the length of description is developed as follows:

Table 4-2: Effective Complexity of proposed new grinder design.

Proposed Design ? ***Fixture function***

a) Motions

				4-Grinder System: Qty	Common Information (+)	Distinct Information (*)	Total Information				
Rx = Y		3 bits	(11 0)					4	3		7
1st Assembly:											
$T_x = Y$		3 bits	(11 0)								
$T_y = Y$	Ry = N	5 bits	(11 0 1 0)								
$T_z = N$	Rz = N	5 bits	(11 0 1 0)								
1st Assembly:		13		4	13		17				
2nd & 3rd additional fixtures :		26		4	26		30				
		2 bits	Joint	4	2		6				

b) Number of Components

Item	Description	Qty	$c_{j, product}$	Length	Total	Quantity				$c_{j, product}$			
1	Armature	1	0.80	16	17	4	1		5	4	17		21
2	Fixture Slide Mech	3	0.80	16	19	4	3		7	4	19		23
3	Fixture Fingers	3	0.40	8	11	4	3		7	4	11		15
4	Actuating Cyl	3	0.30	6	9	4	3		7	4	9		13
5	Pins for Cylinder	6	0.40	8	14	4	6		10	4	14		18
6	Shoes	3	0.60	12	15	4	3		7	4	15		19
7	Bolts for Shos	3	0.20	4	7	4	3		7	4	7		11
	Joint	6		6	12	4	6		10	4	12		16
					104							136	
				2 bits	Joint			4	2		6	Joint	
	Number of Components	28						60					

Total Length of string for description: 178 bits	Four-Grindr System 262 bits

Armature	1	$c_{j, product} = 0.65$[10]	bits = 13 + 1 = 14
Pins	3	$c_{j, product} = 0.7$	bits = 14 + 3 = 17
Finger Fixture	1	$c_{j, product} = 0.4$	bits = 8 + 1 = 9
Actuating Cyl	2	$c_{j, product} = 0.3$	bits = 6 + 2 = 8
Pins for Cylinder	4	$c_{j, product} = 0.4$	bits = 8 + 4 = 12
Shoes	3	$c_{j, product} = 0.6$	bits = 12 + 3 = 15
Bolts for Shoes	3	$c_{j, product} = 0.2$	bits = 4 + 3 = 7
Separation blocks	6	Separation blocks	6

Number of Components = 23 bits   Component Complexity = 88 bits

The total description is 13 00 23 00 88 or 128 bits for the clamping fixture alone. Similarly, Table 4-2 illustrated the description necessary for the proposed improved grinder. Note that, as expected, an increase in effective complexity is observed as per the AIC of the machine using abilities approximation. This approach yielded a 39.06% increase in complexity of the grinder fixtures; it increases from 128 to 178 bits. Similarly, for system of four grinders each dedicated to an alternate pin is calculated as follows:

<u>Motions</u>: 4 Grinders + 13 bits for equal motions = 17

<u>Separation</u>: 4 Grinders + 2 bits for equal structure = 6

<u>Quantity & $c_{j, product}$</u>:

4 Grinders * 1 Armature = 4	$c_{j, product}$ total = 14 * 4 Grinders = 56
4 Grinders * 3 Pins = 12	$c_{j, product}$ total = 17 * 4 Grinders = 68
4 Grinders * 1 Finger Fixture = 4	$c_{j, product}$ total = 9 * 4 Grinders = 36
4 Grinders + 2 Actuating Cyl = 6	$c_{j, product}$ total = 8 + 4 Grinders = 12
4 Grinders + 4 Pins for Cylinder = 8	$c_{j, product}$ total = 12 + 4 Grinders = 16
4 Grinders * 3 Shoes = 12	$c_{j, product}$ total = 15 * 4 Grinders = 60
4 Grinders + 3 Bolts for Shoes = 7	$c_{j, product}$ total= 7 + 4 Grinders = 11
4 Grinders + 6 Separation blocks = 10	Separation blocks = 6 + 4 Grinders = 10

Number of Components = 63 bits   Component Complexity = 269 bits

[10] Assumed values for $c_{j, product}$

Then total description is 17 6 63 8 269 or 363 bits for clamping fixtures of a system of four grinders. Note a decrease of 27.82% is observed from 363 to 262.

4.3 Current Manufacturing Complexity Measures and Indices

"It is generally agreed that the real or perceived complexity of engineering products and their manufacturing operations, processes, and systems is related to the information to be processed. It arises due to the exhibited variety and the uncertainty created by the variety or lack of information. Increased variety generates more information and provides opportunities for the product, process, or system to behave in unexpected manners (ElMaraghy H.A., *et al.*, 2005). "

An approach for determining the static complexity of a system using the amount of information needed to describe the system and its components using an entropy approach was used by W.H. ElMaraghy and Urbanic. They developed methods for calculation of complexity indices for 'Product and Process Complexities (ElMaraghy W.H., *et al.*, 2003), and 'Human Performance & Effort' (ElMaraghy W.H., *et al.*, 2004). ElMaraghy H.A. (*et al.*, 2005; 2006) developed methods/codes for assessing the structural complexity for 'Process, Equipment and Layout'. A summary of methods for estimation of manufacturing complexities and others described in literature is as follows in Table 4-3.

Table 4-3: Dimensions of Manufacturing Complexity.

MANUFACTURING LEVEL	REF	TYPE OF COMPLEXITY	DEFINITION	LEVEL
a) Product Complexity	ElMaraghy W.H. (2003), Suh N.P. (2005, pp.5	Real - Time Independent	It is a function of product information entropy, diversity ratio, and relative complexity coefficient, which is based on general manufacturing principles and is independent of process type or volume. Its value increases with the effort required to produce the final part. It depends on number and diversity of feature (shapes, geometry, tolerances, datum points, etc.) and the requirements of each (appearance, cleanliness, hardness, torque, porosity, etc.).	Product
b) Process Complexity	(ElMaraghy W.H (2003)	Real - Time Independent	It uses a similar approach as that for Product Complexity and it depends on number and diversity of equipment, material handling systems, tools, gauges, etc. It corresponds to physical process elements of fixtures, tools, gauges, and machines.	Machine Components
c) Operational Complexity - Effort	ElMaraghy W.H (2004)	Real - Time Independent	Complexity at the operational level directly affects the system usability and is relevant to the product quality and the process output. It addresses the physical (intensity & environment) and cognitive (control level) facets of effort and operation complexity.	Human Factors
d) System Complexity [System Availability Index]	ElMaraghy H.A. (*et al.*, 2005; 2006)	Real - Time Independent	Measure of anticipated system complexity which addresses the alternative choices or configurations with varying degrees of complexity a manufacturing systems designer encounters. It describes information required to describe system complexity of the various types of equipment and their inter-relationships: (1) Layout or (2) Equipment (Transporters, Machines, and Buffers) Complexity Code.	Machine Types and Layout Configuration
e) Scheduling Complexity	Suh N.P (2005, pp.146)	Combinatorial - Time Dependent	A system which was designed with reduction of real complexity in mind might still experience Time Dependent Combinatorial Complexity as it is with the scheduling problem. This states a cluster of machines might exhibit a progressively worsening of effects from interference, or transition patterns, due to outputs of individual stations and the material handling system. Loss of production observed.	Cycle Patterns

Just as with manufacturing flexibility, complexity measures have applications at all levels of the firm, and its deployment is done with respect to independent components. This is analogous to applying flexibility to fixtures, equipment, and material handling which are distinct elements of the same level. However, in a similar argument, its strategic implementation is the key to achieve economic and responsive advantage which is desirable for agile competition.

Identification of the "Dimensions of Manufacturing Complexity" as in Table 4-3 provides the necessary tools for a speedy analysis. The types of manufacturing complexity discussed in Table 4-3 are summarized as follows in Sections 4.3.1 through 4.3.5.

4.3.1 Product Complexity

ElMaraghy W.H. (*et al.*, 2003) described product complexity to be considered in a manufacturing environment as having three basic elements: (1) the absolute quantity of information, (2) the diversity of information, and (3) the information content. Furthermore, using utility charts, they determined the product complexity index, $CI_{product}$, to be,

Equation 11: $$CI_{product} = (D_{R\_product} + c_{j, product}) * H_{product}$$

Where,

$D_{R\_product}$ = *Diversity ratio* is defined as a ratio of distinct information to the total information given.

$c_{j, product}$ = *Product relative complexity coefficient* "is based on general manufacturing principles and is independent of process type or the volume. Its value increases with the effort required to produce the final part."

$H_{product} = \log_2 (N + 1)$

4.3.1.1 Example: Product Complexity & Product Catalogue.

ElMaraghy W.H. (*et al.*, 2003) product complexity is identified as it arises because of the number of features and the difficulty to produce these features. The importance of this supports the discussion of Section 7.2.

At product design, the application of this type an analysis is paramount. Product catalogue is limited to only those products which are of interest in the 'strategic plan of the firm'. Thus, during Step 1 of Figure 5-4 is important to minimize the dissimilarities between common work planes among all products in the family. That is, ***Product Unity Relation***:

Equation 12: $$(\text{Complexity}_{\text{product}})_{\text{catalogue range}} \rightarrow 0,$$

Then,

$$\text{Product}_i \rightarrow \text{Product}_{\text{unity}}$$

This is difficult to achieve. However, it notes the necessity to make features common. That is, as features or work-planes in a product catalog reach a single identity, so will product catalog reach a product unity.

4.3.2 System Complexity

ElMaraghy H.A. (*et al.,* 2005; 2006) developed a code to be used in computed complexity in manufacturing systems. It is based on the fact that increased variety generates more information and provides opportunity for the product, process, or system to behave in unexpected manners. This increases the complexity of operating and managing the resulting consequences.

"The proposed manufacturing systems code represents the information required to describe the complexity of the various types of equipment and their inter-relationships as shown in" Figure 4-3 (ElMaraghy H.A., 2006).

H.A. ElMaraghy (2006) stated that "A Code based Complexity index (I_s) that takes into account both the quantity and diversity of information, similar to those developed for the Equipment Complexity Codes, is proposed as follows and may also be used for comparison:"

Equation 13:
$$I_x = D_R * H = \text{Complexity Index}$$
$$= (n / N) * \log_2 (N + 1)$$

Where,

D_R = Diversity Ratio = (n/N)

H = Information Entropy Measure = $\log_2 (N+1)$

N = total quantity of information

n = quantity of unique information

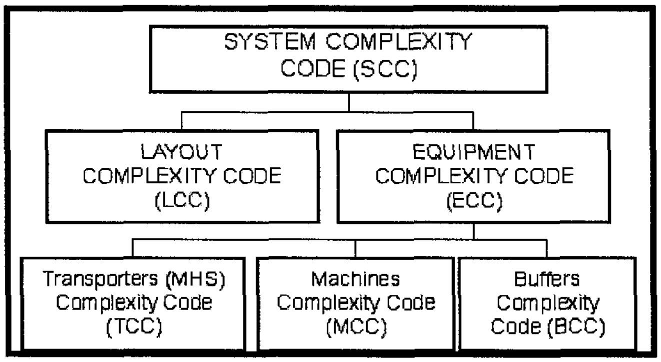


Figure 4-3: Manufacturing Systems Characteristics and Components (ElMaraghy, H.A. 2006).

Table 4-4: Manufacturing System Equipment Codes (ElMaraghy, H.A. 2006).

Machine Type Code – Field 1																		
							Tooling						Fixtures					
Structure*	Axes		Heads		Spindles		Fixed		Adjust.		Tool Magazine*		Fixed Pin		Special		Buffers*	
	N	n	N	n	N	n	N	n	N	n	N	n	N	n	N	n	N	n

Buffer Type Code – Field 1													
Manual		FIFO		LIFO		Indexable Table		Carousel		Magazine		Random Access	
N	n	N	n	N	n	N	n	N	n	N	n	N	n

Material Handling Type Code – Field 1																			
Conveyors		Load / Unload		Monorail		Fork Lift Trucks		AGVs		O/H Cranes		Gantries		Robots		Grippers		Pallets	
N	n	N	n	N	n	N	n	N	n	N	n	N	n	N	n	N	n	N	n

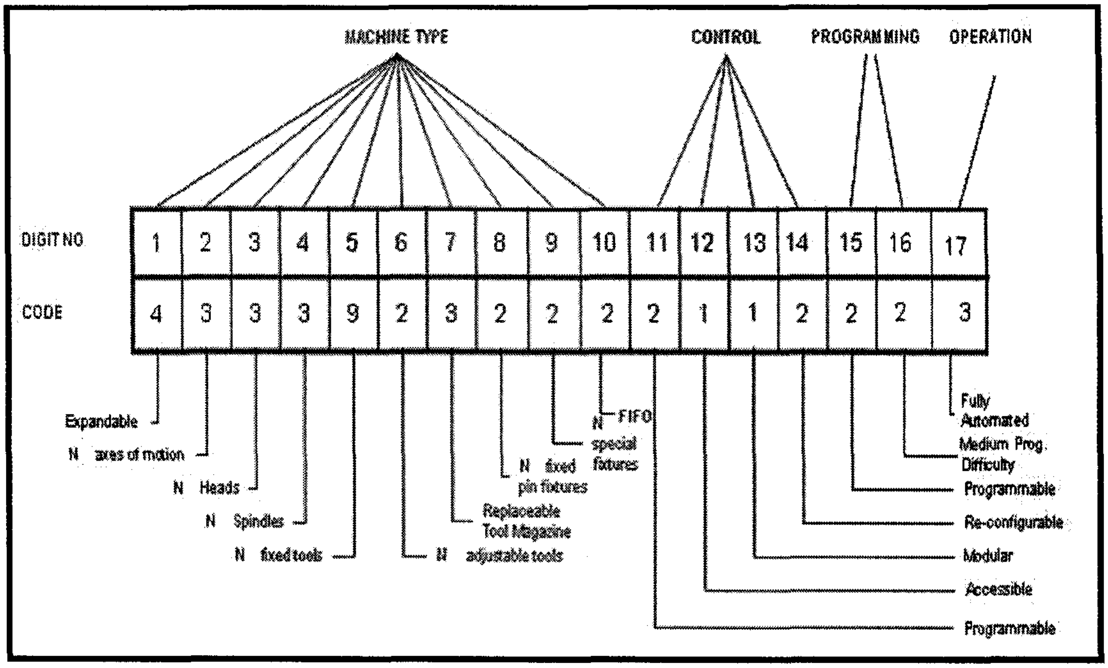


Figure 4-4: A Complete Machine Complexity Code (MCC) String for an Example of a Multi-Axis Multi-Spindle Machine (ElMaraghy, H.A. 2006).

Then, the Complexity Ratio for the System, I_s, is the sum of all indexes in the machine description or string, $I_s = \sum I_x$. Figure 4-4 is an example of Machine Complexity Code string as presented by ElMaraghy H.A. (2006).

Furthermore, the structure for measuring the three type of equipment types: Machine, Buffers and Material Handling are illustrated in Table 4-4. These are interchangeable components of the code as illustrated in Figure 4-4. The rules for filling out this information are given in Figure 4-5. Additional guidelines for Layout Complexity codes are given in the paper but are omitted from this discussion.

A) Machines Complexity Code (MCC)

Field 1: Type
Digit No., Value and Description
1 Structure
  1 Fixed / Dedicated
  2 Fixed / Modular
  3 Expandable / Dedicated
  4 Expandable / Modular
2 N Axes of motion *
3 N Heads
4 N Spindles
5 N Fixed tools
6 N Adjustable tools
7 Tool magazine
  1 None
  2 Fixed
  3 Replaceable
8 N Fixed pin fixtures
9 N Moving pin/supports fixtures
10 Integrated buffers
  1 None
  2 FIFO
  3 Indexing table

B) Transport (MHS) Complexity Code (TCC)

Field 1: Type
Digit No., Value and Description
1 Conveyor
  1 Un-powered (gravity)
  2 Powered, uni-directional, synchronous
  3 Powered, uni-directional, asynchronous
  4 Powered, bi-directional, synchronous
  5 Powered, bi-directional, asynchronous
1 Monorail
2 Fork Lift Trucks
3 Automated Guided Vehicle (AGV)
4 Overhead Cranes
5 Gantries
6 Robots
7 Pallets

Digits numbers 2-8 of the MHS code are similarly detailed but are not shown here due to space limitations.

C) Buffers Complexity Code (BCC)

Field 1: Type / Storage Mode
Digit No., Value and Description
1 N Manual buffers
2 N FIFO buffers
3 N LIFO buffers
8 N Indexing tables
5 N Carousels
6 N Magazines
7 N Random access systems

D) Common Fields for Machines, Buffers & Transporters (MHS)

Field 2: Controls
Digit No., Value and Description
1 1 Manual
  2 Programmable
2 Accessibility:
  1 Open
  2 User Hooks
  3 Closed
3 Modularity:
  1 Yes
  2 No
4 Reconfiguration:
  1 No
  2 Yes

Field 3: Programming
Digit No., Value and Description
1 Programmability:
  1 Manual
  2 Programmable
2 Programming Difficulty:
  1 Low
  2 Medium
  3 High

Field 4: Operation
Digit No., Value and Description
1 Mode:
  1 Manual
  2 Semi – automated
  3 Fully –automatic

* N is the total number of items in a class.

Figure 4-5: Manufacturing Systems Equipment Complexity Code (ECC) Structure (ElMaraghy, H.A. 2006).

The calculation of system complexity index depends on type of arrangement; it can take two basic forms: serial or parallel system. First, the complexity index of each individual equipments is necessary; this is as previously expressed, $I_s = \sum I_x$. Then, ElMaraghy H.A. (2006) expressed the relation for serial arrangement as the sum, $\sum I_{s,i}$, of all complexity indices 'I_s' of each unit 'i' which belongs in the serial system.

However, the calculation presented for parallel systems presented is strongly influenced by the total amount of information, N, and unique information, n, in the system. The consideration is that complexity decreases sharply with increase redundancy in the system; that is, as the number of parallel and identical machines increases. This is arguably correct to a point. The effort of controlling the system is improved given increase of commonality and with familiarity of the equipment.

However, it is believed based from observations made in this paper that this will hold only to a certain point. Then, complexity effects as those observed in serial arrangements are predominant. For example, one operator who runs three identical machines has an easier time that if the same operator would have to run five, ten, or twenty machines. Thus, after a certain number of machines the calculation approaches that of serial arrangements.

Therefore, the development of this thesis does not follow the exact structure of the SCC as specified for complete parallel system indices in ElMaraghy H.A. (2006). Rather, a modified calculation is assumed. The development is as follows.

It was specified earlier that calculation of a station/machine indices depends on $I_s = \sum I_x$. That is, the calculation of complexity index of a system, I_s, is the sum of complexity index of each component of the system as specified by string structure; Figure 4-4. Therefore, if we introduce t as the station-machine units which make up a series or parallel arrangement, we obtain the relation for Complexity index in serial arrangement as presented in ElMaraghy H.A. (2006):

Equation 14: $I_{serial\ system} = \sum_t (I_s)$
$= t * I_s$ (for identical stations in series)

Furthermore, using same notation it can be inferred that for parallel arrangements the relation from ElMaraghy H.A. (2006) is as follows for identical station-machines units:

Equation 15: $I_{parallel\ system} = (1/t)\ (I_s)$
$= \sum (n/t\ N) * \log_2 (N+1)$

The two relations that are investigated to replace Equation 15 are as follows:

Equation 16: $I_{parallel\ system} = (t - 1/t) * \sum \log_2 (N + 1)$

Equation 17: $I_{parallel\ system} = (t * 1/t^x) * \sum \log_2 (N + 1)$
$= t^{1-x} * \sum \log_2 (N + 1)$

After analyzing the shape of the curve it was found that Equation 16 drops off quickly and the effects from parallel system are negligible; therefore, this relation is discarded. However, Equation 17 provides some advantageous characteristics. Note first the range $0 = x = 1$. The importance of this equation is that as $x \to 0$, the calculation of Equation 17 approaches serial system; Equation 14. Similarly, as $x \to 1$, it approaches Equation 15; parallel system. Then, given the assumption stated before where parallel systems behave favorable as redundancy increases until a certain level is reached, Equation 17 provides an example for analysis of this property.

Figure 4-6 and Figure 4-7 are illustrations of Equation 17. The slope of each of the curves can be understood as the rate of increase of complexity as redundancy is increased by increasing the number, t, of identical parallel equipment in a system. Each curve is plotted for constant Diversity Rations. The limit of the functions is the same as the serial arrangement; that is, infinity is approached as the number t of units reaches infinity. This is reasonable assumption since infinitesimal complexity can be expected with an infinite number of machine units. However, reduce rate of increase is expected with use of identical units.

Note the solid bold-line on both figures which depicts the serial case with Diversity Ratio of 1/1. It is the extreme case this equation can take. The comparison between the two figures is that Figure 4-6 is the case for small 'x'. Note the slope of the first curve, $D_R = 1/1$, is close to that of the serial case. That is, the increment in complexity is reduced by a marginal rate.

Figure 4-7 is the case for large 'x'. The slope difference between the two cases, serial or parallel, both for $D_R = 1/1$ is substantial. Therefore, there must be a variable 'x' such that it is a practical representation of how well the system is capable of benefiting from redundancy.

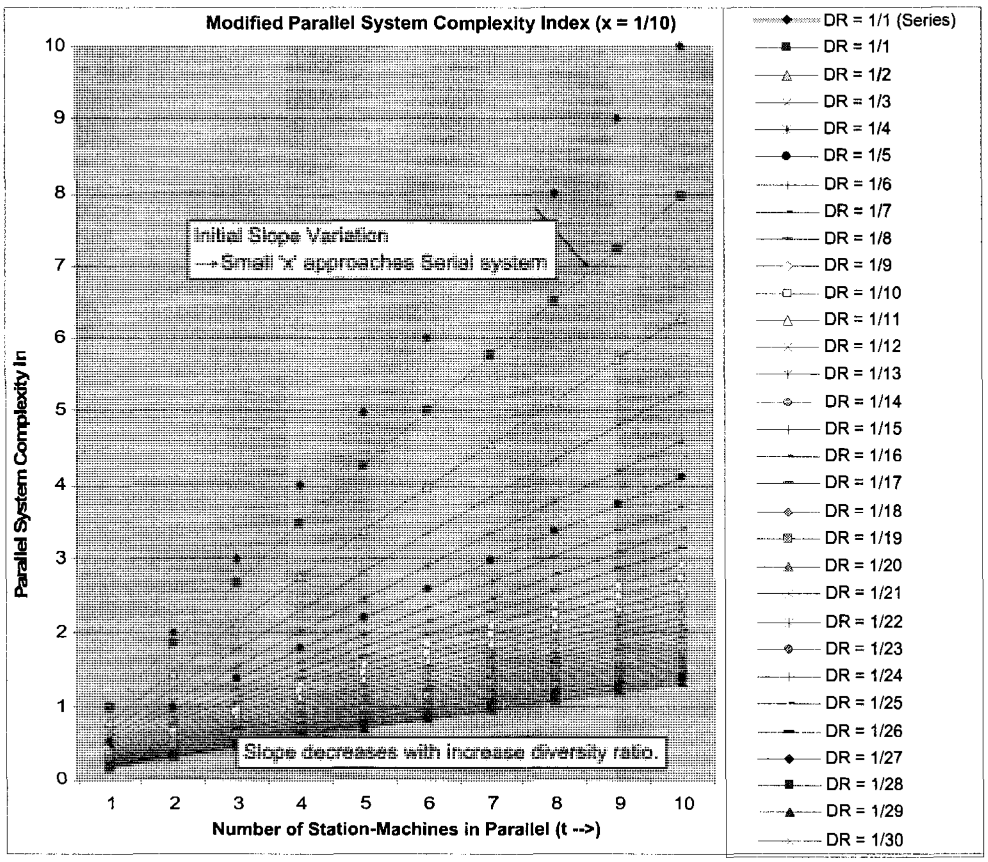


Figure 4-6: Modified Parallel System Complexity Index (Equation 17) → Small 'x'.

Nevertheless, the discussion in this thesis is limited to the high level description of the complexity of the system. Further analysis of the acquired precision that Equation 17 provides is not required to support the arguments. Therefore, modified Equation 15 is assumed for calculating SCC hereafter as follows:

Equation 18:

$$I_{\text{parallel system}} = t * (I_s)$$
$$= t * \sum (n/t\ N) * \log_2 (N+1)$$

(for purely redundant systems)

Where,

I_s = the Complexity Index as presented by ElMaraghy H.A. (2006).

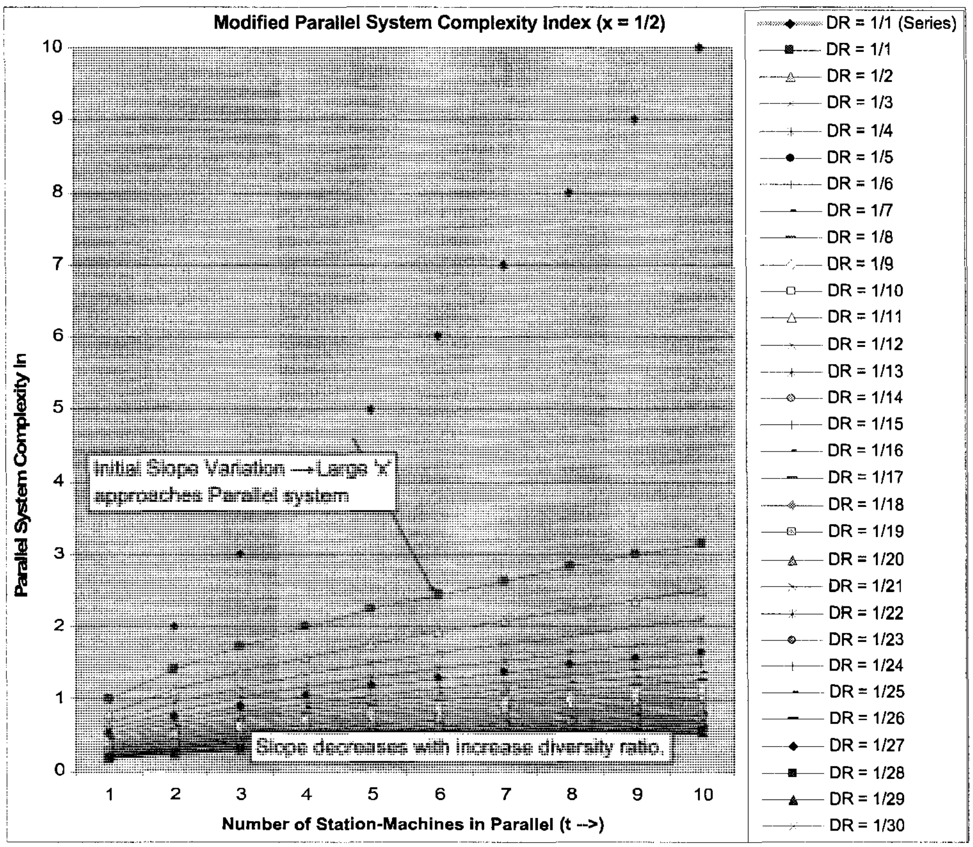


Figure 4-7: Modified Parallel System Complexity Index (Equation 17) → Large 'x'.

Further research of this property is suggested as an opportunity. An additional property to be noted is that slope of the curve is reduced as Diversity Ratio is also reduced regardless of start condition.

4.3.2.1 Example: System Complexity Code (SCC)

Recall the pin-grinder example from previous effective complexity discussion of Section 4.2.3. Only the complexity changes between current and new design at the individual unit level are discussed. Furthermore, Section 4.2.1 proposes the use of effective complexity discussion to refine estimations of individual indices in ElMaraghy H.A. (2006). It is stated that SCC is most powerful when discussing the complexity of a system.

Table 4-5 illustrates the change in complexity from current to new pin grinder design using SCC method. This method shows an increase of 37.68% for the revised design. Compared this to the Effective Complexity method where a 39.06% increase is observed.

Table 4-5: SCC for one Single-Pin vs. modified Multi-Pin grinder.

Pin Grinder - Equipment Complexity
? dedicated fixture to grind one pin.

	Equipment	Value	Total, N	Distinct, n	H	DRx	H*DRx
Machine Type (Field 1)							
1	Structure	1					
2	Axis		2.00	2.00	1.58	1.00	1.58
3	Heads		1.00	1.00	1.00	1.00	1.00
4	Spindles		1.00	1.00	1.00	1.00	1.00
5	Fixed Tools		1.00	1.00	1.00	1.00	1.00
6	Adjustable Tools	0					
7	Tool Magazine	1					
8	Fixed Pin Fixtures		3.00	3.00	2.00	1.00	2.00
9	Moving Pin/Support Fixtures	0					
10	Integrated buffes	1					
	Complexity Index (Field 1) - Sum						6.58
Control (Field 2)							
11	Manual/ Programmable	2					
12	Accesibility	1					
13	Modularity	1					
14	Reconfiguration	2					
Programming (Field 3)							
15	Programmability	2					
16	Programming Difficulty	2					
Operation (Field 4)							
17	Mode	3					
Complexity Index - Sum							**6.58**

Pin Grinder - Equipment Complexity
? Machining four pins in one grinder

	Equipment	Value	Total, N	Distinct, n	H	DRx	H*DRx
Machine Type (Field 1)							
1	Structure	1					
2	Axis		3.00	3.00	2.00	1.00	2.00
3	Heads		1.00	1.00	1.00	1.00	1.00
4	Spindles		1.00	1.00	1.00	1.00	1.00
5	Fixed Tools		1.00	1.00	1.00	1.00	1.00
6	Adjustable Tools	0					
7	Tool Magazine	1					
8	Fixed Pin Fixtures		3.00	3.00	2.00	1.00	2.00
9	Moving Pin/Support Fixtures	0	3.00	3.00	2.00	1.00	2.00
10	Integrated buffes	1					
	Complexity Index (Field 1) - Sum						9.00
Control (Field 2)							
11	Manual/ Programmable	2					
12	Accesibility	1					
13	Modularity	1					
14	Reconfiguration	2					
Programming (Field 3)							
15	Programmability	2					
16	Programming Difficulty	2					
Operation (Field 4)							
17	Mode	3					
	Complexity Index - Sum						**9.00**

Inputs for SCC for design under discussion in Table 4-5 are selected according to guidelines of Figure 4-5 and using structure of Figure 4-4. However, 'Control', 'Programming' and 'Operation' fields are omitted to facilitate comparison with method using Effective Complexity approach since it has no provisions to account for these effects. Details for selected inputs are as follows:

Before

1) Axis: 1 - Wheel Feed

    1- Work-Piece Rotation

    2 Axis Total

2) Heads: 1 – Grinding Wheel
3) Spindles: 1 – Grinding Wheel
4) Fixed Tools: 1- Grinding Wheel
6) Fixed Pin Fixtures: 3 – Anchor Locations
7) Moving Pin/Support Fixtures: Zero

After

1) Axis: 1- Wheel Feed

    1- Work-Piece Rotation

    1- Wheel Reposition

    3 Axis Total

2) Heads: 1 – Grinding Wheel
3) Spindles: 1 – Grinding Wheel
4) Fixed Tools: 1- Grinding Wheel
6) Fixed Pin Fixtures: 3 – Anchor Locations
7) Moving Pin/Support Fixtures: 3 – Allowed Reposition

Table 4-6: SCC for system of four Single-Pins vs. modified Multi-Pin grinders.

Pin Grinder - Equipment Complexity
? dedicated fixture to grind one pin.

	Equipment	Value	Total, N	Distinct, n	H	DRx	H*DRx
Machine Type (Field 1)							
1	Structure	4					
2	Axis		8.00	2.00	3.17	0.25	0.79
3	Heads		4.00	1.00	2.32	0.25	0.58
4	Spindles		4.00	1.00	2.32	0.25	0.58
5	Fixed Tools		4.00	1.00	2.32	0.25	0.58
6	Adjustable Tools	0					
7	Tool Magazine	1					
8	Fixed Pin Fixtures		12.00	12.00	3.70	1.00	3.70
9	Moving Pin/Support Fixtures	0					
10	Integrated buffes	1					
	Complexity Index (Field 1) - Sum						6.23
Control (Field 2)							
11	Manual/ Programmable	2					
12	Accesibility	1					
13	Modularity	1					
14	Reconfiguration	2					
Programming (Field 3)							
15	Programmability	2					
16	Programming Difficulty	2					
Operation (Field 4)							
17	Mode	3					
Complexity Index - Sum							**6.23**

Four Machines in Series: 24.94

Pin Grinder - Equipment Complexity
? Machining four pins in one grinder

	Equipment	Value	Total, N	Distinct, n	H	DRx	H*DRx
Machine Type (Field 1)							
1	Structure	4					
2	Axis		12.00	3.00	3.70	0.25	0.93
3	Heads		4.00	1.00	2.32	0.25	0.58
4	Spindles		4.00	1.00	2.32	0.25	0.58
5	Fixed Tools		4.00	1.00	2.32	0.25	0.58
6	Adjustable Tools	0					
7	Tool Magazine	1					
8	Fixed Pin Fixtures		12.00	3.00	3.70	0.25	0.93
9	Moving Pin/Support Fixtures	0	12.00	3.00	3.70	0.25	0.93
10	Integrated buffes	1					
	Complexity Index (Field 1) - Sum						4.52
Control (Field 2)							
11	Manual/ Programmable	2					
12	Accesibility	1					
13	Modularity	1					
14	Reconfiguration	2					
Programming (Field 3)							
15	Programmability	2					
16	Programming Difficulty	2					
Operation (Field 4)							
17	Mode	3					
Complexity Index - Sum							**4.52**

Four Machines in Series: 18.07

First, the Effective Complexity method presents an estimation of complexity that is due to the physical characteristics of the equipment. Therefore, it provides the ability to make fine comparisons between equipment which differ at a physical level rather than functional. This extra capability, however, comes with its limitation. It presents cumbersome and time consuming calculations when making estimations at a system level.

Table 4-6 details the results of the Pin grinder example using a system of four grinders working in series (current design) and in parallel (proposed design). The estimation is done using SCC method. A decrease in complexity of 27.55% is observed. This can be compared to a decrease of 27.82% observed using the Effective Complexity approach.

4.3.3 Process Complexity

Process Complexity Index (ElMaraghy, *et al.*, 2003) is developed similarly to product complexity and is defined as the sum of the individual constituent complexity values and the product complexity:

Equation 19:

$$PI_{process} = \sum pc_{x} + CI_{product}$$

Where,

the x^{th} individual process complexity index is:

$$pc_{x} = (D_{R\_process, x} + c_{process, x}) + H_{process, x}$$

4.3.3.1 Example: Process & System Complexities

The processing of the particular work plane is of interest. Many alternatives for individual steps and means of transfer are available for each application. The overall design determines the size (information) of the system. Its information content impacts inherent availability and maintenance requirements. Therefore, a minimization of complexity will result in favorable improvements for FR1 of Section 6.1 by Assumption 3.

Example of reduction of *system complexity* is done by reviewing the processing of the Oil Pan and Main Bearing Cap bolt holes work-plane for a cylinder block. Two alternate system options are presented as a multi-spindle dedicated system and a C.N.C. flexible one. A creative alternative is introduced as a flexible-dedicated option by installing one multi-spindle head as in dedicated system in a multi axis spindle table. In addition, a reduction in *system complexity from tooling* can also be presented. Detailed examples are as follows:

1) Transfer System: {Drill Holes} + {Ream Holes} + {Tap Holes} → finished product

This scenario is a typical example found in many transfer, or dedicated, machining systems. In this type of equipment stations which are identical in hole-cutting arrangement/pattern are installed serially in order to complete every machining step. In this case, the processing has the first station for drilling holes, the second for reaming or finishing the diameter(s), and the last for tapping or forming threads. Note although each station is identical in hole-pattern the functioning requirements are most likely different; differences can be expected to accommodate varying rpm's, cutting loads, reverse feed, holders, etc.

Each of the given stations is fixed motion to forward or feed direction; single axis. A single head is installed at each station with twenty spindles each, which are split into ten spindles for two different size tools. However, adjustment in tools is non-existent at either station. Tool changes for these stations are manually so tool magazines are never seen in this type of equipment. Table 4-7 illustrates the SCC index for each station and the entire system.

Two ten spindle assemblies are taken for large and small size diameter tools. The drilling station has the spindle, two bearing supports, a tool holder along side with a collet and a collet nut. The reaming head is of the same composition. However, the tapping station has a tool holder adapter instead of collet and nut. Furthermore, a brass nut, brass nut key, a brake and brake actuators are required to establish forward and reverse rotation-feed motions required to form the thread. Note the spindle has ability to rotate and feed simultaneously. Table 4-8 summarizes the results from the Effective Complexity analysis of the Drill + Ream + Tap system discussed.

Table 4-7: SCC Analysis of Dedicated Drill-Ream-Tap Oil Pan & M.B.C. Bolt Holes.

		Structure	Axis	Heads	Spindles	Fixed Tools	Adjustable Tools	Tool Magazine	Fixed Pin Fixtures	Moving Pin/ Support Fixtures	Integrated buffes	Mann./Progr.	Accesibility	Modularity	Reconfiguration	Programmability	Progr. Diffc.	Mode	
Dedicated		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
{Drill 20 Holes}	**Total N**	1	1	1	20	20	0	1	2	1	1	2	1	2	1	1	1	2	
	Distinct n		1	1	2	2	0	1	2	1	1								
	H		1.00	1.00	4.39	4.39	0.00	1.00	1.58	1.00	1.00								
	DRx		1.00	1.00	0.10	0.10		1.00	1.00	1.00	1.00								
	H*DRx		1.00	1.00	0.44	0.44		1.00	1.58	1.00	1.00								7.46
{Ream 20 Holes}	**Total N**	1	1	1	20	20	0	1	2	1	1	2	1	2	1	1	1	2	
	Distinct n		1	1	2	2	0	1	2	1	1								
	H		1.00	1.00	4.39	4.39	0.00	1.00	1.58	1.00	1.00								
	DRx		1.00	1.00	0.10	0.10		1.00	1.00	1.00	1.00								
	H*DRx		1.00	1.00	0.44	0.44		1.00	1.58	1.00	1.00								7.46
{Tap 20 Holes}	**Total N**	1	1	1	20	20	0	1	2	1	1	2	1	2	1	1	1	2	
	Distinct n		1	1	2	2	0	1	2	1	1								
	H		1.00	1.00	4.39	4.39	0.00	1.00	1.58	1.00	1.00								
	DRx		1.00	1.00	0.10	0.10		1.00	1.00	1.00	1.00								
	H*DRx		1.00	1.00	0.44	0.44		1.00	1.58	1.00	1.00								7.46
												[Required parallel stations]							1
												System Complexity							22.39

Table 4-8: Effective Complexity Results for Drill + Ream + Tap System.

System Unit	*System*
Drilling Station	674
	2
Reamer Station	674
	2
Tapping	738

Total Length of Description 2,090

2) Transfer System (alternate): {Drill Holes} + {Tap Holes} → finished product

This system is identical to the previously discussed Drill + Ream + Tap system with the exception that the reaming station is removed. Therefore, after some minor modifications, Table 4-9 summarizes the final complexity calculations using SCC and Table 4-10 using Effective Complexity method.

Table 4-9: SCC Analysis of Dedicated Drill-Tap Oil Pan & M.B.C. Bolt Holes.

		Structure 1	Axis 2	Heads 3	Spindles 4	Fixed Tools 5	Adjustable Tools 6	Tool Magazine 7	Fixed Pin Fixtures 8	Moving Pin/ Support Fixtures 9	Integrated buffers 10	Mann./Progr. 11	Accesibility 12	Modularity 13	Reconfiguration 14	Programmability 15	Progr. Diffc. 16	Mode 17	
Dedicated {Drill 20 Holes}	**Total N**	1	1	1	20	20	0	1	2	1	1	2	1	2	1	1	1	2	
	Distinct n		1	1	2	2	0	1	2	1	1								
	H		1.00	1.00	4.39	4.39	0.00	1.00	1.58	1.00	1.00								
	DRx		1.00	1.00	0.10	0.10		1.00	1.00	1.00	1.00								
	H*DRx		1.00	1.00	0.44	0.44		1.00	1.58	1.00	1.00								7.46
{Tap 20 Holes}	**Total N**	1	1	1	20	20	0	1	2	1	1	2	1	2	1	1	1	2	
	Distinct n		1	1	2	2	0	1	2	1	1								
	H		1.00	1.00	4.39	4.39	0.00	1.00	1.58	1.00	1.00								
	DRx		1.00	1.00	0.10	0.10		1.00	1.00	1.00	1.00								
	H*DRx		1.00	1.00	0.44	0.44		1.00	1.58	1.00	1.00								7.46
												[Required parallel stations]							1
												System Complexity							14.93

Table 4-10: Effective Complexity Results for Drill + Tap System.

System Unit	*System*
Drilling Station	674
	2
Tapping	738

Total Length of Description 1,414

3) Flexible System B or C: {Drill Holes} + {Tap Holes} → finished product

This system type for a machining station is considerably different than the dedicated structures previously discussed. The simplified structured discussed is modeled from a flexible C.N.C. machining center of four axis. It has one machining head with a single spindle. However, there are four axis of motion available. The first two are motion of the spindle head with one feed and another traverse direction through way-slides mechanism. The third is for vertical motion of the machining head by means of two opposite rotating ball-screw and nut mechanism. Lastly, a rotation of the work-piece table around the center vertical axis accounts for the forth axis of motion. It is assumed the table is rotated through a worm-gear & center pin mechanism. Four tools are used for this set-up. There is a drill & tap for both sizes of holes.

Table 4-11: SCC Analysis of Flexible Dedicated Drill-Tap Oil Pan & M.B.C. Bolt Holes.

Flexible {Drill & Tap 20 Holes}	Structure 1	Axis 2	Heads 3	Spindles 4	Fixed Tools 5	Adjustable Tools 6	Tool Magazine 7	Fixed Pin Fixtures 8	Moving Pin/ Support Fixtures 9	Integrated buffes 10	Mann./Progr. 11	Accesibility 12	Modularity 13	Reconfiguration 14	Programmability 15	Progr. Diffc. 16	Mode 17	
Total N	4	28	7	7	28	0	21	14	7	7	2	3	1	2	2	2	3	
Distinct n		4	1	1	4	0	1	2	1	1								
H		4.86	3.00	3.00	4.86	0.00	4.46	3.91	3.00	3.00								
DRx		0.14	0.14	0.14	0.14		0.05	0.14	0.14	0.14								
H*DRx		0.69	0.43	0.43	0.69		0.21	0.56	0.43	0.43								3.87
[Required parallel stations]																		7
System Complexity																		27.11

Table 4-11 illustrates the System Complexity Code analysis for this equipment example. Note that seven identical stations are required to meet the production rate comparable to that of the dedicated example. Table 4-12 is the analysis of the same system but using the Effective Complexity approach.

Table 4-12: Effective Complexity Analysis of Flexible System.

	Effective Complexity	
System Unit	***System (7)***	***Unit***
Feed-Axis Ways	232	100
	2	2
Traverse Axis Ways	232	100
	2	2
Spindle (Single Spindle)	295	140
	2	2
Double Screw (Vertical Axis)	744	121
	2	2
Rotating Table	252	194
Total Length of Description	1763	663

Since performance of a system can be substantially affected by good tooling and equipment technology application, two additional alternatives are introduced with upgrade to a drill-thread mill tool and unique theoretical system design as follows:

a) Flexible System B or C: {Drill-Thread Mill} → finished product

This scenario uses flexible C.N.C. stations identical to those from example three discussed previously. However, instead of drilling and tapping, a combination tool is utilized which has capability to drill the hole in the forward motion and mill-threads just before exiting the hole. A decrease in number of stations is the major factor for the improvement; only three stations are now required. Table 4-13 is the SCC analysis for this example and Table 4-14 for the Effective Complexity approach.

Table 4-13: SCC Analysis of Flexible Drill-Thread Mill Oil Pan & M.B.C. Bolt Holes.

Flexible
{Drill & Tap
20 Holes}

	Structure	Axis	Heads	Spindles	Fixed Tools	Adjustable Tools	Tool Magazine	Fixed Pin Fixtures	Moving Pin/ Support Fixtures	Integrated buffes	Mann./Progr.	Accesibility	Modularity	Reconfiguration	Programmability	Progr. Diffc.	Mode	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
Total N	4	12	3	3	6	0	9	6	3	3	2	3	1	2	2	2	3	
Distinct n		4	1	1	2	0	1	2	1	1								
H		3.70	2.00	2.00	2.81	0.00	3.32	2.81	2.00	2.00								
DRx		0.33	0.33	0.33	0.33		0.11	0.33	0.33	0.33								
H*DRx		1.23	0.67	0.67	0.94		0.37	0.94	0.67	0.67								6.14
[Required parallel stations]																		3
System Complexity																		18.42

Table 4-14: Effective Complexity Analysis of Flexible System with Drill + Thread Mill.

	Effective Complexity	
System Unit	System (3)	Unit
Feed-Axis Ways	152	100
	2	2
Traverse Axis Ways	152	100
	2	2
Spindle (Single Spindle)	243	140
	2	2
Double Screw (Vertical Axis)	360	121
	2	2
Rotating Table	215	194
Total Length of Description	1130	663

b) Dedicated head on Multi axis spindle table: {Drill-Thread Mill} → finished product

This system example is one which is not common to industry; rather, it is a suggestive example meant to incite curiosity on towards radical designs. This is for both system and equipment design. Many details to make this work in real application were assumed and overlooked. Excluding the spindle head, it is similar to the flexible examples discussed in (3) and (a) where four-axis C.N.C. stations are reviewed. However, a multi-spindle head as in example (1) and (2) is used instead of the single-spindle one. A drill-thread-mill is used given the availability of the vertical and traverse axes.

Furthermore, it is important to note the requirements on system-axis, spindle, and tool loading would be different for this system than flexible system counterparts given cycle time parameters. It is not un-common for parameters such as feed/traverse rates and rpm's to be two, three, four or more times faster in flexible single-spindle system compared to dedicated ones. This was reflected on specific system details incorporated in the Effective Complexity measures. Table 4-15 and Table 4-16 illustrate the results of the SCC and Effective Complexity calculations for this system.

It is clear from analysis in Table 4-7 through Table 4-16 that creative tooling and process design can lead to considerable reduction in total process complexity for this one work plane. Also, an analysis with the axiomatic cost design matrix as discussed in Chapter 6 will give insight on cost advantages. Furthermore, design analyzed in Table 4-15 provides further support to one of the arguments of this thesis; that is, trades in flexibility level of a manufacturing system can be made at the design level with favorable results.

Table 4-15: SCC Analysis of Flexible/Dedicated Drill-Thread Mill.

Flex.-Ded. {Drill & Tap 20 Holes}	Structure 1	Axis 2	Heads 3	Spindles 4	Fixed Tools 5	Adjustable Tools 6	Tool Magazine 7	Fixed Pin Fixtures 8	Moving Pin/ Support Fixtures 9	Integrated buffes 10	Mann./Progr. 11	Accesibility 12	Modularity 13	Reconfiguration 14	Programmability 15	Progr. Diffc. 16	Mode 17	
Total N	4	4	1	20	2	0	3	2	1	1	2	3	1	2	2	2	3	
Distinct n		4	1	2	2	0	1	2	1	1								
H		2.32	1.00	4.39	1.58	0.00	2.00	1.58	1.00	1.00								
DRx		1.00	1.00	0.10	1.00		0.33	1.00	1.00	1.00								
H*DRx		2.32	1.00	0.44	1.58		0.67	1.58	1.00	1.00								9.60
																	[Required parallel stations]	1
																	System Complexity	9.60

Table 4-16: Effective Complexity Analysis of Flexible-Dedicated System with Drill + Thread Mill.

System Unit	*System*
Feed-Axis Ways	84
	2
Traverse Axis Ways	84
	2
10 Spindle (small)	284
	2
10 Spindle (large)	284
	2
Double Screw (Vertical Axis)	130
	2
Rotating Table	96

Total Length of Description 972

4.3.4 Operational Complexity (Effort)

This complexity deals with the operational complexity and effort due to human physical and cognitive parameters. These are important to manufacturing systems because humans play a major role in the long term performance of a manufacturing system whether automated or manual.

4.3.4.1 Example: Operational Complexity – Human Performance & Effort

In ElMaraghy W.M. (*et al.*, 2004), it is stated that "the general complexity model is extended to encompass complexity at the operational level. This directly affects the system usability and is relevant to the product quality and the process output. Manufacturing Complexity increases with: (i) the number and diversity of features to be manufactured, assembled and tested and (ii) the number, type and effort of the tasks to produce the features".

This dimension of manufacturing complexity will have great impact on labour cost and other areas such as maintenance cost and availability. For example, for a regular production task such as scheduled part checks, it is of importance depending on ease in which the task can be performed; avoiding great effort, skills, or experience. This will drive labourer skill and time to perform the task. It will depend on the complexity of the product and equipment used. Similar argument is true for tasks performed to maintain and use production equipment.

ElMaraghy W.H. (*et al.*, 2004) describes this type of operational complexity. It can be dependent on the product, process and environment. The product can introduce challenges with part checks or process variables due to product behaviour; this makes it difficult to predict or understand the behaviour of the system.

Process might required constant difficult adjustments, and the environmental factors such as temperature, humidity, noise, confined space, control level, etc. directly affect labour performance. Therefore, this is an important consideration for FR3 = Operational Cost in Chapter 6.

4.3.5 Scheduling Complexity

This complexity can be observed in a manufacturing environment as a set of events that occur due to the stochastic effect of certain manufacturing variables. It is discussed by Suh N.P. (2005, pp.145). It is commonly due to scheduling interference or cycle phase error among associated equipment.

A simplistic example is the delivery and material transfer interference. Here, production losses are attributed to manufacturing equipment waiting for parts load-unload. This can occur when two or more machines are fed by a common overhead gantry as in the pin grinder example. Downtime would occur as soon as the gantry is delayed. A worsening effect would follow until the cycle is re-initiated. Thus, failure is controlled by the probability of having machine-gantry cycle interference. Therefore we have,

$$P\{\text{Interference}\} = \frac{(\text{Part Unload/Load Cycle})\,(\text{Number of Stations})}{(\text{Total Available Cycle Time})}$$

4.3.5.1 Example: Scheduling Complexity

This next example is important because it is used in Chapter 6 to demonstrate the incorporation of complexity measures into the Cost Function. Arguably, the losses due to effects time dependent combinatorial complexity will have direct effects on the performance of the system. It was first discussed in this thesis that these effects can be minimized from the cost function by means of Assumption 1. Production capacity requirements are affected (FR1).

Further analysis of the serial four-grinder system reveals additional improvement considerations with the redesign given the effects of combinatorial complexity. Assume an original design cycle time of 45 seconds from which 8 seconds is assigned for load-unload of parts. Thus, in a complete cycle, the gantry must complete four load/unload and transfer cycles for a total time of 32 seconds. It accounts for 30% free time, or 71%

probability that a station would be waiting for the gantry (probability of failure), '1' in Figure 4-8.

However, for the design alternative each grinder is capable of grinding all four pins. There are four independent grinders to meet the desired production rate. Then, the cycle time would be 37 sec (45 sec – 8 sec) x 4 = 148 seconds. Including time for part exchange, 8 seconds, and for any additional reposition, 8 seconds; this gives a new cycle of 164 sec. The new effective cycle time for a parallel system of four stations is 41 seconds (from 45 seconds). The new probability of a grinder waiting for part exchange is 19.5%, '2' in Figure 4-8.

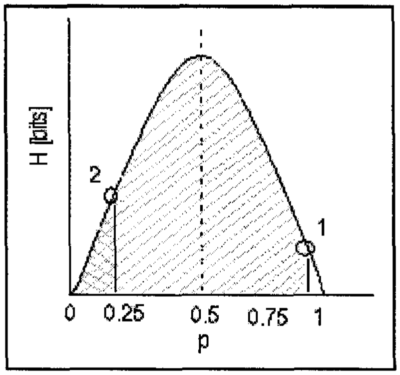


Figure 4-8: Plot of Shannon's Complexity of scenario 1 & 2.

Shannon's Complexity as defined, "$-\sum p_i \log p_i$" (Shannon C. E., 1964, pp 50), is the area under curve in Figure 4-8 from $p_1 = 0.71$ to 0.00 for the original case, '1', and from $p_2 =$ 0.19.5 to 0.00 for the improved design, '2'. Thus, the new design is more robust for protecting against losses due to scheduling or combinatorial complexity. Application of this analysis and Assumption 1 into the cost design matrix allows a design without having to compensate with additional non-necessary capacity into FR1 = Target JPH (Jobs per Hour).

Chapter 5 System Flexibility, Reconfigurability, and Design Optimality

Figure 1-3 is introduced as the original design model. It is further developed in this chapter to its final form. First, it is extended to include an additional axis: a metric for *'product size'*. It is argued that to describe completely a manufacturing system we need a single model. This model incorporates cost and complexity parameters, a scale for level of flexibility implementation, and now introduced a product size metric. This last one is to denote the minimum and maximum size of work-piece the equipment is able to handle. This is the final limitation needed for description of a system is product size.

***Product Size Axis or product axis** is the maximum diagonal chord-length between opposite corners of the smallest cube required to inscribe the product, or work envelope.*

That is, description until now is an assembly of all functional characteristics of the product-system. That is,

A = Description of a Product Family

A1 = description of a group of products

A2 = united by set of common characteristic (root characteristics)

A3 = describes features

B = Description of a Manufacturing System

B1 = description of an element of a manufacturing system

B2 = united into 'work planes'; groups

B3 = describes features (or root characteristics) of a product

Then, System Flexibility Scale is a property given by assembly AB; that is, union of product requirement given by Composite Product Model and the inherent design of the system. Therefore, in general,

System Flexibility = a relation given from assembly AB

Performance of a System is given by its design and its behaviour; both are affected by complexity or information content; thus,

C = Performance of a Manufacturing System

C1 = behaviour compared to intended design

C2 = affects Cost

C3 = depends on information content of a system (Complexity)

Then, a functional description of a flexible system is the real behavior compared to what it was design to do 'C', and information about its flexibility given by 'AB'. These are directly related to cost and complexity. Therefore, objects which are identical in the functional domain have identical functional characteristics AB and C. The only means of distinguishing is size. That is,

If set of objects x1, x2... xn

Where,

(C)AB {x1, x2... xn} = (C)AB x1, (C)AB x2 ... (C)AB xn}

→ identical characteristics

Then,

x1, x2... xn are distinguish by their (scaling) size

Figure 5-1 is the updated theoretical design diagram. It is as described in section 1.2 with the addition of the Product Size axis. Its usefulness is evident with discussion of System Range, Product Plane, and Product Family Curve as a unified theory. Consequently, Reconfigurability is also discussed.

System-product plane or product plane *is the plane left over by fixing the system Flexibility Level in Figure 5-1. It is inscribed by cost-complexity vs. product size. System is fixed so product plane is property related to product.*

Fixing system flexibility level in model given in Figure 5-1 results in the Cost/Complexity vs. Product Size plane. Thus, suggesting the following relations among these.

From previous discussion, current description is one given by descriptions of product and System, AB. It directly affects system behaviour C. Thus, the assembly (C)AB is obtained. Furthermore, system behaviour C is affected by Complexity D; thus proportionality exists. This in turn is proportional to Cost E. Hence,

$$C = k\,D = m\,E$$

Therefore, if system is fixed, (C)AB can be simplified as (C)A. Thus, once system is chosen, performance depends on product.

$$(C)A = (kD)A = (mE)A$$

Performance of system is limited by product. Hence, once system is chosen product complexity and cost is main variable. Therefore, to make design in Figure 5-1 logical, there must exist a relation such that, under specified condition:

Equation 20: *Cost/Complexity = f (Product Size)*

i) *Cost = f (Product Size)*

→ *Increasing/decreasing product size has a similar effect on cost given increased/decreased required material, tooling, equipment size, etc.*

This can be easily proven since increasing/decreasing product size has a similar effect on cost given increased/decreased required material, tooling, equipment size, etc. There might be special cases where it might be argued that decreasing product size increases manufacturing costs due to special requirements but it is assumed these are outside of current argument since main focus is on high volume machining systems of common automotive components.

ii) *Complexity = f (Product Size)*

Two *main characteristic are:*

I. ***Magnification Increase/Decrease*** *– A product might be increased in size by a magnification scale. Complexity changes minimally.*

For example, a '1 x 1 x 1' cube with 0.5 through hole compared to a '2 x 2 x 2' with 1 through hole.

II. ***Scalable Increase/Decrease*** *– A product's complexity might be scaled by multiples of some unit of symmetry. Complexity changes drastically.*

For example, V or I engines might be re-designed by adding or removing cylinder bulk-heads.

Cost/Complexity = f (Product Size) depends on the path taken within a product family. Thus, introduce Product Family Curve.

The selected ***'Product Family Curve'*** *will be the range described by the curve which intersects all the discrete product types within a family.* See Figure 5-1.

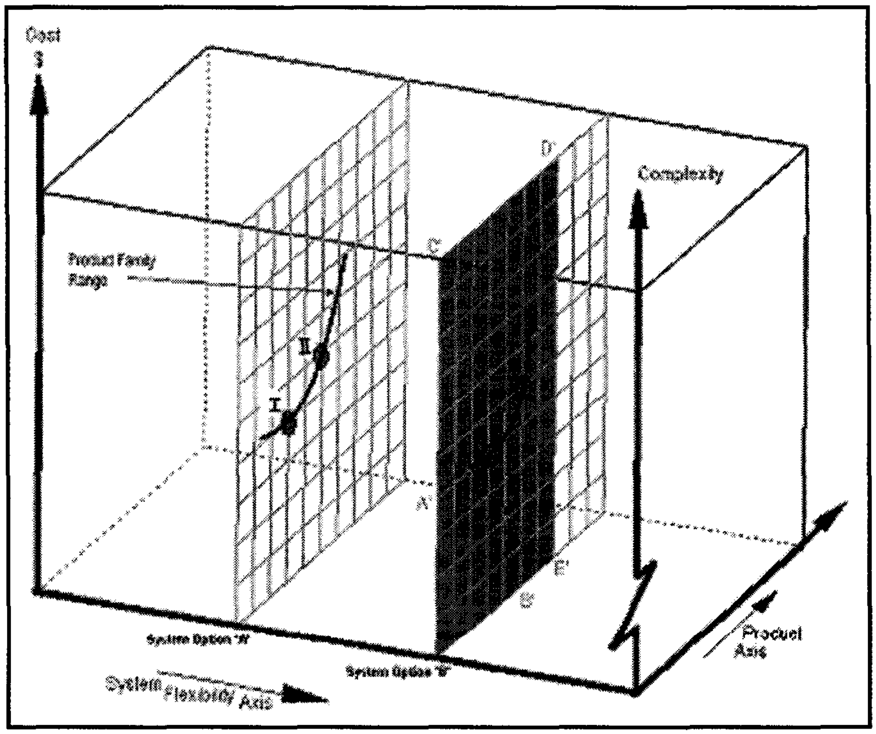


Figure 5-1: System Design Model.

For example, a range from smallest to largest cylinder block will look like discrete areas as are shown in of Figure 5-1 (I, II). Increments in size might be by multiples of groups of features. This can be by increasing the number of cylinder bores, which increases size of engine and the complexity of the block; it also multiplies common features such as frost plugs and bearing mounts.

'System Range' *is the highlighted area in Figure 5-1. It is the range in the product plane in which the system is capable of operating once its design has been decided.*

For example, consider System Design options A-B. Both systems are assumed to be an operation of cylinder block machining line. Options of two product size are given; that is, a V6 and a V8 Product namely I and II. System Design A is a dedicated line with one station for product I and a second one for product II. System range A is highlighted giving a small range in both the complexity-cost and size directions. This is true because only minor modifications are possible in either direction.

It follows that for System Option B, which uses a single spindle drilling head on a C.N.C. machine, variations are acceptable. However, additional products which are smaller or larger in size or number of holes could also be processed. System range is denoted by area C'-D'-E'.

The argument of reconfiguration can also be thought off from the aspect of 'Generic Composite Product'. One might change a product either by modifying, adding or removing features within a work plane. Work planes can be added or removed. Also, gc's can be modified. Consequently,

Reconfigurability *is the activity of modifying the System Range. This might be accomplished by means of changing/modifying hardware and/or software. Similarly, it also can be considered as addition or replacement of one product family curve by another, or extension of an existing one.*

The right-most plane of the model in Figure 5-1 is denoted as Figure 5-2 and is used to describe products within the catalog of offerings, the system range, and reconfiguration. First, product A and B are of approximately the same size but A has larger complexity. For example two equal size cubes where A has more holes than B. In contrast, product C is of comparable complexity as B but it is larger; this can be the case of having two identical cubes where C is twice the size of B. This is a true comparison for all remaining products.

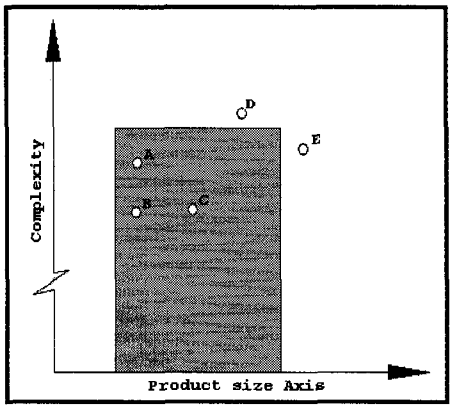


Figure 5-2: Product vs. Complexity Plane: Product Catalog & System Range.

The shaded area in Figure 5-2 is the system range; introduced earlier. It denotes a one spindle machining center. There are two opportunities for reconfiguration to include products D and E. First we analyze D; it is at a higher complexity level than either A, B, or C. This means that we might need to work on some programming to increase the number of holes. An update to tools or spindle might be required to process increased complexity of product D.

Product E is on the right side of the size limit of the machine. Space occupancy is now of interest. In other words, the part does not fit within the safe operating range of the machine; this is a physical limitation. A solution can be to increase the operating range of the equipment. This can present a limiting challenge since replacement of the machine might be required.

Important statement can be extracted from the proposed model for both dedicated and flexible systems; in particular from Figure 5-2. First, a continuous flexibility is described as the products inside the system range. This is an important outcome provided by this type of model. It sets the limitation that production must be continuous or (1) *Synchronous Production* for product-systems arrangements to be considered flexible. That is, production is able to move back-and-forth between products without any additional expense.

Otherwise, system-product arrangements fall into the (2) *Reconfigurable Production*. Hence, products which are not capable of being produced simultaneously in consecutive or mixed rates are because reconfiguration is required. Therefore, an expense or loss must be incurred. For intent of purpose, Reconfigurable Production will approach Synchronous Production when this *Cost of Reconfiguration* approaches zero.

Reconfigurable Production is further divided into two classifications: Batch and Inclusive. First, *Batch Reconfigurable Production* is when an investment is required to change system range to include a particular product; however, the exclusion of previous products can be observed. Back-and-forth motion between products will require subsequent reconfigurations. Investment is generally low to mid level. Example is applications such as dies which need to be reset to change products at the expense of temporarily loosing the ability to manufacture previous product.

Inclusive Reconfiguration Production is the extreme of reconfiguration. Losses can be substantial but might take production to either Synchronous or Batch production. Addition of stations or major modification to existing equipment might be required.

The establishment of these relations is the basis used for analysis of cost considerations vs. product mix of Section 6.5. The comparison with production volume is expanded using these statements.

5.1 Implementation Effectiveness Strategy

*The **strategic level of manufacturing flexibility implementation** is defined from* Figure 5-2 *as the percentage of products within the system range to total number in the Opposing-demands Products catalog. Values are 100% for best implementation and 0% for worse.*

This measure is important since it describes flexible systems in two basic extremes. First, a system achieving 100% implementation will be capable of producing all the products a firm might need to offer. This is the ideal implementation of a flexible system.

Secondly, any flexible system which covers very few products within the catalog of offerings would be considered to have a very poor implementation. The value of strategic implementation will be close to 0%. A system made of flexible equipment under this type of implementation approaches strategic performance of a dedicated one.

It is important to align the strategic plan of the firm when implementing Flexible Manufacturing systems. This is noting that economy of scale needs full production schedules. A firm which designs equal factories capable of running all products in opposing-demands product catalog will be much more capable of running at an optimum operational cost; therefore, establish as ***twin-cell design*** at multi-plant level.

The explanation for twin cell design is not difficult. First consider the simplistic equation for cost expressed as follows:

Cost (per unit) = {Production Cost} + {Overproduction Cost}

Or

Cost (per unit) = {Cost / Units Produced} + {CPU * quantity inv. * interest rate * time in inv.}

It states that cost transferred to consumers is simply the cost of producing the good plus the cost of carrying the inventory until final sale and delivery. Furthermore, it is arguable that the cost of manufacturing a product is related to operation and labor requirements at the factory.

This cost is modified to maximize efficiency during ‘current-shift production schedule’. It is disbursed over the number of parts produced in this period. However, as schedules are reduced it becomes increasingly difficult to decrease the cost burden for the reduce volume production.

Similar statement can be made for overproduction. Inventory size and storage time tends to increase as demand decreases. Therefore, Figure 5-3(a) shows the cost vs. demand plot based on this argument for product A. Opposing-demand products implies that for a product A with decreasing demand there is a related product B such that its demand is increasing or opposite (Figure 5-3(b)).

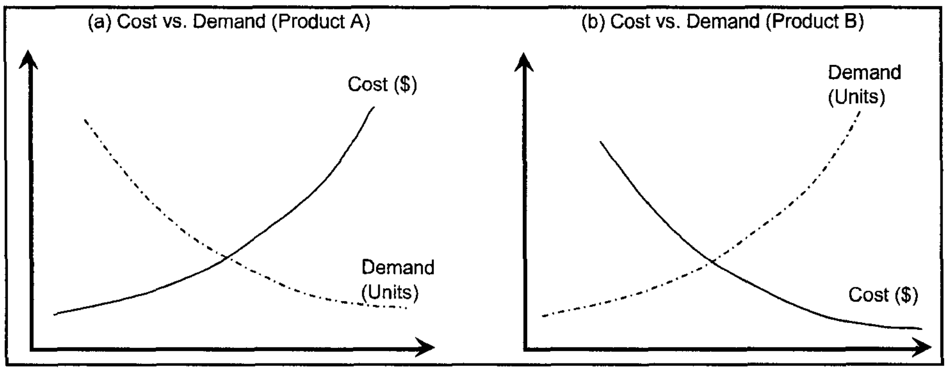


Figure 5-3: Note that (a) is an assumed Cost-Demand plot for product A; (b) is the plot for product B which has opposite demand as that of A.

Therefore, the twin-cell idea implies that production schedules of a factory can be maintained at an optimal level if multiple factories are designed to allow production of any product in the product family. This is of special importance when products of opposite demands such as A and B are under consideration. The discussed idea fits well in the model presented in this thesis since it sets an additional limitation for utilization of flexible factories-equipment. It is also stated that equipment upgrades should be made to this generic process independently of product; this is in contrast to traditional disposal of both equipment and product practices of the past at end of cycle. New lines are only introduced with a new product.

5.2 Optimality Condition

The model assembled thus far is the Strategy for Design of Flexible Manufacturing Systems illustrated in Figure 5-1. The remaining question is how to use this strategy to be applied not only to the equipment level but also to the strategic level of a firm. That is, how to take advantage of this argument to decrease a firm's overall production cost while also increasing the ability to respond to changes in market demands. Figure 5-4 is a schema of the implementation plan.

Step '1' in Figure 5-4 is to define strategic plan of the firm, which is in accordance to the marketing forecast plan. This, in turn, is translated using the 'generic product model' into product catalog range, size and capacity parameters used to initiate the design of the system. Note that opposing-demands products concept is a consideration. Then, flexibility design alternatives are developed to be evaluated from flexibility standpoint, **Step '2'**.

A Cost-Complexity Matrix must be prepared for evaluation, **Step '3'**, given the industry application. The system parameters in the Axiomatic Design Cost Matrix will provide insight about the investment and operation performance of the system as well as the cost and agility to reconfigure. The input in this Chapter is the particulars of the equipment and its utilization as well as desired production schedule.

Once the design matrix is known, an iterative process, **Step '4'**, is conducted to refine the design parameters for most economical design. Furthermore, it is convenient to introduce a secondary variable into model, **Step '5'**, to account for ***probability, or necessity, for reconfiguration*** of a particular work plane. This is to reinforce the decision making process. Systems which meet a predetermined limit of P {no reconfiguration} within equipments Return on Investment, ROI, and period tend to accept a dedicated design.

Probability for reconfiguration *is necessary to distinguish those work planes which will tend not to have necessity for change during the product's life or ROI period. Dedicated system could be the economical option. It is the probability of an event occurring.*

Or

Equation 21: P_{ROI} {Reconfiguration or Work Plane Redesign} = Guideline

→ Dedicated tendency if condition is met (example, guideline = 0.90).

→ Flexible tendency otherwise (example, guideline = 0.50 or less)

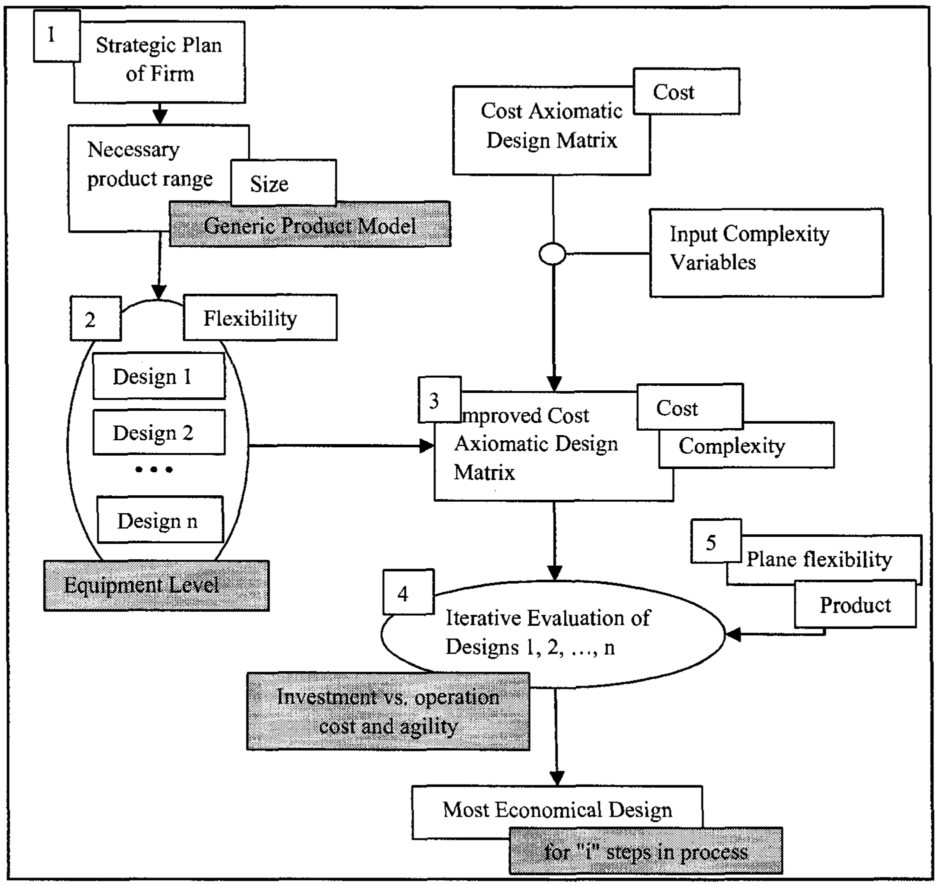


Figure 5-4: Overall application plan.

Chapter 6 Cost function

Two major cost considerations are evident when designing a manufacturing system: capital cost and operational burden. The first depends on the number of machines, transfers, gantries, gages, etc required at initial installation. The second is the cost to operate this equipment on a year- by-year basis over the life span of the program. This is of utmost importance since it is the real burden that must be inherited and it is also the most difficult to change once the equipment is purchased. It depends on the following (for a high volume machining line):

- *Tool Cost:* Typically ranges between 2-10% of total operational cost and is controlled by the technologies chosen for the application. Care must be taken since this is the single factor with most significant impact on subsequent direct and indirect manufacturing cost and performance.

- *Maintenance and utilities:* These are directly related to the choice of tools and equipment for the application. Also, it is effect of management disciplines which are usually influenced by the burden from equipment design. That is, there is a great influence of cumulative practices during past production life of the equipment. This are such as Preventive Maintenance (PM) disciplines, quality of past repairs/rebuilds, utilization of equipment (excessive crashes), etc. Here, the concepts of flexibility introduced above and the cost performance will be appreciable.

- *Labour Cost:* This refers to the direct and indirect labour that will be required to operate and maintain the equipment, recondition of tooling, and the required management and engineering structure.

Axiomatic Design methodology (Suh N.P., 2001) is used to identify and design a structure for the 'cost function model' which encompasses all desirable characteristics of any manufacturing system. This refers back to the vertical axis, cost axis, in Figure 1-3, Figure 1-4 and Figure 5-1.

Axiomatic Design Cost Model *is the model which best describes capital and operational cost through the life cycle of the program.*

It follows that once a cost model is found for an industry application; a comparison between different design alternatives will be possible. Therefore, we define the following desirable 'Customer Needs', CN's, for a manufacturing system and the subsequent 'Function Requirements', FR's, as follows in Figure 6-1.

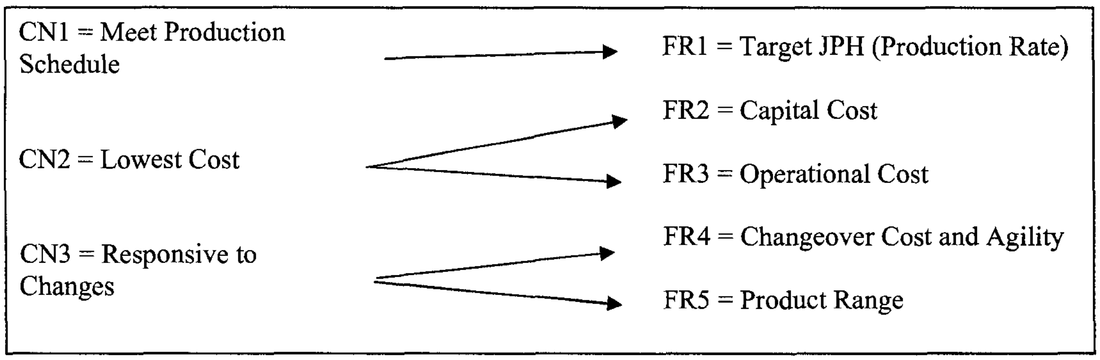


Figure 6-1: Customer Needs (CN) and Functional Requirenments (FN) for setup of cost model.

These requirements were chosen by experience and by realizing which characteristics are most desirable from a manufacturing system. An interesting argument is that some may argue that maximizing FR4 with use of flexible equipment also increases undesirables such as FR2 and FR3.

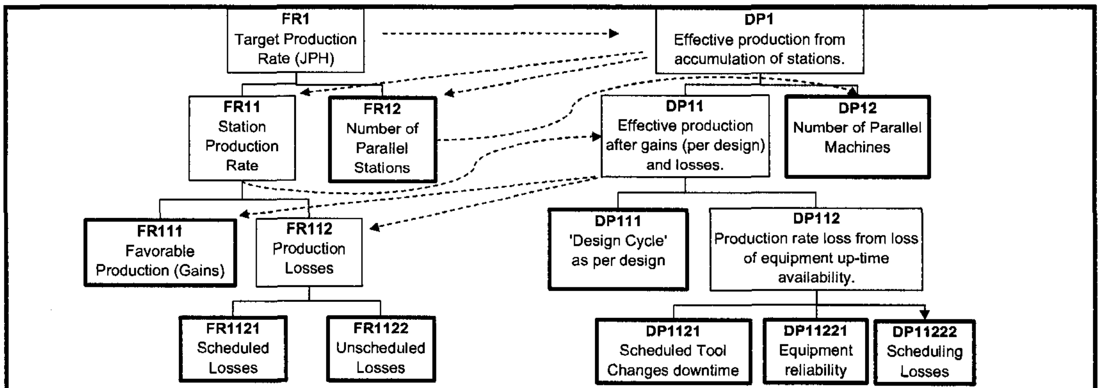
The axiomatic design is expanded noting three important notes:

- the *design corresponds to a particular work plane of a product*
- *the final net effect depends on the accumulation of all work planes*

- Assumption 3 *is used to minimize effect of cost variables; thus, further simplifying design with use of complexity analysis*

6.1 FR1 = Target Jobs-Per-Hour (JPH; Production Rate)

Figure 6-2 illustrates the Zig-Zag and design table exercise used to expand FR1 into design parameters. Production rate does not only depend on the accumulated effect of a number of parallel stations and their individual production rates. It also must take the effects of production losses due to regularly scheduled activities such as tool changes and unknowns such as breakdowns. These correspond to tool and equipment reliability.



				DP12 = No. of Parallel Machines in Cell	DP111 = Station Cycle by design {JPH}	DP11211 = Tool Life {frequency of tool changes}	DP11212 = Cycle to change a tool	DP11221 = Cell Availability	DP11222 = Combinatorial Complexity	*** MTTF of components ***	*** Axis Reliability (MTTF) ***	*** Spindle Reliability (MTTF) ***
FR1 = Target Production Rate {Achievable}	FR12 = Size of machining cell			X								
	FR11 = Station Production Rate	FR111 = Favorable Production Rate		X	X							
		FR112 = Production Losses	FR1121 = Sched. Prod. Loss	FR11211 = Number of Tool changes	X		X						
				FR11212 = Avg. Time per Tool Change				X					
			FR1122 = Unsched. Prod. Loss	FR11221 = Unsched. Prod. Loss - Availabiltiy	X	X			X		X	X	X
				FR11222 = Unsched. Prod. Loss - Scheduling						X			

Figure 6-2: Zig-Zag and Design Table for FR1 = Target JPH.

Therefore, functions for this level of design might be stated as follows:

$$FR111 = \{\text{Favorable Production Rate}\} = \frac{(\text{Sta. Cycle by design}) \quad [JPH]}{(\text{Num. of Parallel Machines})}$$

$$FR1121 = \{\text{Scheduled Production Loss}\} = \frac{(\text{avg. \# of tool changes per hr})^{*}(\text{avg. time per tool change})^{1} \quad [JPH]}{(\text{Num. of Parallel Machines})}$$

$$FR11221 = \{\text{Unsched. P.L., Availability}\} = \frac{(1 - \text{Availability, A}) * JPH}{(\text{Num. of Parallel Machines})}$$

A discussion of relation of availability and equipment reliability as summarized from Barlow and Proschan (1975) is given in APPENDIX D(a).

FR11222 = (Scheduling Losses) = (Effects that are due to scheduling interference between equipment. **Combinatorial Complexity**)

= P (equipment interference)

$$= P \left(\frac{(\text{Part exchange, t}) \ (\text{No. of Sta})}{\text{Overall Cycle, t}} \right)$$

6.2 FR2 = Capital Cost

Figure 6-3 illustrates breakdown of capital cost. This is a simple calculation since it only depends on the number of machines required from 'FR1' and the cost of each. Secondly, the number of material handling devices will depend on the number of parallel machines and the scheduling complexity determined in FR1222.

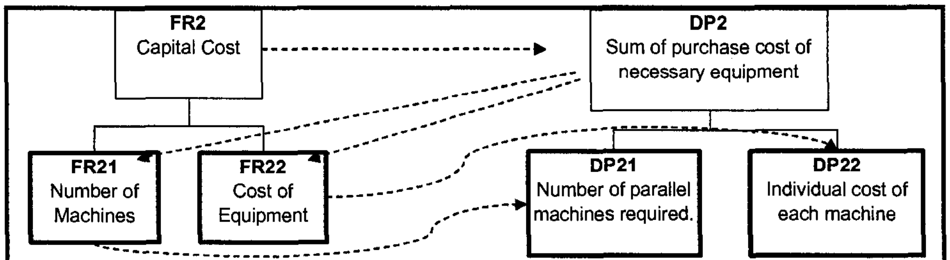
Therefore,

$FR21_{production} = \sum$ (# of Equipment) $_i$ (Cost of each equipment) $_i$

$FR22_{mt'l\ handling} = \sum$ (# of Material Handling Equipment) $_i$ (Cost of each) $_i$

Where,

(# of Material Handling Equipment) = required to satisfy combinatorial complexity



			*** Complexity ****	DP211 = No of Parallel Machines	DP212 = Cost of Individual station	DP222 = Cost depending on type used	DP221 = # of units required
FR2 = Capital Cost	FR21 = Production Equipment	FR211 = Number of Equipment Required		X			
		FR212 = Cost of each unit			X		
	FR22 = Material Handling Equipment	FR222 = Cost of each unit				X	
		FR221 = # of Material Handling Equip. Req'd.	X	X		X	X

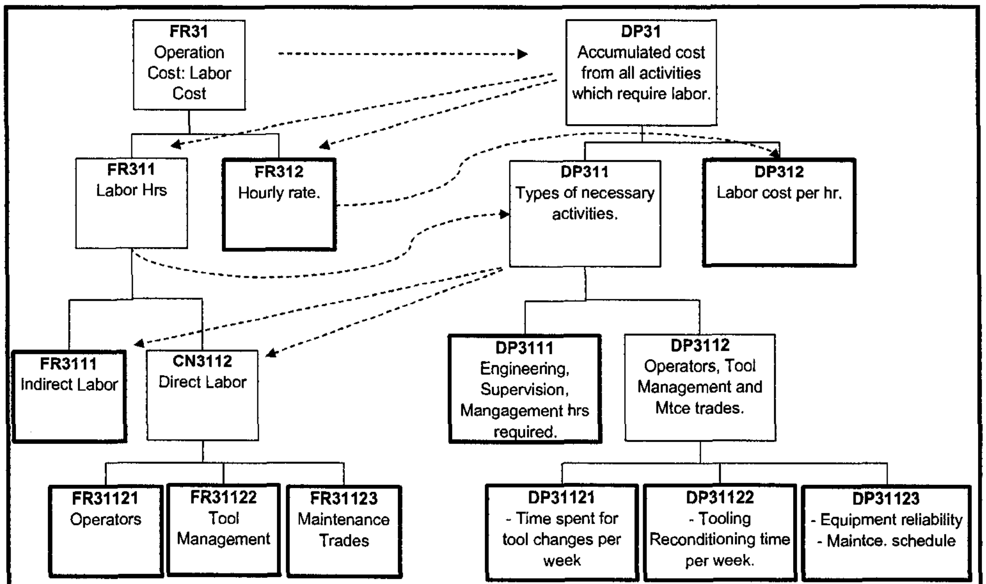
Figure 6-3: Zig-Zag for FR2 = Capital Cost.

6.3 FR3 = Operational Cost

Operational Cost refers to the year-over-year cost incurred to operate and maintain the manufacturing equipment and tools during the production life. It is made up of three components:

i) FR31 = Labour Cost

There are only a few remarks that need to be made about the Labour Cost breakdown shown in Figure 6-4. First, cost of operators is determine by 'DP31121 = hrs of Schedule Activity' which simply denotes the level of work load so that operator is busy a certain maximum amount of time (i.e. 60%). These are routine tasks such as tool changes and quality checks. Free time allowance is for monitoring and diagnostics.



				*** Tool Life ***	*** Cycle to Change Tool ***	*** Downtime = (1 - Availability) ***	DP312 = labour cost per hr	DP3111 = Suport labour Hrs	DP31121 = hrs of Schedule Activity (tool changes, quality checks)	DP31122 = Tool Reconditioning Effort [hrs]	DP31123 = Avg. Number of trades req'd. per repair
FR31 = Operation Cost: labour	FR312 = Hourly rate						X				
	FR311 = labour Hours	FR3111 = Indirect labour					X	X			
		FR3112 = Direct labour	FR31121 = Cost of Operators	X	X		X	X	X		
			FR31122 = Tool Management [hrs]	X			X	X		X	
			FR31123 = Maintenance Trades [hrs]			X	X	X			X

Figure 6-4: Zig-Zag for FR31 = Operational Cost: Labour Cost.

Furthermore, the measure of equipment availability can be used to determine the labour hour necessary for maintenance of equipment since downtime is equal to (1 – Availability) and we are under the presumption that this is when maintenance of equipment is occurring. A good practice is to schedule production time around the requirements for maintenance; that is, bundle repairs for one or two days a week and run production the remainder. Although this is difficult to practice because cost limitations.

Two types of complexities are applicable. System complexity as discussed earlier affects maintenance and operation of equipment. Then, it will have a proportional effect on labour hours. The second is a combination of product and cognitive (effort) complexities and was discussed in Section 4.3.4.1.

ii) FR32 = Maintenance Materials

The costs of maintenance materials depend purely on the failure of the components; that is, on the reliability of each unit in terms of cycles before failure, or Mean-Time-To-Failure, MTTF. Only need to consider MTTF obtained from a reliability analysis as in FR1 for availability analysis. Figure 6-5 illustrates the axiomatic design. There is also a direct correlation between complexity analysis and this effort.

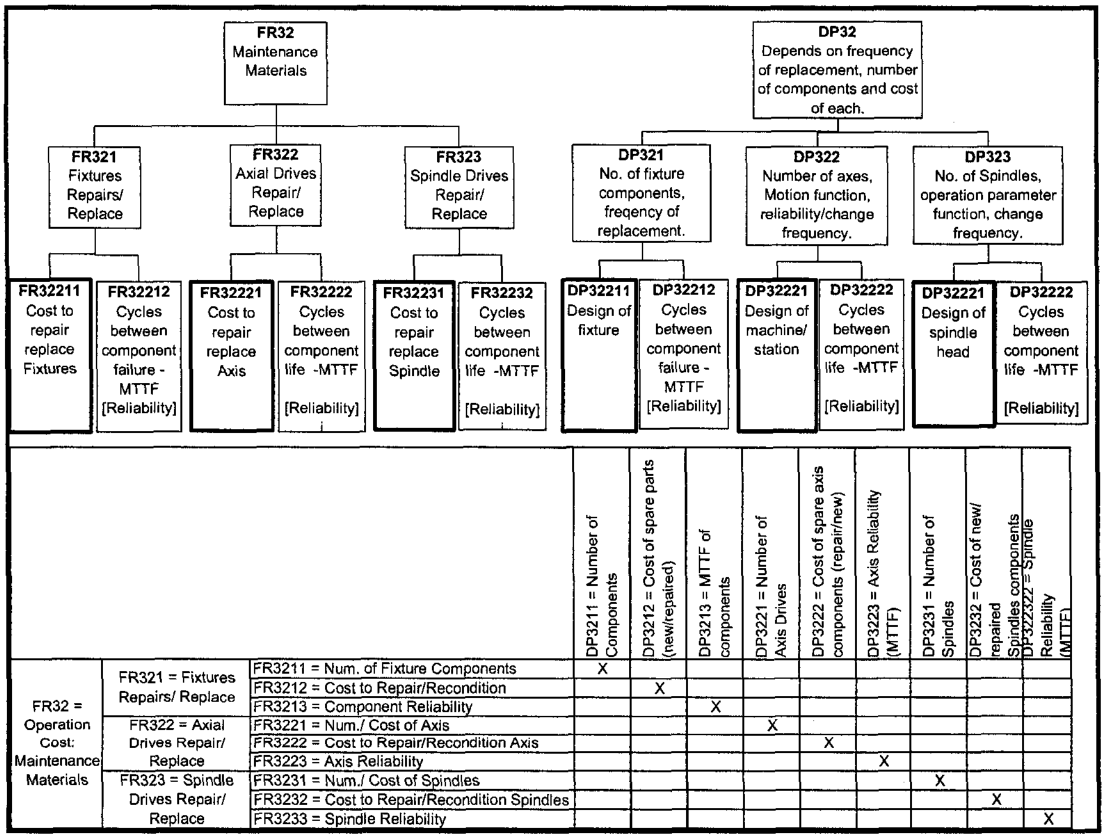
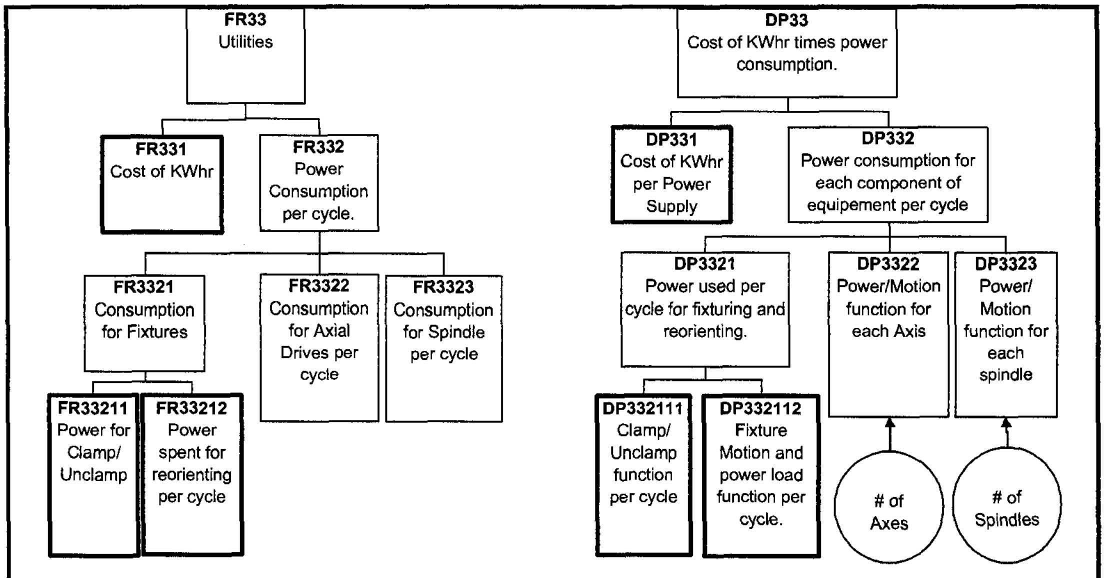


Figure 6-5: Zig-Zag for FR32 = Operational Cost: Maintenance Materials.

iii) FR33 = Energy Consumption

This Chapter depends on three factors: the utilization or cycle diagram for each spindle-axis-fixture and power draw per cycle, the number or quantity of products under the same diagram, and the cost of energy supply in kWhr. Figure 6-6 shows the Axiomatic design table for this component.



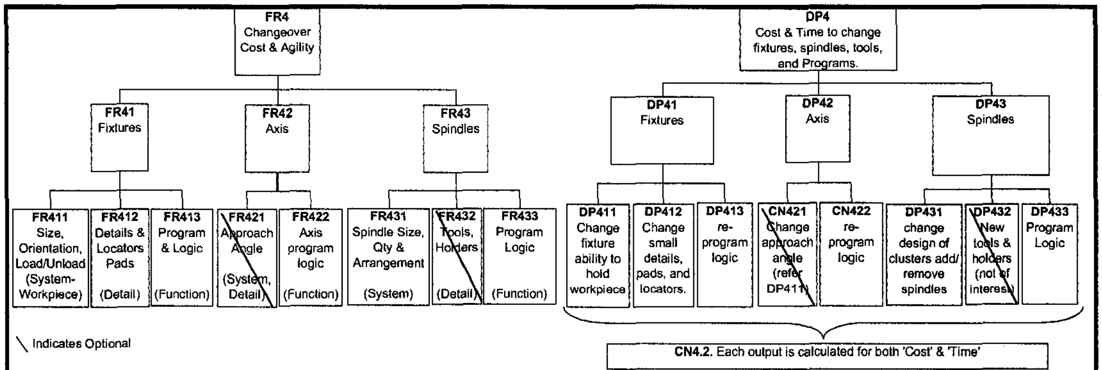
				*** Number of Axes ***	*** Number of Spindles ***	DP331 = Cost of Power Supply [$ per kWhr]	DP33211 = Power function for Clamp/Unclamp	DP33211 = Power function for rotate table	DP3322 = Power/Motion function for each Axis	DP3323 = Power/Motion function for each spindle
FR33 = Operation Cost: Utilities	FR331 = Cost of kWhr					X				
	FR332 = Power Consumption per cycle.	FR3321 = Consumption for Fixtures	FR33211 = Power for Clamp/Unclamp				X			
			FR33212 = Power for Orientation					X		
		FR3322 = Consumption for Axial Drives per cycle		X					X	
		FR3323 = Consumption for Spindle per cycle			X					X

Figure 6-6: Zig-Zag for FR33 = Utilities.

6.4 FR4 = Changeover Cost & Agility

The most important consideration for designing flexible systems is the agility and cost of changeover to different products (retool). Figure 5-4 outlines the strategy to be used for implementation in a manufacturing firm. It can be deduced that, for flexible manufacturing systems, the range needs to be designed close to the catalog of product offerings; thus avoiding expensive changeovers or utilization of system approaching dedicated implementation.

Figure 6-7 illustrates the axiomatic design for this last classification of cost. Most important is that each variable has to be defined in terms of both cost of materials, labour required and time of lost production which must be committed. The complete design table for the axiomatic design function is shown in Figure 6-8.



				*** # of Parallel Machines ***	*** Station Cycle ***	*** labour cost ***	*** support labour hour ***	*** Number of trades required ***	*** Number of Fixture Components ***	*** Number of Axes ***	*** Number of Spindles ***	DP411 = Change fixture ability to hold workpiece	DP412 = Change small details, pads, and locators.	DP413 = re-program logic	DP422 = re-program logic	DP422= change design of clusters add/ remove spindles	Program Logic	DP411 = Change fixture ability to hold workpiece	DP412 = Change small details, pads, and locators.	DP413 = re-program logic	DP422 = re-program logic	DP422= change design of clusters add/ remove spindles	Program Logic
FR4 = Change-over Cost & Agility	Cost	FR41 = Fixtures	FR411 = Size, Orientation, Load/Unload			X	X	X	X			X											
			FR412 = Details & Locators Pads			X	X	X	X				X										
			FR413 = Program Parameters & Logic			X	X	X	X					X									
		FR42 =	FR422 = Axis program logic			X	X	X		X					X								
		FR43 = Spindles	FR431 = Spindle Size, Qty & Arrangement			X	X	X			X					X							
			FR433 = Program Paramameters & Logic			X	X	X			X						X						
	(Cost per cycle lossed) * (loss cycles for retool)	Time — FR41 = Fixtures	Load/Unload	X	X			X	X									X					
			FR412 = Details & Locators Pads	X	X			X	X										X				
			FR413 = Program Parameters & Logic	X	X			X	X											X			
		Time — FR42 = Axis	FR422 = Axis program logic	X	X			X		X											X		
		Time — FR43 = Spindles	FR431 = Spindle Size, Qty & Arrangement	X	X			X			X											X	
			FR433 = Program Paramameters & Logic	X	X			X			X												X

Figure 6-7: Zig-Zag for FR4 = Changeover Cost and Agility.

		CN1 = Target Production Rate (Achievable)						CN2 = Capital Cost			CN31 = Operation Cost: Labor					CN32 = Operation Cost: Mtce Materials									CN33 = Operation Cost: Utilities					CN4 = Change Over Cost & Agility											
		CN12 = Size of machining cell	CN11 = Station Production Rate					CN21 = Cost for Production Equipment	CN22 = Cost for Mt'l Handling Equipment		CN312 = Hourly rate	CN311 = Labor Hours				CN321 = Fixtures Repairs/ Replace			CN322 = Axial Drives Repair/ Replace			CN323 = Spindle Repair/ Replace			CN331 = Cost of kWhr	CN332 = Power Consumption per cycle				(Cost per cycle lossed) * (loss cycles for retool)											
			CN111 = Favorable Production Rate	CN112 = Production Losses								CN3112 = Direct Labor			CN3111 = Indirect Labor											CN3321 = Fixture Consumption				Cost						Time					
				CN1121 = Sched. Prod. Loss		CN1122 = Unsched. Prod. Loss																								CN41 = Fixtures			CN42 = Axis	CN43 = Spindles		CN41 = Fixtures			CN42 = Axis	CN43 = Spindles	
				CN11211 = Number of Tool changes	CN11212 = Avg Time per Tool Change	CN11221 = Unsched. Prod. Loss - Availabiltiy	CN11222 = Unsched. Prod. Loss - Scheduling		CN222 = Cost of each unit	CN221 = # of Mt'l Handling Equip Req'd		CN31121 = Operators [hrs]	CN31122 = Tool Management [hrs]	CN31123 = Mtce Trades [hrs]		CN3211 = Num of Fixture Components	CN3212 = Cost to Repair/Recondition	CN3213 = Component Reliability	CN3221 = Num/Cost of Axis	CN3222 = Cost to Repair/Recondition Axis	CN3223 = Axis Reliability	CN3231 = Num/Cost of Spindles	CN3232 = Cost to Repair/Recondition Spindles	CN3233 = Spindle Reliability		CN33211 = Power for Clamp/Unclamp	CN33212 = Power for Orientation	CN3322 = Consumption for Axial Drives per cycle	CN3323 = Consumption for Spindle per cycle	CN411 = Size, Orientation, Load/Unload	CN412 = Details & Locators Pads	CN413 = Program Parameters & Logic	CN422 = Axis program logic	CN431 = Spindle Size, Qty & Arrangement	CN433 = Program Paramameters & Logic	Load/Unload	CN412 = Details & Locators Pads	CN413 = Program Parameters & Logic	CN422 = Axis program logic	CN431 = Spindle Size, Qty & Arrangement	CN433 = Program Paramameters & Logic
	DP12 = No of Parallel Machines in Cell	X	X	X		X		X		X																										X	X	X	X	X	X
	DP111 = Station Cycle by design (JPH)		X			X																														X	X	X	X	X	X
	DP11211 = Tool Life (frequency of tool changes)			X								X	X		X																										
	DP11212 = Cycle to change a tool				X							X			X																										
	DP11221 = Cell Availability					X								X	X																										
	DP11222 = Combinatorial Complexity						X			X																															
	DP212 = Cost of Individual Prod. Equip. station							X																																	
	DP222 = Cost depending on type Mt'l Handling unit u								X	X																															
	DP221 = # of mat'l handling units required									X																															
	DP312 = Labor cost per hr										X	X	X	X																X	X	X	X	X	X						
	DP31121 = hrs of Schedule Activity (tool changes, quality checks)											X			X																										
	DP31122 = Tool Reconditioning Effort [hrs]												X		X																										
	DP31123 = Avg Number of trades req'd per repair													X	X															X	X	X	X	X	X	X	X	X	X	X	X
	DP3111 = Fraction of supervision per supervised hou														X															X	X	X	X	X	X						
	DP3211 = Number of Fixture Components															X														X	X	X				X	X	X			
	DP3212 = Cost of spare parts (new/repaired)																X																								
	DP3213 = MTTF of components					X												X																							
	DP3221 = Number of Axis Drives																		X									X					X						X		
	DP3222 = Cost of spare axis components (repair/new)																			X																					
	DP3223 = Axis Reliability (MTTF)					X															X																				
	DP3231 = Number of Spindles																					X							X					X	X					X	X
	DP3232 = Cost of new/ repaired Spindles components																						X																		
	DP322322 = Spindle Reliability (MTTF)					X																		X																	
	DP331 = Cost of Power Supply [$ per kWhr]																								X																
	DP33211 = Power function for Clamp/Unclamp per cy																									X															
	DP33211 = Power function for rotate table per cycle																										X														
	DP3322 = Power/Motion function for each Axis per c																											X													
	DP3323 = Power/Motion function for each spindle pe																												X												
$$$	DP411 = Change fixture ability to hold workpiece																													X											
	DP412 = Change small details, pads, and locators.																														X										
	DP413 = re-program logic																															X									
	DP422 = re-program axis logic																																X								
	DP422= change design of clusters add/ remove spin																																	X							
	Program Logic																																		X						
time	DP411 = Change fixture ability to hold workpiece																																			X					
	DP412 = Change small details, pads, and locators.																																				X				
	DP413 = re-program logic																																					X			
	DP422 = re-program logic																																						X		
	DP422= change design of clusters add/ remove spin																																							X	
	Program Logic																																								X

Figure 6-8: System Design Table: Implementation & Operation Cost & Agility.

6.5 Cost Considerations vs. Product Variety (Mix) & Production Volume

The objective of this chapter until now is to develop the calculations required to model the mechanics of manufacturing costs. The requirements instituted for this relation are that cost is accounted for the design-to-disposal of the equipment system. The design analysis tool used is the Axiomatic Design process. The outcome of this effort is Figure 6-8 or the System Cost Design Table. However, the real benefit of this is presented in Figure 6-9 as the system's Cost Report Card. Only the dedicated system example is illustrated here but all remaining sections are discussed in further detail in the Conclusions section.

a) Report Card - Dedicated System			
FR1 = Achievable Production Rate {Achievable}	156	[JPH]	
FR2 = Capital Cost	$600,000	[$ - USD]	
FR31 = Operation Cost: Labor	$0.02	[CPU - USD]	
FR32 = Maintenance Materials	$0.06	[CPU - USD]	
FR33 = Operation Cost: Utilities	$0.25	[CPU - USD]	
FR4 = Change Over Cost & Agility	$243,758	[$ - USD]	
	5.32	[time - days]	
$255,485.16 [$ - Tot. Incl. Prod. Loss]			
$0.26 [CPU - per Sched. changeover]			
FR51 = % of Strategic Level Flexibility Implementation	20%	[%]	
FR52 = % Equipment Utilization (current Plane)	50%	[%]	
Estimated CPU	$0.59		
Changeover Time [Days]	5.32	$0.21	***
Overall CPU	$0.80		

*** Amortized One-Month Period [15 days]
(3 working weeks remaining in current month)

Figure 6-9: Cost Report Cad for Dedicated System.

The next important consideration is to understand how this model will behave as manufacturing requirements such as product variety and production volume changes. This is an important characteristic because it will determine how a firm should deploy its manufacturing flexibility strategy. Therefore, first to be reviewed are the effects of production volume requirements. The following equation is the basis for this annex to the Cost Report Card of Figure 6-9. This equation is important to establish a relation for capital cost disbursement and its impact on production cost.

In Fraser (*et al.*, 2000, p. 61) the "Capital Recovery Formula" is presented as follows:

Equation 22: $$A = (P - S)\,(A/P, i, N) + Si$$

Where,

A = savings incurred by purchase of asset per period

P = asset purchase price

S = asset salvage value at disposal

i = interest rate

N = number of periods

(A/P, i, N) = capital recovery factor

$$= \frac{i\,(1+i)^N}{(1+i)^N - 1}$$

"The capital recovery factor can be used to find out, for example, how much money must be saved over N future periods to 'recover' a capital investment of P today. ... this is sometimes combined with the sinking fund factor for its salvage value after N years ..." (Fraser, *et al.*, 2000). Therefore, this can be understood as the cost disbursement of capital investment P over N periods. Furthermore, this equation can be divided by number of disbursement periods, N, to give A/N or the cost which must be absorbed per each production period.

An additional set of variants which depend on manufacturing utilization policies must be set from assumptions. These are as follows:

N = Assume to 1-month periods. This is to align with would be typical manufacturing accounting practices.

T = scheduled daily running hours per day. This depends on shift policies from which the plant is utilized; for example, three eight-hour shift operation per day or two ten-hour shift per day.

U = running days per week under regular production schedule (5 working days).

V = weeks in a month (4 weeks)

Then,

N {hr} = 20 hrs/~~day~~ * 5 ~~days/week~~ * 4 ~~weeks~~/month

= 400 hrs/month

Or, related to production rate (JPH),

N {piece} = 400 hrs/month * JPH

Then, from Equation 22,

Equation 23:

$$\frac{A}{N} = \frac{A}{400 * JPH} = \frac{(P - S)(A/P, i, N) + Si}{400 * JPH}$$

Furthermore, Groover (2001, p. 3) makes the following classification for annual production in a given factory into three categories:

1. *"Low Production*: Quantities in the range of 1 to 100 units per year.
2. *Medium Production*: Quantities in the range of 100 to 10,000 units annually.
3. *High Production*: Production quantities are 10,000 to millions of units.

The boundaries between the three ranges are somewhat arbitrary (author's judgment). Depending on the types of products we are dealing with, these boundaries may shift by an order of magnitude or so".

However, for the purpose of this thesis the following subdivision of production categories is appropriate:

1. *Low Production*: Quantities in the range of 1 to 10,000 units per year.
2. *Medium Production*: Quantities in the range of 10,000 to 250,000 units annually.
3. *High Production Mid-Range*: Production quantities are 250,000 to 2 million units.
4. *High Production*: Production quantities are 2 million to millions of units.

Consider system scenarios presented as examples of determination of Flexibility Level of Section 3.2. A 'dedicated' system is presented as option 'A'; it consisted of a transfer machining system. A 'flexible' C.N.C. single spindle machining station is used for example 'B' and a 'flexible-dedicated' one is example 'C' where multi-spindle adaptor is introduced to C.N.C. station of scenario 'B'.

Figure 6-10 and Figure 6-11 are the cost plots for these examples as required production volumes change. Note that the flexible-dedicated systems has a minimum cost range covering the Medium Production range and partly into the High Production Mid-Range. However, this case only illustrates single product production. As expected, dedicated system is the minimum cost option for high production volumes and flexible system is for low production volumes. Interesting effects can be expected for these plots as product variety increases.

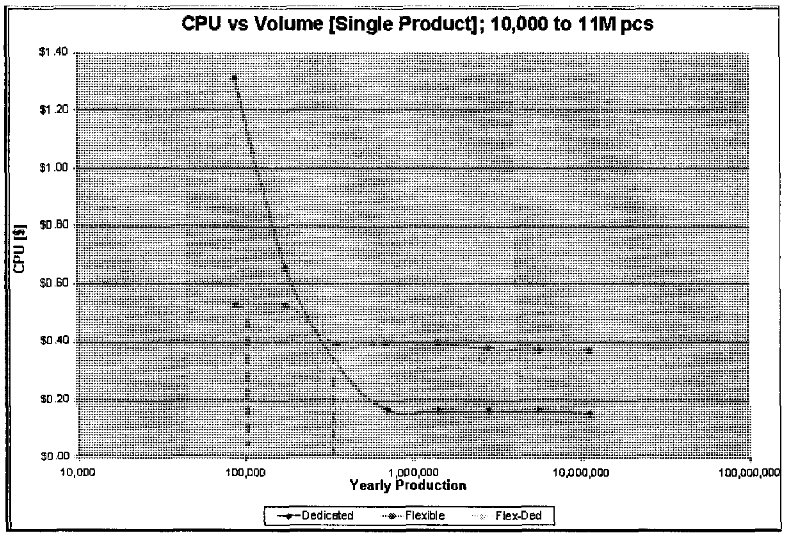


Figure 6-10: Effect of Production Volume on Cost per System Design (Medium to High Production).

Product variety, P, is represented by Groover (2001, pp.35) as the total number of different product part styles. It is linked to production quantity Q or annual quantity of style j by following relationship:

Equation 24: $$Q_f = \sum_{j=1}^{P} Q_j$$

Where,

Q_f = total quantity of all parts or products made in the factory

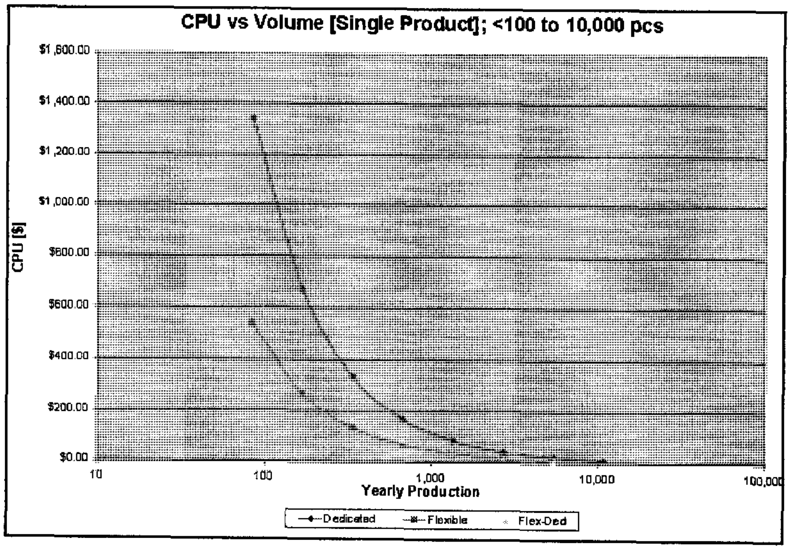


Figure 6-11: Effect of Production Volume on Cost per System Design (Low Production).

Furthermore, product variety is subdivided into 'hard product variety' or 'soft product variety. Hard product variety, P1, is products which differ substantially. It is the number of distinct product lines. 'Soft product variety, P2, is those products which have only small difference between them. It is the number of products in a product line. Then, measure product variety simply by the number or quantity of product styles.

Production is described by the level and style of variety in Chapter 5. Flexibility is described as Synchronous Production where all products within a system's range are produced at any given time with zero or negligible burden. This type of product mixed is inherent to initial design and provides minimal effects through the life of the system.

However, from the remaining two: Batch and Inclusive Reconfigurable Production, it is the second one which provides the most beneficial example. For the example to be discussed, it will be assumed that this type of reconfiguration is introduced every one million parts produced. Therefore, the cost for each reconfiguration event must be absorbed within that period. Greater product variety introductions will have to absorb cost for increased number of events.

Figure 6-12 illustrates the effects of production volume and product variety on cost based on the model discussed in this thesis and for systems examples A, B, and C. That is, a dedicated, a flexible, and a flexible-dedicated system respectively. Product Variety is introduced by increasing the absorbed cost for each system per period of time. That is, increasing the number of Inclusive Reconfigurable Production through similar production periods.

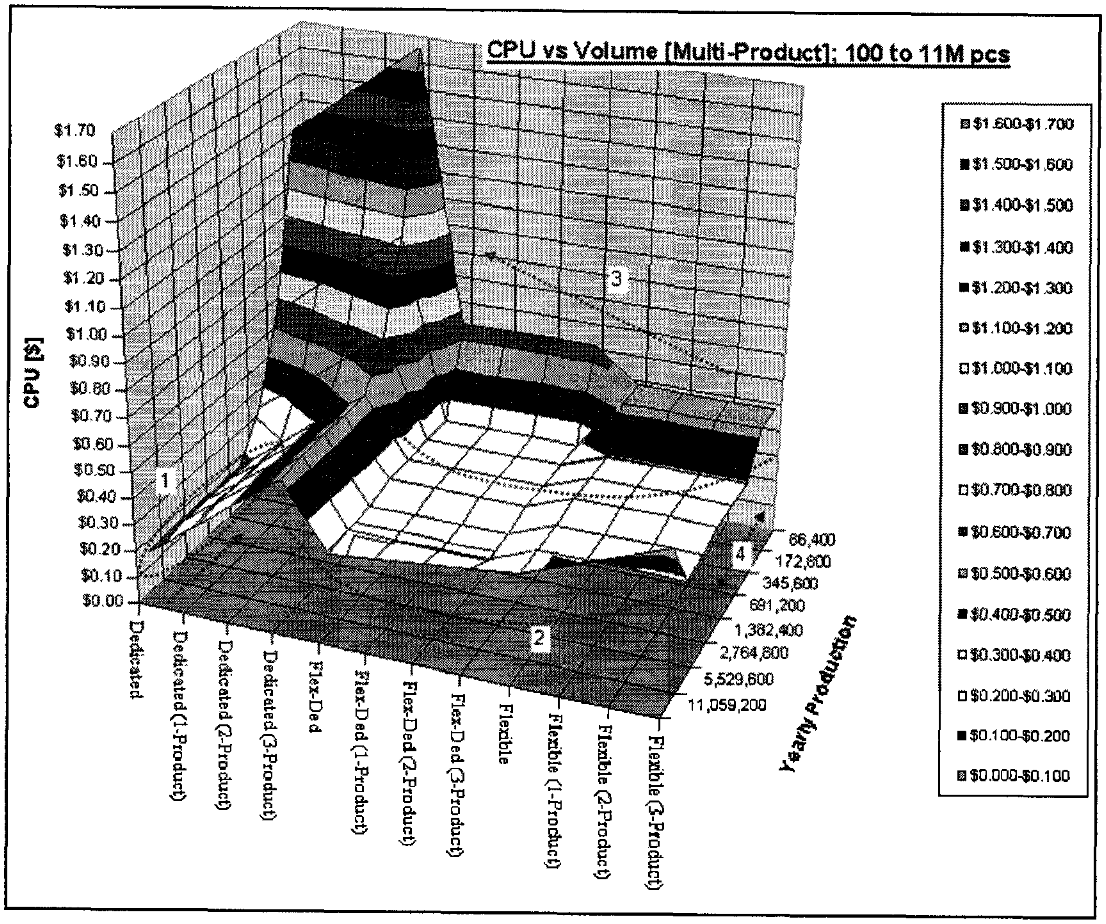


Figure 6-12: Cost vs. Production Volume and Product Variety.

Some observations can be made from Figure 6-12 as follows:

(1) Dedicated system is minimum cost option when production volumes are high and product variety is low. This is as expected. However, cost increases as product variety increases.

(2) Flexible-Dedicated system is a minimum cost option for a substantial area of the system range. This is mainly from mid-range to high volume production once product mixed for dedicated system has increased a certain amount.

(3) Flexible system is economical option at the low level production with disregard for product mix. This is because more can be done with less equipment at such small production rates.

(4) Flexible system has cost maxima to itself at either the low volume production mainly because of disbursement rate and at the high level production. This second is because investment increases substantially because of number of equipment needed to match production. At this point, dedicated or flexible-dedicated system should be considered.

6.6 Cost-Complexity Relation: After Runoff

Great effort has been made to create a unification model based on practical application and, consequently, care is taken to provide statements and examples at the same level. Furthermore, it is of interest to understand the behaviour of the model and system after design and installation is complete; after runoff. This is presented Figure 6-13 as an interesting development from the model in Figure 5-1 and Equation 2. Recall that this equation relates complexity to cost given the design parameters which influence the outcome behaviour of the system. That is, from variables selected during design and for a developed inherent cost to operate the system.

However, a second declaration can be made once system is put into production. Although the complexity cost relation remains unchanged as long as the design is untouched, behaviour of system complexity and cost is influenced by decisions taken through its operation cycle. General wear and tear and miss use of the system induce random behaviour over time. Therefore, a magnification of cost effect is identified which is dependent on 'invested cost' or 'operational decisions' over the useful life of the system.

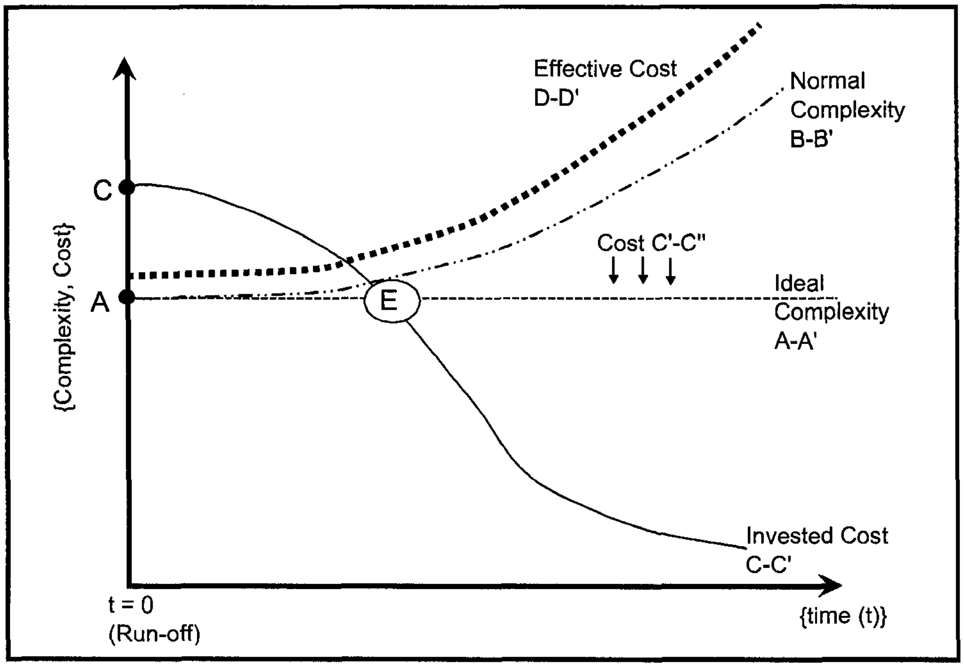


Figure 6-13: Cost-complexity behaviour over time after equipment runoff.

At the installation or runoff of equipment, all of flexibility level, system design cost and complexity are fixed. That is, the system of given flexibility is introduced into production at the complexity level 'A' and at the cost of operation burden 'C'. A natural decrease of 'invested cost' commences (line C-C'); this commonly continues until the decommissioning of the system. Refer to 'invested cost' as the cost sunk into the equipment for maintenance and general activities to keep the equipment running as designed. Note: this is a choice by managers of the equipment; whereas, 'operation cost' as previously discussed is set by the design.

Statements can also be made about the behaviour of complexity over time. A theoretical normal curve for complexity over time is B-B'. It implies that as the equipment is utilized over time, and equipment remains untouched, random behaviour increases naturally. Then, it is the job of maintenance and management activities (C'-C'') to make the right investments to keep the complexity curve (and cost) approaching ideal behaviour (A-A'). This is a balance between operational dollars and the allowances present in product-system relations. A magnification of cost effects is observed based on this increased complexity (D-D'). This satisfies Equation 2 but it is now influenced by changes introduced by equipment utilization over time.

Therefore, a theoretical intercept 'E' must exist, where, if invested cost is reduced further, random behaviour tends to dominate and increase the cost burden. Cost savings from reduced invested cost are or may even be surpassed by the burden from random behaviour. Therefore, after 'E', subsequent cost savings will need to be supported by improvements which decrease the designed complexity of the system through process improvements.

Chapter 7 Application: Flexible-dedicated design

7.1 Grouping: Main approach for reduction of operation cost

In the following example the Main Bearing Cap (M.B.C.) and Oil Pan bolt holes of a cylinder block are presented to illustrate a practical design application. We will consider using Options A, B, and C of Table 3-3. Figure 7-1 illustrates the composite product variations for either Inline or V-engine types for this work plane.

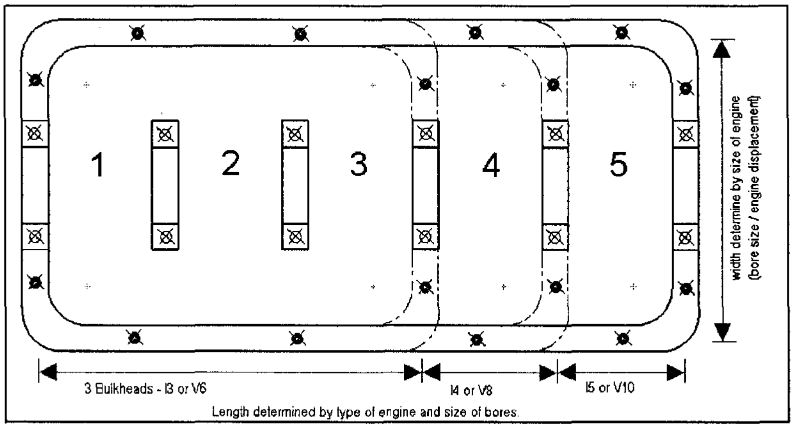


Figure 7-1: Composite Product Model – Block "Bottom Face" work plane (M.B.C. and Oil Pan Bolts).

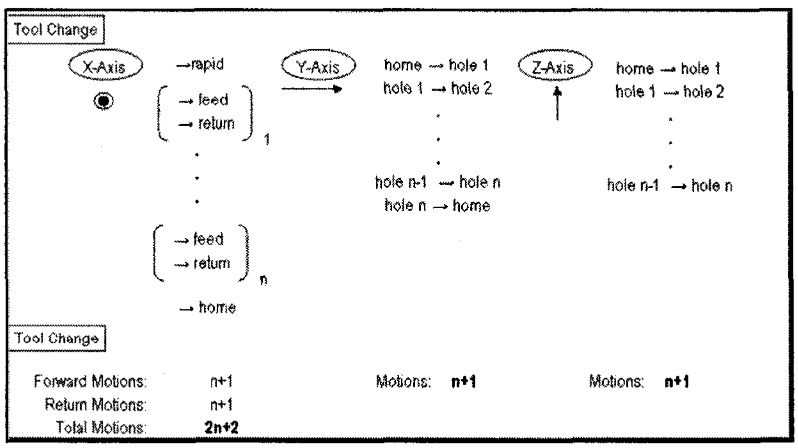


Figure 7-2: Motion Stack-Up for Axes of a Single Spindle Machining Center.

The factor controlling both the operational cost and design cycle of a machine is the number of motions carried out by each axis during each cycle. It is important to understand the system motions at the individual machine – machine spindle(s) level. Therefore, an analysis of motion is as follows:

- Figure 7-2 illustrates how patterns of motions stack up in a stitch drilling cycle of a machining centre, where '*n*' is the number of holes. Table 7-1 summarizes number of motions for each product option given under stitch drilling condition. The effect of multi-spindle drilling is to reduce the effective number of holes n. For example, changing stitch drilling for four holes (n = 4) to a multi-spindle adapter of four tools will reduce n to 1. Thus,

Equation 25:

$$n_{effective} = \frac{n_{current}}{n_{spindle\ adapter}}$$

Table 7-1: Motions stack-up of single spindle C.N.C. machining of Composite Cylinder Block – "Bottom Face".

	X-Axis			Y-Axis			Z-Axis		
No. of Bulkheads	3	4	5	3	4	5	3	4	5
M.B.C. Holes	18	22	26	9	11	13	9	11	13
Oil Pan Holes	18	22	26	9	11	13	9	11	13
Totals:	36	44	52	18	22	26	18	22	26

	X	Y	Z	Totals Motions
Total 3-Bulkhead	36	18	18	72
Total 4-Bulkhead	44	22	22	88
Total 5-Bulkhead	52	26	26	104

- The effect of dedicated equipment is to reduce effective 'n' to a minimum. For example, a dedicated head with 20 spindles to drill both Main Bearing

Cap and Oil Pan bolt holes of a V8 block will have $n_{effective} = 1$ since all holes are drilled in one shot.

- Option B in the machine example previously studied utilizes a C.N.C. machining center with a multi-spindle adapter. Figure 7-3 illustrates a breakdown of a design which uses the symmetry across a product family to implement grouping. This approach reduces n to 2, 3, and 4 respectively for each design with two types of adapters. Total motions reduced follows in Table 7-2 for each axis which are by about 80%.

Table 7-2: Reduced motions stack-up.

	X	Y	Z	Totals Motions	% Reduction
Total 3-Bulkhead	6	3	3	12	83.3 %
Total 4-Bulkhead	8	4	4	16	81.81 %
Total 5-Bulkhead	10	5	5	20	80.77 %

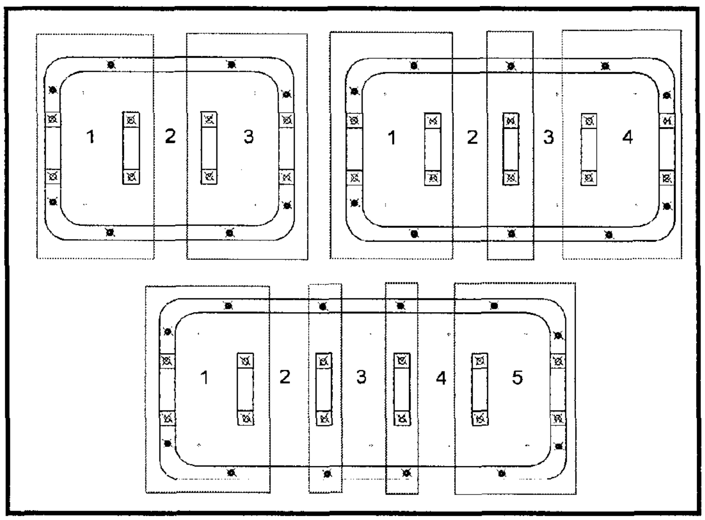


Figure 7-3: Product family symmetry and spindle grouping.

- An analysis will prove cycle time is decreased. This will then allow new determination of equipment requirements. Thus,
-

Equation 26:

$$\text{Number of Parallel Machines Required} = \frac{\text{Time per machine cycle}}{\text{Effective cycle required}}$$

Equation 27:

$$\text{Machine Savings} = (\text{machines req'd})_{\text{stitch}} - (\text{machines req'd})_{\text{adapter}}$$

Spindle grouping affects cycle time and equipment performance. It can be accomplished in many ways and is somewhat subjective to the designer and limited by technology. Figure 7-4 shows an alternate arrangement of groups which might be more realistic than Figure 7-3. Furthermore, Figure 7-5 shows types of set-ups already available in industry.

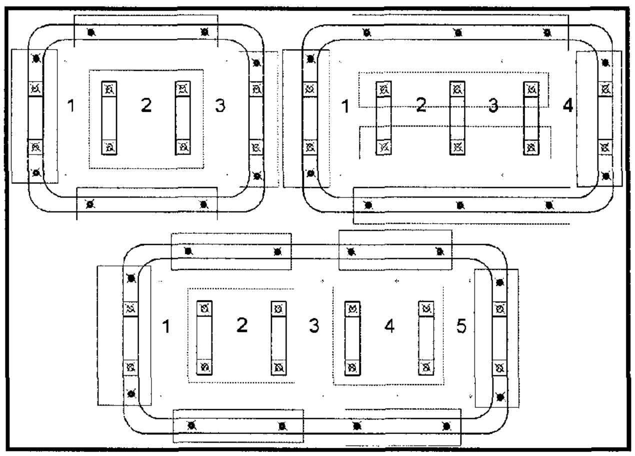


Figure 7-4: Improved spindle adapter grouping.

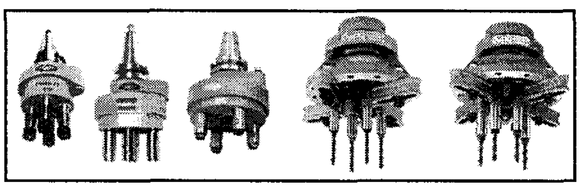


Figure 7-5: Industry available spindle adapters (Shou Ming Industrial Co., 2007).

7.2 Product

The cylinder block example, which is used to evaluate the introduced strategy, must also be viewed from the product stand point. For this, Table 7-3 illustrates possible catalogue of offerings; there are a total of 16 types of possible engine block configuration. Section 4.3.1.1 illustrates utilization of product complexity analysis.

Table 7-3: Assumed Strategic Product Offerings of firm under analysis.

I4	I6	V6	V8	V10
Sm Al	Md Al	Sm Al	Sm Al	Md CI
Sm CI	Md CI	Sm CI	Sm CI	Lg CI
Sm CI	Lg CI	Md CI	Md CI	
Md CI			Lg CI	
Sm – Small Md – Medium Lg - Large			Al – Aluminum CI – Cast Iron	

7.3 Design Alternatives

Further opportunities for equipment alternatives can be realized if automotive components are divided into two major groups: Cylinder and Cubic Product Types; detailed in Figure 7-6. First is cylinder like products, which are those that have its primary axis covering most of the features which need to be machined. Cubic products are generally larger in size and have multiple accessibility axes. Thus, this is generalizing product variations into common groups with intent of reducing complexity of work plain. Then, two machining activities are applicable: axial such as drilling, spot facing, reaming tapping, etc, and normal such as milling.

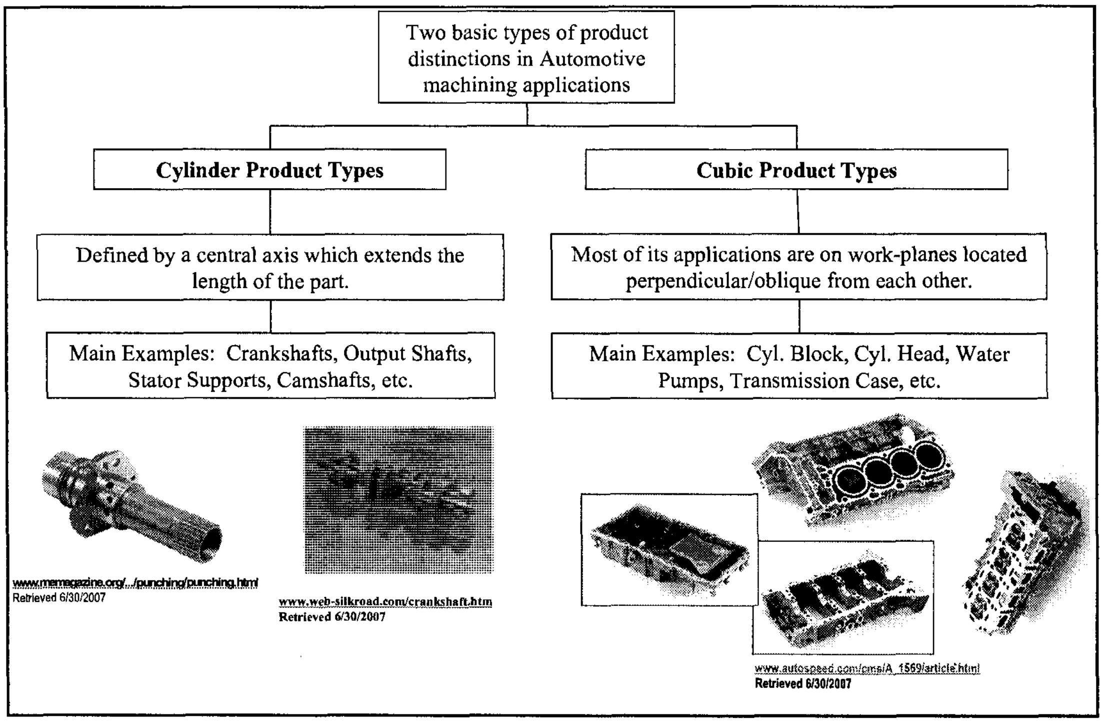


Figure 7-6: Automotive Machining Product Categories.

Furthermore, after a review of cylinder block product example it is stated that two rotations of the product and three axis of translation on the spindle are required to cover all possible machining applications. This also holds true for the prismatic products as illustrated in Figure 7-7. Two types of equipment setups are then identified.

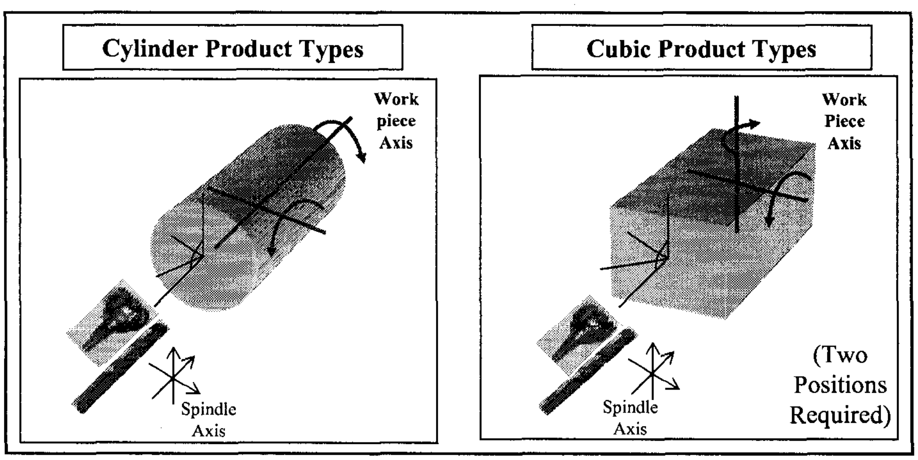


Figure 7-7: Motion and cutting applications for generic product types.

The discussion to follow is an alternative to maximize the utilization of this arrangement. There are two basic equipment setup alternatives: (1) multi-work piece and (2) multi-spindle. This is shown in Figure 7-8. The first is an arrangement of parts in a common work-table each part having an axial rotation axis. The table has the remaining axis necessary for accessibility of remaining possible work planes. A multi spindle head is then available on a one-to-one product to spindle basis. Hence, alterations have been made to the equipment to approach benefits observed in dedicated equipment while still maintaining a certain level of flexibility.

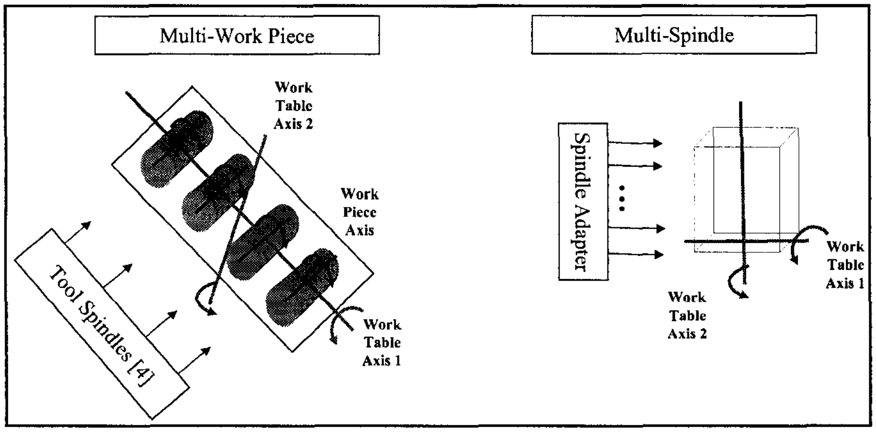


Figure 7-8: Alternative machine arrangements.

In contrast, one product can also be placed with a multi-spindle head. This is particularly helpful when multiple holes are arranged in symmetrical groups. For example, cylinder blocks have symmetric arrangements in bolt patterns for head deck, M.B.C., M.B.C. side bolts, etc. Application of clever and generic ideas is the tool towards a maximum strategic flexibility.

Chapter 8 RESULTS & DISCUSSIONS

The following points summarize the original five objectives identified for completion of the enclosed model:

- Determine method to measure flexibility of a manufacturing system

A mathematical method to measure system flexibility to serve as basis for comparing systems is established in Chapter 3. It is presented as the Scale for Manufacturing Flexibility Level or Flexibility Level.

The proposed metric depends on physical-functional attributes of a system fixed at the design stage. This is an innovative approach as compared to examples found in literature since it diverts from methods which commonly depend on functional behavior of the system or product mix. Examples are provided in Chapter 2. It describes manufacturing system design as a continuous scale of flexibility.

This method is used to compare four competing system designs for machining of an assumed 'cubic product'; namely:

- System A or dedicated alternative uses a multi-spindle dedicated head,
- System B or flexible alternative uses a single spindle machining center,
- System C is a flexible-dedicated where the flexibility level of machining center of System B is reduced by use of spindle adapters, and
- System D is the option of maximum attained flexibility through introduction of work-piece rotation capability to System B.

The results from this calculation are illustrated in Table 8-1. This method proposes a scale from '0' as the dedicated extreme to '1' as the flexible extreme.

Table 8-1: Manufacturing System Results – Flexible, Dedicated and Flex.-Dedicated Examples.

	A	B	C	D
	Dedicated Line	CNC (single spindle tool)	CNC with dedicated spindle adapters	Fully Flexible Machine (single-spindle tool)
	Option A	Option B	Option C	Option D
Flexibility Factor:	0.11	0.68	0.57	0.98

Dedicated Extreme → "0" ... ***"1" ← Flexible Extreme***

Figure 3-1 (page 24) describes Flexibility Scale as a bi-axis development which starts at the 'Product Family' extracted from Firm's Catalog of product offerings. The metric is a comparison of descriptions of Root Characteristics between the 'Real Systems' to the 'Idealized System', or 'Industry Application', which is capable of handling all products in the Product Family.

- Develop unified system model to be used to described performance of manufacturing systems in general and make assertions

A unified model to serve as general structure to describe manufacturing systems and their performance is achieved by setting a relation for cost and flexibility. It is established by Equation 1 where it is assumed that varying flexibility of a design has and inherent effect on the overall cost performance of the designed system. Equation 2 is developed as a tool to facilitate the use of Complexity Analysis to minimize cost and is based on manufacturing system behaviour. Statements deduced from this model for common properties of manufacturing systems are discussed and listed as follows:

- Flexibility Level
- System-Product-Plane
- Product Axis (Size)
- System Range
- Product Family Range
- Reconfigurability

- System Level
- Product Level

- Product-Production Variety or Mix
  - Synchronous Production
  - Batch Reconfigurable Production
  - Inclusive Reconfigurable Production
- Strategic level of manufacturing flexibility implementation
- Probability for reconfiguration

The complete model, which includes and additional axis for 'Product Size', is illustrated in Figure 5-1 (page 84). Figure 5-4 (page 91) is an application plan proposed to be used for design and deployment of manufacturing flexibility.

- Use developed model to measure performance of sample manufacturing systems with varying levels of flexibility design

The performance of systems is measured using a cost function developed in Chapter 6 using axiomatic design methodology. This is the determination of manufacturing costs observed from system design perspective and is illustrated in cost matrix of Figure 6-8 (page 101). The achievement is the development of the 'Cost Report Card' shown in Table 8-2, Table 8-3, and Table 8-4 for A, B and C examples.

The cost per unit (CPU) is plotted in Figure 8-1 for single production with no reconfiguration; note the minimum cost design is the dedicated option at \$0.59. However, once a single reconfiguration per million parts is introduced, the flexible-dedicated alternative becomes the most cost effective at \$0.80 since the CPU of dedicated production is increased to \$0.84.

Table 8-2: Cost Report Card for Dedicated System.

FR1 = Achievable Production Rate {Achievable}	156	[JPH]
FR2 = Capital Cost	$600,000	[$ - USD]
FR31 = Operation Cost: Labor	$0.02	[CPU - USD]
FR32 = Maintenance Materials	$0.06	[CPU - USD]
FR33 = Operation Cost: Utilities	$0.25	[CPU - USD]
FR4 = Change Over Cost & Agility (Losses included in $)	$253,531	[$ - USD]
	5.32	[time - days]
	$0.25	[CPU]

$253,530.55	[$ - Tot. Incl. Prod. Loss]
$0.26	[CPU - per Sched. changeover]

FR51 = % of Strategic Level Flexibility Implementation	20%	[%]
FR52 = % Equipment Utilization (current Plane)	50%	[%]

Estimated Operation CPU	$0.59	
Changeover Time [Days]	5.32	[days]
Changeover Capital & loss CPU	$0.25	
Overall CPU	$0.84	

Table 8-3: Cost Report Card for Flexible System (C.N.C. single spindle).

FR1 = Achievable Production Rate {Achievable}	161	[JPH]
FR2 = Capital Cost	$1,600,000	[$ - USD]
FR31 = Operation Cost: Labor	$0.07	[CPU - USD]
FR32 = Maintenance Materials	$0.11	[CPU - USD]
FR33 = Operation Cost: Utilities	$0.75	[CPU - USD]
FR4 = Change Over Cost & Agility	$18,831	[$ - USD]
	0.26	[time]
	$0.02	

$19,623.89	[$ - Tot. Incl. Prod. Loss]
$0.02	[CPU - per Sched. changeover]

FR51 = % of Strategic Level Flexibility Implementation	80%	[%]
FR52 = % Equipment Utilization (current Plane)	100%	[%]

Estimated Operation CPU	$0.95	
Changeover Time [Days]	0.26	[days]
Changeover Capital & loss CPU	$0.02	
Overall CPU	$0.97	

Table 8-4: Cost Report Card – Flex.-Ded. System (C.N.C. w. dedicated adapter).

FR1 = Achievable Production Rate {Achievable}	144	[JPH]
FR2 = Capital Cost	$1,200,000	[$ - USD]
FR31 = Operation Cost: Labor	$0.10	[CPU - USD]
FR32 = Maintenance Materials	$0.10	[CPU - USD]
FR33 = Operation Cost: Utilities	$0.50	[CPU - USD]
FR4 = Change Over Cost & Agility	$31,831	[$ - USD]
	0.26	[time]
	$0.03	

$32,406.86	[$ - Tot. Incl. Prod. Loss]
$0.07	[CPU - per Sched. changeover]

FR51 = % of Strategic Level Flexibility Implementation	80%	[%]
FR52 = % Equipment Utilization (current Plane)	100%	[%]

Estimated Operation CPU	$0.77	
Changeover Time [Days]	0.26	[days]
Changeover Capital & loss CPU	$0.03	
Overall CPU	$0.80	

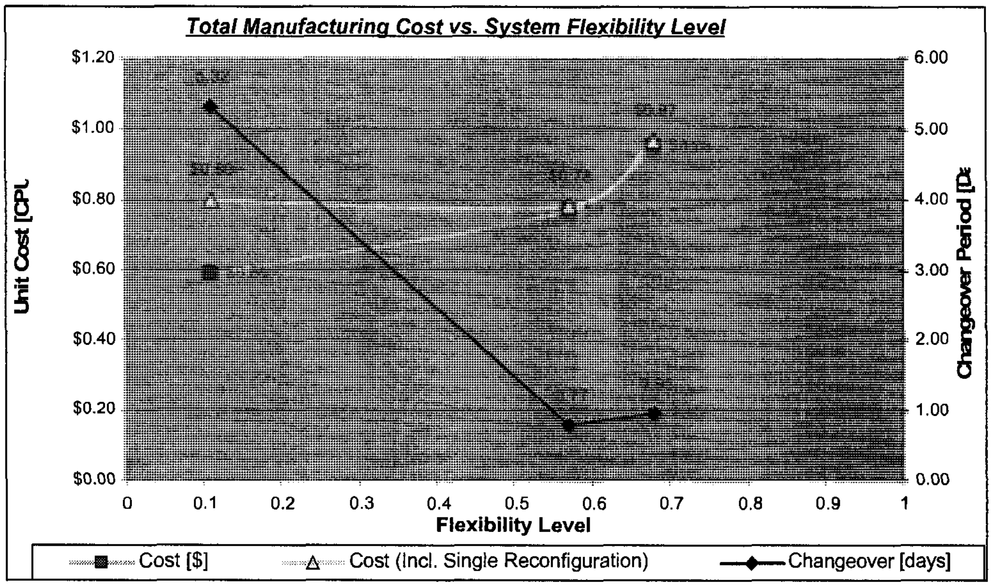


Figure 8-1: Summary of Cost vs. Flexibility Level for Design Options A, B and C

The next consideration for cost is to understand the effects of production volume and product mix on the findings of this thesis. This is to give insight on parameters which make flexible-dedicated design favorable. The first case to be considered is for impact of production volume on cost. The comparison is illustrated in Figure 8-2 and observations are made as follows:

- Dedicated System is minimal cost option in approx. 0.5M to >10M parts per year.
- The Flexible-Dedicated System is most favorable in range of approx. 0.1M to 0.5M parts per year.
- The range for pure Flexible System is below 0.1M parts per year mainly because reduced capital cost investment observed through use of this type of equipment.

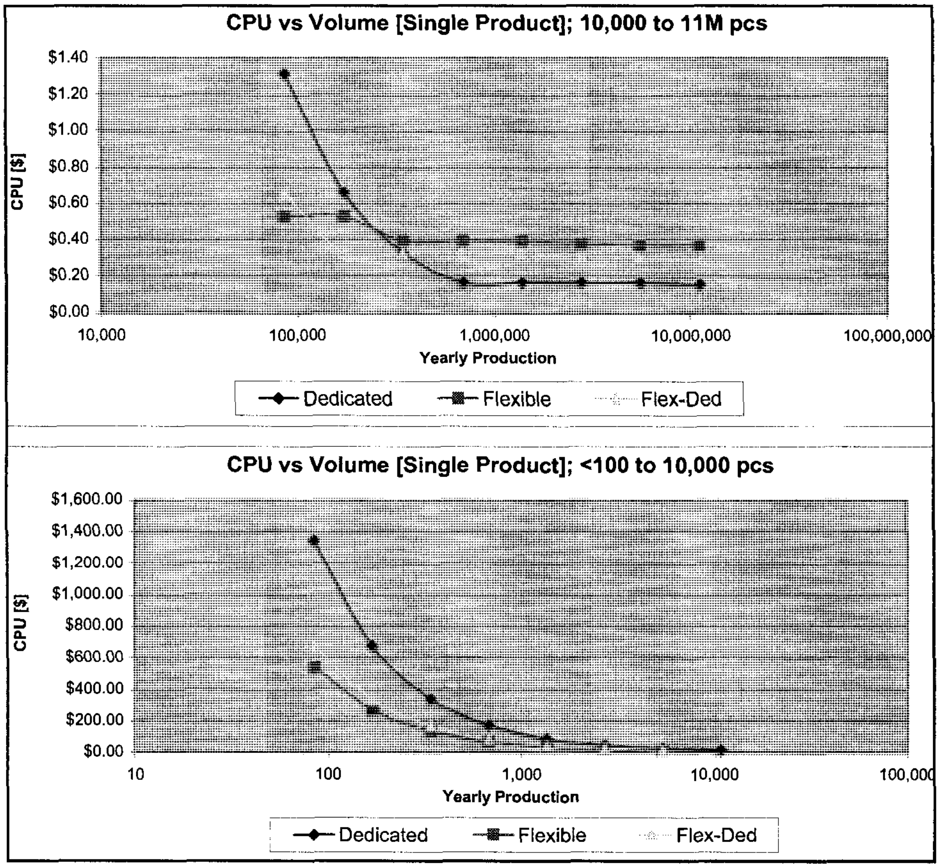


Figure 8-2: Cost vs. Production Volume (Competing Systems, No Reconfiguration).

Figure 8-3 is a plot of cost vs. production volume and product variety. Only inclusive reconfigurable production is assumed. Recall that this option would be the one which has greatest impact on changeover due to unexpected circumstances. Some properties from Figure 8-3 are identified as follows:

- Global minimum cost occurs at high level production, single product with dedicated equipment. Cost then increases sharply with increase in product variety.

- Flexible-Dedicated system is minimum cost for medium level to high production once product variety is increased.
- Low production range is dominated by flexible systems.
- A cost maximum is observed at high production ranges for flexible system.

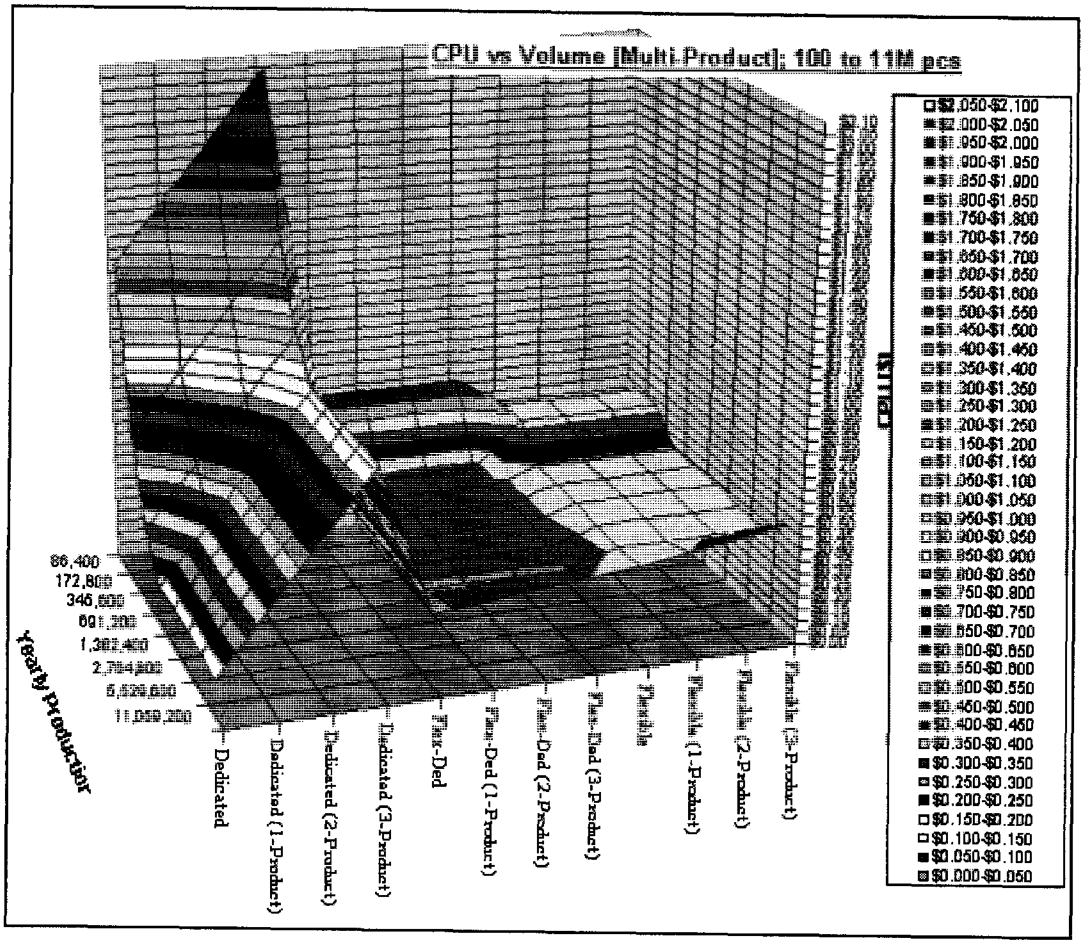


Figure 8-3: Cost vs. Production Volume and Product Variety.

- Incorporate Complexity Analysis into proposed design strategy

Complexity analysis is introduced into the design model of Chapter 5 as a tool for minimization of cost using the Cost-Complexity proportionality relation of Equation 2. This is a choice to be taken by a designer. It is identified as an increase in sensitivity of cost analysis gained by introducing complexity measures into the equations.

A review of literature is done to identify available manufacturing complexity measures based on entropy, and examples are provided to support their use. This is accomplished in Section 4.3 and identified elements are as follows:

- Product Complexity - Section 4.3.1
- System Complexity (System Complexity Code, SCC) - Section 4.3.2
- Process Complexity (effects of process on SCC)- Section 4.3.3
- Operational Complexity (Effort & Human Performance) - Section 4.3.4
- Scheduling Complexity - Section 4.3.5

ElMaraghy, H.A. (2006) provides the System Complexity Code (SCC) as a method to measure process and system-equipment complexities based on Shannon's entropy, s. In comparison, the methodology introduced in Section 4.2 uses Effective Complexity for measuring system-equipment complexities as a measure of knowledge as discussed by Gell-Mann & Lloyd (1996). This is measured as the Algorithm Information Content or Kolmogorov Complexity, $K_U(s)$ (Cover & Thomas, 2006). Gell-Mann & Lloyd (1996) proposed Total Information $\sum$ as the sum of Effective Complexity, e, or knowledge, and Shannon's entropy, s, or ignorance.

Further discussions introduce the combined use of Effective Complexity and System Complexity code to expand the sensitivity of the SCC measurements. This is since Effective Complexity is capable of detecting small changes in complexity. However, this method is cumbersome for large measurements where the SCC can simplify the task.

Figure 8-4 illustrates the results from reviewed cases. Note that in the first section of the figure, (a), details are provided for the crank pin grinder example. Here, a 4-grinder system is modified from a dedicated system with each grinder only able to process a single pin. Thus, all grinders are installed serially until all four pins in the crank are processed. The improved design allows each grinder to process all four pins in the crank, which places the grinders in parallel arrangement. Note the increase in complexity using either the Effective Complexity method or the SCC is similar in trend.

a) Effective Complexity Analysis of Grinder Fixture

		Dedicated Grinder	Redesigned Flexible Grinder		
		[Fixture Only]	[Fixture Only]		
Algorithm Information Content	AIC	128	178	39.06%	Increase
		4-Grinder System	4-Grinder System		
Algorithm Information Content	AIC	363	262	27.82%	Decrease

→ Using System Complexity Code (SCC) results obtained were 6.58 to 9.00 or 36.78% increase for individual grinder.

→ Using System Complexity Code (SCC) results obtained were 6.23 to 4.52 or 27.44% decrease for four-grinder system.

b) Effective Complexity Ratio Detail Analysis Opportunity (Sensitivity)

		Gravity Roller Conveyor [10 Rollers]	Gravity Roller Conveyor [15 Rollers]	Motorized Chain Conveyor [15 Rollers]
Algorithm Information Content	AIC	52	57	285
Effective Complexity Ratio	L_u	1	1.096	5.481

Figure 8-4: Summary of Effective Complexity vs. SCC Measures (Increased Sensitivity).

However, Figure 8-4 (b) illustrates the advantage of the Effective Complexity method. In this example, gravity roller conveyors are increased in length by increasing the number of rollers. Note that this method was able to detect an increase of 9.6% in complexity by increasing from 10 to 15 rollers. This is an important development since such an example plays a key role in the performance of such conveyance systems. Increased length of the system increases the probability of jam-ups.

Figure 8-5 is introduced as evidence to support validity of Equation 2. Statements throughout this thesis emphasize the existence of a cost curve as illustrated in Figure 1-3. A cost maximum is observed at either flexible or dedicated design extremes. This trend must also hold true for complexity measures for Equation 2 to be valid since it represents proportionality between cost and complexity.

Figure 8-5 illustrates an example of system design of various flexibility levels using both the Effective Complexity and SCC methods. Five process cases were studied to produce identical 20 drilled and taped holes. The first system is a Drill + Ream + Tap with three dedicated station installed serially with a multi spindle head. The second option is the same as the first but with the reaming station eliminated.

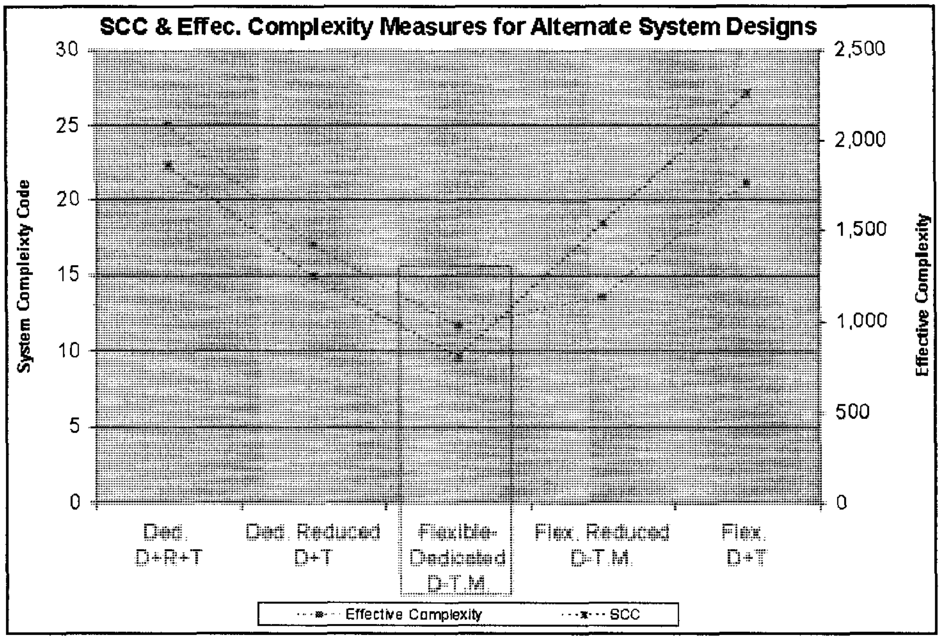


Figure 8-5: Effective Complexity & SCC Result of equipment comparison.

The last two options are both four-axis C.N.C. equipment with single spindle heads with the only difference is the tooling used. Option five (Flexible D + T) uses a drill and tap process (two pass) while option four uses a combination drill & thread mill tool (one pass). The option in the middle of the graph is a flexible-dedicated option where a multi-spindle head, as in dedicated options, is installed on the four-axis machine of flexible option. This is a theoretical application where the tooling used is a drill & thread mill combination tool.

- Investigate behaviour of model after design and implementation

Finally, Section 6.6 looks at the behaviour of the relations which make up the proposed model after equipment runoff rather than from the design perspective. It is stated that cost and complexity performance is directly influenced by invested cost and policies over operating time.

Furthermore, a theoretical relation intercept 'E' of Figure 6-13 is identified as a critical balance between further cost savings from invested cost and operating costs requirements from equipment design. At this point, reduction of invested cost might result in increased cost burden from random system behaviour. Therefore, further cost savings activities have to be supported by process design changes which also reduce system complexity, or increase robustness of the system.

8.1 Future Research Opportunities

1) General Composite Product Model → Study of "Product Families" and model to develop database of product families and interrelations between variants or different products. Develop Composite Product Models and identify 'general characteristics' critical to reconfiguration variables.

2) Effective Complexity & Equipment/System Complexity Codes (E/SCC) → Comprehensive research equipment currently in use in industry with intent of maturing Effective Complexity approach and its conjunction to System Complexity Code. Develop tables/equations of complexity values for common equipment types. Expand on Equation 2 and develop an understanding of complexity and system performance and stability.

3) Improve Axiomatic Design Analysis of Total Manufacturing Cost → Review of equipment in use in industry for details on mechanics of cost. Relate this to System Design Level (Flexibility Level) and Complexity measures. Improve sensitivity of Figure 8-1, Figure 8-2 and Figure 8-3 and further test the behaviour proposed by Figure 6-13.

4) Roadmap to equipment Design → Use knowledge from (1), (2), and (3) along side theory proposed in this thesis to develop a roadmap for equipment design.

Chapter 9 CONCLUSIONS

The most important accomplishment of this research is the identification of a flexible-dedicated design which can lead to significant cost savings and strategic gains for the manufacturing firm. This if flexible manufacturing systems is implemented according to guidelines provided in Section 9.1. Importance of this statement impacts many levels of the design task.

Identification of this type of design is permissible only by assigning manufacturing system design with a continuous scale of flexibility level as proposed in this thesis. That is, flexibility level is a characteristic of system design. This is the basic foundation block which coupled with some performance metrics form the design model of Figure 5-1.

The enclosed argument raises the bar for flexible manufacturing system design for both the overall cost performance and the strategic value brought by its implementation. An advanced design is achieved which encompasses only favorable characteristics of flexible design while avoiding increased cost typical with this type of systems. Utilization strategies are such that flexible systems are expected to be available to produce as necessary rather than requiring changeover.

The picture to be painted is for a manufacturing firm which produces variants of a product family and uses flexible manufacturing equipment technology. However, the new description as presented in this thesis has critical characteristics imposed in part through 'guidelines for flexibility implementation' of Section 9.1. This system in general is flexible in the sense that it can produce any variant of the product family without burden. This is critically important for products of opposing demands.

Capacity is achieved with utilization of twin-cell factories capable of flexible manufacturing operation as previously stated. Then, production schedules can be driven by consumer sales for only those products which are required. Idling of factories or non-ideal schedule operation can be avoided since capacity is shared across multiple product demands. Forced or discount sales can also be avoided. This also implies product introduction is done without elimination of previous products; this minimizes risk.

9.1 Guidelines for Flexibility Implementation

Thus, for a manufacturing system design with the intent of maximizing flexibility effectiveness, the guidelines for implementation of Manufacturing System Flexibility based on proposed model are as follows:

1. ***Product Side:*** The starting point is the strategic level of the firm. Define "Product Family" or "Product Range" (It should be inline with current plans and future possible developments or market trends).

   Incorporate "Opposing-demands product" strategy (Section 3.3) and establish requirements for achieving "Comprehensive" design. Develop a "Composite Product Model" as a roadmap to process all products in the product family. Finally, assign applicable "General_Characteristics" and establish requirements for system agility.

2. ***System Side:*** Achieve description for a system "Industry Application" or "Idealized Manufacturing System" that is comprehensive for the product family (from Guideline 1). Identify all "root characteristics". That is,
   (1) Select design alternatives of real systems,
   (2) Measure "Flexibility Level", "Cost Performance" and "Improved Cost Analysis with Complexity" of system alternatives (generate model),
   (3) Use the iterative process proposed in Figure 5-4 and Section 5.2 to eliminate or improve design options and pursue "Product Plane Unity" for key work-planes, and
   (4) Manage flexible-dedicated tradeoff through "Probability of Reconfiguration".

3. ***Flexibility Utilization:*** The minimum cost and successful implementation will have met the following properties:
   - *Strategic Level of Manufacturing Flexibility Implementation* – Ensure the use of acquired flexibility (use flexibility).
   - *Achieve Synchronous Production* for all products in system range (use flexibility correctly).
   - Twin-Cell design at strategic level – Use flexibility in synchronous fashion through share capacity across all available products and production facilities (use flexibility correctly and with scope).

REFERENCES

Accel-Team.com (©2005); "What is productivity?"; Retrieved August 20, 2006; from http://www.accel-team.com/productivity/productivity_01_what.html

Aksin O.Z., Karaesmen F.; "Characterizing the performance of process flexibility structures"; Operations Research Letters; 35 (2007) 477 – 484

Akturk M. S., Yayla H. M.; "Management of product variety in cellular manufacturing systems"; Int J Flex Manuf Syst; 17(2006): 93–117

Aldaihani M.M., Savsar M.; "A stochastic model for the analysis of a two-machine flexible manufacturing cell" Computers & Industrial Engineering; 49 (2005) 600–610

Barlow E. R., Proschan F.; "Statistical Theory of Reliability and Life Testing Probability Models"; Holt, Rinehart and Winston, Inc.; 1975

Bourbaki N.; "Elements of Mathematics: Theory of sets", © Springer-Verlag Berlin Heidelberg; 2004

Boyer K. K., Leong K. G.; "Manufacturing Flexibility at the Plant Level"; Int. J. Mgmt. Sci.; Vol. 24, No. 5, pp. 495-510 (1996)

Boyle T.A.; "Towards best management practices for implementing manufacturing flexibility"; Journal of Manufacturing Technology Management; Vol. 17 No. 1, 2006; pp. 6-21.

Shannon E. C.; "The mathematical theory of communication"; The University of Illinois press, Urbana;

Cover T.M., Thomas J.A.; "Elements of Information Theory", Hoboken, N.J.: J.Wiley, 2006

Du J., Jiao Y.-Y., Jiao J.; "A real-option approach to flexibility planning in reconfigurable manufacturing Systems"; Int J Adv Manuf Technol (2006) 28: 1202–1210

EDRIVE ACTUATORS®; "Eliminator HD™; Retrieved: Feb. 22nd, 2007; from http://www.edriveactuators.com/catalogs/eliminator_web.pdf

ElMaraghy H.A., Kuzgunkaya O., Urbanic R.J.; "Manufacturing System Configuration Complexity"; CIRP Annals, v.54/1, pp. 445-450; 2005

ElMaraghy H.A; "A Complexity Code for Manufacturing Systems"; Proceeding of MSEC2006-21075 Oct 8-11, 2006, Ypsilanti, MI; 2006

ElMaraghy W.H., R.J.Urbanic; "Assessment of Manufacturing Operational Complexity"; CIRP Annals; v.53/1, pp. 401-406; 2004

ElMaraghy W.H., Urbanic R.J.; "Modeling of Manufacturing Systems Complexity"; CIRP Annals; v.53/1, pp. 363-366; 2003

Evans J. L., Zhang D., Vogt N., Thompson J. R.; "INVESTMENT ANALYSIS FOR AUTOMOTIVE ELECTRONICS MANUFACTURING: A CASE STUDY"; The Engineering Economist; 49:159–183

Fraser N.M., Bernhardt I., Jewkes E.M., Tajima M.; "Engineering Economics in Canada Second Edition"; Prentice-Hall, Inc; 2000

Freiheit T., Wang W., Spicer P.; "A case study in productivity-cost trade-off in the design of paced parallel production systems"; International Journal of Production Research; Vol. 45, No. 14 (2007) 3263–3288

Gell-Mann M., Lloyd S.; "Information Measures, Effective Complexity, and Total Information"; Complexity; © John Wiley & Sons, Inc; 1996

Groote X.; "The flexibility of production process: a general framework". Manage Sci 40 (1994) 7: 933–945

Groover M.P.; "Automation, Production Systems, and Computer-Integrated Manufacturing Second Edition"; Prentice-Hall, Inc; 2001

Hennie F.; "Introduction to Computability"; Addison-Wesley Pub. Co.; 1977

http://209.202.75.197/digi/sar/; "Boring ninety-six holes simultaneously with a Foortburt boring machine, 1946 Courtesy of Windsor Star, P8945"; Retrieved: 3/25/2006; http://209.202.75.197/digi/sar/images/part3/fordmanufacturing.jpg

http://209.202.75.197/digi/sar/; "Machining boring cases for automobile engines at General Motors, 1937, Courtesy of Windsor Star, P8946[10]"; Retrieved: 3 25 2006; http://209.202.75.197/digi/sar/images/part3/fordmanufacturing.jpg

http://209.202.75.197/digi/sar/; "Manufacturing in Ford of Canada plant, 1915 Collection of Windsor's Community Museum, P8423[1]"; Retrieved: 3 25 2006; http://209.202.75.197/digi/sar/images/part3/fordmanufacturing.jpg

Lorincz J.; "MULTITASKING MACHINING"; Manufacturing Engineering; Feb 2006; 136, 2 pg. 45; ABI/INFORM Global

Jordan W.C., Graves S.C.; "Principles on the benefits of manufacturing process flexibility"; Management Sci; 41 (4):577–594 (1995)

Katz R.; "Design principles of reconfigurable machines"; Int J Adv Manuf Technol (2007) 34: 430–439

Koste L.L., Malhorta M.K.; "A theoretical framework for analyzing the dimensions of manufacturing flexibility", Journal of Operations Management, 18, pp 75-93;1999.

Kurtoglu A.; "Flexibility analysis of two assembly lines"; Robotics and Computer-Integrated Manufacturing; 20 (2004) 247–253

Landauer T. K. and Nachbar D. W., "Selection from Alphabetic and Numeric Menu Trees Using A Touch Screen: Breadth, Depth, and Width", Bell Communications Research Morristown, N.J., CHI '85 PROCEEDINGS APRIL 1985

Lau Y.K. Henry, Mak K.L.; "The design of flexible manufacturing systems using an extended unified framework"; Journal of Manufacturing Technology Management; Vol. 15 Num 3; (2004); pp.222-238

LEXICON, "The New Lexicon Webster's Dictionary of the English Language", Lexicon Publication Inc, 1988 Edition

LiCON MT L.P.; "Flexible Rotary Transfer Machining: Shortens cycle time, produces quality parts, cost-savings"; Tooling and Production; April 2005

Matsura Machinery; Retrieved: 3 25 2006; http://www.matsuura.co.uk/news?action=view&newsID=41

Palmer R. J., Davis H. H.; "Cost accounting for rational FCIM investment analysis"; Journal of Manufacturing Technology Management; Vol. 16 No. 3 (2005) pp. 254-264

Phukan A., Kalava M., Prabhu V.; "Complexity metrics for manufacturing control architectures based on software and information flow"; Computers & Industrial Engineering; 49 (2005) 1–20

Shou Ming Industrial Co. Ltd.; "Multi-Spindle Adapters"; Retrieved *February 22, 2007,* http://www.multi-shaft.com.tw/com.htm

Spicer P., Carlo H.J.; "Integrating Reconfiguration Cost Into the Design of Multi-Period Scalable Reconfigurable Manufacturing Systems"; Transactions of the ASME; Vol. 129 pp 202-210; 2007.

Suh E.S., de Weck O., Kim Y. II, Chang D.; Flexible platform component design under uncertainty"; J Intell Manuf (2007) 18:115–126

Suh, N.P.; "A Theory of Complexity, Periodicity and the Design Axioms"; Research in Engineering Design; v.11, p.116-131; 1999

Suh, N.P.; "Axiomatic Design: Advances and Applications"; Oxford University Press; 2001

Suh, N.P.; "Complexity: Theory and Applications"; Oxford University Press; 2005

Turkcan A, M. Akturk M.S, Storer R.H.; "Due date and cost-based FMS loading, scheduling and tool management"; International Journal of Production Research; Vol. 45, No. 5 (2007) 1183–1213

Urbanic J.; "A system analysis and design approach for modeling of participatory manufacturing systems"; Masters Thesis; University of Windsor; 2002

Van Biesebroeck J.; "The cost of flexibility"; Assembly Automation; 27/1 (2007) 55–64

Webzell S.; "Multi-Spindle technology speaks volumes"; MWP 149 no4; Apr 2005; Copyright 1982-2005 The H.W. Wilson Company.

Webzell, S.; "Two heads are better than one"; MWP pp. 31-32; Feb 2005; Copyright 1982-2005 The H.W. Wilson Company.

Wikipedia.com; "Fitt's Law"; Retrieved April 14, 2007; from http://en.wikipedia.org/wiki/Fitts%27_law

Wikipedia.com; "Flexible Manufacturing System"; Retrieved: Oct 20th, 2007; from Website: http://en.wikipedia.org/wiki/Flexible_manufacturing_system

Wikipedia.com; "Hick's Law"; Retrieved April 14, 2007, from http://en.wikipedia.org/wiki/Hick%27s_law

APPENDIX A: Proofs (Manufacturing Flexibility Model)

a) Manufacturing Flexibility vs. Cost

'A *flexible manufacturing system (FMS)* is a manufacturing system in which there is some amount of flexibility that allows the system to react in the case of changes, whether predicted or unpredicted. This flexibility is generally considered to fall into two categories, which both contain numerous subcategories.' The first is *machine flexibility* and the second is called *routing flexibility*. (www.wikipedia.org, search: "flexible manufacturing system", Oct 20th, 2007)

Flexibility is n. the quality of being flexible. (Lexicon, 1988)
Flexible adj. easily bent, not rigid … || pliable … || adaptable, capable of being modified, a flexible plan || responsive to changing conditions, a flexible mind || … (Lexicon, 1988)

b) Manufacturing Behaviour: Cost-Complexity Proportionality

→ *Ensemble* is 'n. a thing looked at or judged as a whole or from the point of view of the general effect || …' (Lexicon, 1988).
→ *Ensemble* is 'a group of separate things that contribute to a coordinated whole. Adv, Adj. together. (Math.) A set.' (www.wiktionary.org, search: "ensemble", Oct 20th, 2007)
→ *Ensemble* (also statistical ensemble or thermodynamic ensemble) is an idealization consisting of a large number of mental copies (sometimes infinitely many) of a system, considered all at once, each of which represents a possible state that the real system might be in. (www.wikipedia.org, search: "ensemble", Oct 20th, 2007)

→ *Performance* is 'the act of performing; carrying into execution or action; execution; achievement; accomplishment; representation by action; as, the performance of an undertaking of a duty'. (www.wiktionary.org, search: "performance", Oct 20th, 2007)
→ *Performance* is 'what is accomplished, contrasted with capability' (Lexicon, 1988).

APPENDIX B: Proofs (Flexibility Scale)

Step 1

→ *Family* is a group of people, or a number of domestic groups linked through descent (www.wikipedia.org, search: "family", Sept 30th, 2007)

→ *Product*, in business, is a good economics and accounting which can be bought or sold. In marketing, is anything that can be offered to a market that might satisfy a want or need? In manufacturing, products are purchased as raw materials and sold as goods. (www.wikipedia.org, search: "family", Sept 30th, 2007)

Product - n. something produced, esp. something grown or manufactured || an outcome,

→ *Product Line* is a "group of products that are closely related, either because they function in similar manner, are sold to make customer groups, …" (www.wikipedia.org, search: "family", Sept 30th, 2007)

→ *Use* is the act, state or custom of using or being used || the power to use || usefulness || the right, permission or name || the opportunity to use || function, the purpose for which something is used || … (Lexicon, 1988).

→ *Purpose* … to have as intention … (Lexicon, 1988)

→ *Function* … a characteristic activity or the activity for which something exist, to fulfill a function … (Lexicon, 1988)

→ *Property* is an attribute, characteristic || (logic) an attribute common to a whole class but not necessary to distinguish it from others || …(Lexicon, 1988)

Step 2

→ ***Decision*** is a making of one's mind || the result of making one's mind || ... (Lexicon, 1988).

→ An object is a ***decision*** if obtained by a conscious choice of only one opinion or one action (from a known set called alternatives), and it is designated for an application. (www.wikipedia.org, search: "decision", Oct 11th, 2007)

→ ***Comparison*** is 'a comparing, an attempt to discover what is like and unlike || a resemblance shown for the sake of explanation || the change in form of adjectives and adverbs to show difference of degree (Lexicon, 1988)'.

→ ***Relative*** is 'adj. of something (a quantity, quality, truth, idea, etc.) considered in reference to something else || comparative not absolute || …' (Lexicon, 1988).

Step 3

→ ***Root*** is '…a fundamental or essential part || the original cause of something || …' (Lexicon, 1988).

→ ***Characteristic*** is 'a quality typical of a person, place or object …' (Lexicon, 1988). It is a distinguishable feature of a person or thing. (www. wiktionary.org, Search: "characteristic", Oct 13, 2007)

→ ***Manufacturing System*** is an assembly of all functional objects, system, and characteristics which make manufacturing activity possible. For example,

APPENDIX C: Proofs (Product Flexibility)

→ A ***Model (abstract);*** 'An abstract model (or conceptual model) is a theoretical construct that represents something, with a set of variables and a set of logical and quantitative relationships between them'. (www.wikipedia.org, search: "model", Oct 17th, 2007)

→ ***A Model (physical);*** 'A physical model is used in various contexts to mean a physical representation of some thing. That thing may be a single item or object…' 'Physical models in science and technology allow us to simulate or visualize something about the thing it represents.' (www.wikipedia.org, search: "model", Oct 17th, 2007)

→ A ***Model*** is 'n. 3-D representation, usually in miniature, of a thing to be constructed, sculptured, etc. or of an object already exists || a design intended for mass production || a person of thing considered as an object for imitation || … || (economics) a mathematical representation of the facts, factors, and inferences of an entity or situation || …' (Lexicon, 1988).

→ ***Composite*** is 'adj. made up of parts, each of which is itself a hole or taken from another whole || … || (math) of a number divisible by some number other than 1 without a remainder (cf. prime number) || …' (Lexicon, 1988).

→ ***Composite*** relates to 'Made up of multiple components; compound or complex; a mixture of different components.' (www.wiktionary.org, search: "composite", Oct 17th, 2007)

→ ***General*** is 'adj. pertaining to a whole or to most of its parts, not particular, not local … || prevalent, widespread …' (Lexicon, 1988).

APPENDIX D: Cost Function Discussions

a) FR1 = Target JPH

Availability is defined as (Barlow, *et al.*, 1975, pp.190):

$$A(t) = \overline{F}(t) + \int_0^t \overline{F}(t-u)\, dM_H(u)$$

M_H = Renewal function corresponding to underlying distribution H

F = Common distribution of T_i

H = Common distribution of $T_i + D_i$

T_i = duration of i^{th} functioning period

D_i = downtime for i^{th} repair or replacement

And limiting availability for non-lattice, or non-periodic, distribution with mean μ, which depends only on mean time to failure and mean time to replace, then

$$A_{limiting} = {}^{\lim} \, \text{e} = \frac{ET}{ET + ED}$$

ET = Mean Time to Failure

ED = Mean Time to Repair

Barlow (*et al.*, 1975, pp. 192) present two alternative disciplines for system availability for component failure and repair.

I) System Availability: Independent Component Performance Processes (Barlow, et al., 1975, pp. 192).

In this initial model the components of a system behave in a parallel manner where, when one component is down for repair and replacement, the remaining ones continue to operate. Therefore, the availability A(*t*) of the system at time *t* is given by

$$A(t) = h(A_1(t), \ldots, A_n(t))$$

Where,

h = reliability function of structure f.

And,

→ Limiting availability is given by $A = h(A_1, \ldots, A_n)$

Assuming limiting availability exists, and distribution of $T_{i1} + D_{i1}$ is non lattice for i = 1…n, then

$$A = h\left(\frac{\mu_1}{\mu_1 + v_1}, \ldots, \frac{\mu_n}{\mu_n + v_n}\right)$$

Where,

μ = component mean life

v = component mean time for repair-replacement

II) Series System Availability: Functioning Components Suspend Operation during repair (Barlow, et al., 1975).

In this second model the system is assumed in series so system failure corresponds with component failure. This is better fitted for modeling of an individual station made up of many components of different reliabilities in which any one could cause breakdown of the unit

The subsequent assumptions are that, while the component is undergoing replacement, all other components are not operational. All components resume functioning once the repair is complete. At this time, all components though not new are as good as before the failure. Furthermore, it is also assumed that no two or more components fail at the same time as is true for continuous failure distributions.

This method will almost surely obtain convergence of fractional downtime for each component. Mean Time to Failure (MTTF) for component or system will depend on mean life length, μ_i and replacement period, v'. Then, the limiting average system availability A_{av}[11] is (if the average availability exists):

$$A_{av} = A = \lim_{t\to 8} \frac{EU(t)}{t} = \left(1 + \sum_{j=1}^{n} \frac{v_i}{\mu_i}\right)^{-1}$$

Similarly, the total downtime $D_i(t)$ resulting from failures in component position *i* during [0,*t*] is :

$$D_{av} = A_{av} \sum_{j=1}^{n} \frac{v_i}{\mu_i}$$

And, number of failures $\tilde{N}_i(t)$ in component position *i* during [0, *t*]

$$\lim_{t\to 8} \frac{E\tilde{N}(t)}{t} = \frac{A_{av}}{\mu_i}$$

From Barlow (*et al.*, 1975), the average length of the system functioning periods during [0, t] will converge to a limit, μ. The average length of all replacement periods (system downtimes) during [0, t] will converge to a limit, v. Therefore,

(a) The average of system uptimes converges to:

$$\mu = (\textstyle\sum_1^n (1/\mu_i))^{-1}$$

(b) The average of system down times converges to:

$$v = \mu \textstyle\sum_{i=1}^{n} v_i/\mu_i$$

And, for a one-unit system with a mean life of μ and a mean repair time of v, the limiting average availability is μ/ (μ + v). Then, for the present series system model the limiting average system availability is,

$$A_{av} = \frac{\mu}{\mu + v}$$

Where,

μ and v are defined by (a) and (b) above for system averages from components.

---

[11] Limiting average system availability is a function only of component mean life length and replacement periods, and does not require knowledge of the actual life and repair distributions (Barlow, *et al.*, 1975) pp. 197.

APPENDIX E: Equipment Details

EDRIVE ACTUATORS® (2007) gives details of some typical linear actuator motors. Here we find the life of these in units of inches traveled before failure. For the sake of simplicity it will be assumed the slide has 1.5 times the life as the linear motor. We assume some stipulations for range for product size as a maximum block to be considered in design can be contained in a work volume of a = 480mm x b=480mm x c=600mm. We also assume the work piece will sit either on its bottom or end face. Therefore, the C.N.C. spindle must have a minimum travel of 600mm on both horizontal and vertical axes (850mm max allowed). Furthermore, the C.N.C. spindle is allowed to travel a max of 400mm in its feed axis, and the transfer line is allowed 1200mm to allow access for tool change and maintenance.

It is also assumed that the operating max load for the transfer system is between 6,000-7,000 lbs and the same for the C.N.C. system is 10,500-12,000 lbs. The increase is mainly because of higher speeds and accelerations required for fast operation of the C.N.C. spindle. Then, we obtained the desired life expectancy for the axial drives from EDRIVE ACTUATORS® (2007) – See Figure A-1.

Therefore, the life range for the axial drives is:

- C.N.C. Axis → 50-80 [million inches]; slide → 75-120 [million inches]
- Transfer Axis → 20-50 [million inches]; slide → 30-75 [million inches]

From an analysis such as Table 7-1 we can estimate the number of inches of travel per cycle, or part produced; thus, effectively determining life in cycles.

Then for a C.N.C. machine,

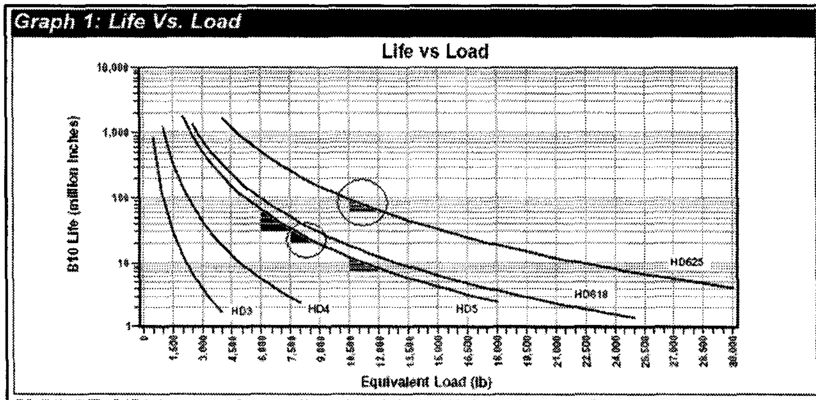
Ver-Axis → Operates 2,084 mm/cycle which corresponds to 792,103 cycles between failures. This contributes 5.70 sec/cycle (@ 14.40 in/sec).
Hor-Axis → Operates 1,824 mm/cycle which corresponds to 905,166 cycles between failures. This contributes 5.99 sec/cycle (@ 14.40 in/sec).
Feed-Axis → Operates 1,510 mm/cycle which corresponds to 1,093,377 cycles between failures. This contributes 185.46 sec/cycle (@ 10.67 in/sec). Note: we can choose to double the feed to reduce cycle time to 93.66 sec/cycle (@ 21.34 in/sec).

Total Cycle for C.N.C. after including two 10 second tool changes and 15 seconds for a part exchange = 231.55 sec, or <u>140.35 sec,</u> if feed is doubled. One would need seven (6.3) machines under this setup to match the production as one dedicated station.

For Transfer System,

Feed-Axis → Operates 1.93" per cycle which corresponds to 7,772,020 cycles between failure. This contributes to 13.3 sec (@ 10.67 in/min) for cutting time and 9 seconds for part exchange. <u>Total Cycle = 22.3 sec</u>.

Therefore we need 6.3 C.N.C. machines to equal a design cycle as compared to a Transfer System.



EQUIVALENT LOAD is the average force over the working stroke, weighted proportionately to the distance traveled. For constant force loads, the equivalent load is the same as the typical or average load. Where forces vary due to gravity, angle of actuator, acceleration and deceleration, friction, and changing dynamic loads at different positions, it is best to determine the equivalent load in order to most accurately predict the B10 life of the actuator.

$$F = \sqrt[3]{\frac{L_1(F_1)^3 + L_2(F_2)^3 + L_3(F_3)^3 + L_4(F_4)^3 + \ldots\ldots L_n(F_n)^3}{L}}$$

Capabilities

Model Number	Thrust Load Rated (lbf)	Thrust Load Max. (lbf)	Linear Velocity Max. (in/s)	Travel Length(1) Max. (in)	Frame Size (in)	Lead(2) (mm)	Ball Screw Diameter (mm)	Ball Screw Speed Max. (RPM)	Torque @ Ball Screw Max. (in-lb)	Dynamic Capacity per million revs (lbf)	Dynamic Capacity per million inches (lbf)	Motor/(3) Gearhead Frame Supported Max. (in)	Unit Weight "U" Motor Mount (lb)	Unit Weight "L" Motor Mount (lb)	
HD406-06	6,000	12,000	18.0	6	4	10	32	2,750	417	14,580	10,690	5.75	76	62	
HD406-12	6,000	12,000	18.0	12	4	10	32	2,750	417	14,580	10,690	5.75	89	75	
HD406-18	6,000	12,000	18.0	18	4	10	32	2,750	417	14,580	10,690	5.75	103	89	
HD406-24	6,000	12,000	18.0	24	4	10	32	2,750	417	14,580	10,690	5.75	116	102	
HD406-30	6,000	12,000	18.0	30	4	10	32	2,750	417	14,580	10,690	5.75	130	116	
HD406-36	6,000	12,000	18.0	36	4	10	32	2,750	417	14,580	10,690	5.75	143	129	
HD406-42	6,000	12,000	18.0	42	4	10	32	2,750	417	14,580	10,690	5.75	157	143	
HD508-06	8,000	15,000	14.0	6	5	12	50	1,780	668	31,250	24,340	8	175	125	
HD508-12	8,000	15,000	14.0	12	5	12	50	1,780	668	31,250	24,340	8	195	145	
HD508-18	8,000	15,000	14.0	18	5	12	50	1,780	668	31,250	24,340	8	216	166	
HD508-24	8,000	15,000	14.0	24	5	12	50	1,780	668	31,250	24,340	8	236	186	
HD508-30	8,000	15,000	14.0	30	5	12	50	1,780	668	31,250	24,340	8	257	207	
HD508-36	8,000	15,000	14.0	36	5	12	50	1,780	668	31,250	24,340	8	277	227	
HD508-42	8,000	15,000	14.0	42	5	12	50	1,780	668	31,250	24,340	8	298	248	
HD508-48	8,000	15,000	14.0	48	5	12	50	1,780	668	31,250	24,340	8	318	268	Transfer Feed Axis
HD516-06	16,000	30,000	14.0	6	5	12	50	1,780	1,337	31,250	24,340	8	175	125	
HD516-12	16,000	30,000	14.0	12	5	12	50	1,780	1,337	31,250	24,340	8	195	145	
HD516-18	16,000	30,000	14.0	18	5	12	50	1,780	1,337	31,250	24,340	8	216	166	CNC Feed Axis
HD516-24	16,000	30,000	14.0	24	5	12	50	1,780	1,337	31,250	24,340	8	236	186	
HD516-30	16,000	30,000	14.0	30	5	12	50	1,780	1,337	31,250	24,340	8	257	207	
HD516-36	16,000	30,000	14.0	36	5	12	50	1,780	1,337	31,250	24,340	8	277	227	CNC Hor & Ver-Axis
HD516-42	16,000	30,000	14.0	42	5	12	50	1,780	1,337	31,250	24,340	8	298	248	
HD516-48	16,000	30,000	14.0	48	5	12	50	1,780	1,337	31,250	24,340	8	318	268	
HD618-06	18,000	30,000	9.8	6	6	12	63	1,450	1,500	35,750	27,840	8	240	185	
HD618-12	18,000	30,000	9.8	12	6	12	63	1,450	1,500	35,750	27,840	8	273	218	
HD618-18	18,000	30,000	9.8	18	6	12	63	1,450	1,500	35,750	27,840	8	306	251	
HD618-24	18,000	30,000	9.8	24	6	12	63	1,450	1,500	35,750	27,840	8	339	284	
HD618-30	18,000	30,000	9.8	30	6	12	63	1,450	1,500	35,750	27,840	8	372	317	
HD618-36	18,000	30,000	9.8	36	6	12	63	1,450	1,500	35,750	27,840	8	405	350	
HD618-42	18,000	30,000	9.8	42	6	12	63	1,450	1,500	35,750	27,840	8	438	383	
HD618-48	18,000	30,000	9.8	48	6	12	63	1,450	1,500	35,750	27,840	8	471	416	
HD625-06	25,000	40,000	14.4	6	6	20	80	1,100	3,481	52,150	48,160	8	247	191	
HD625-12	25,000	40,000	14.4	12	6	20	80	1,100	3,481	52,150	48,160	8	280	224	
HD625-18	25,000	40,000	14.4	18	6	20	80	1,100	3,481	52,150	48,160	8	313	257	CNC Feed Axis
HD625-24	25,000	40,000	14.4	24	6	20	80	1,100	3,481	52,150	48,160	8	346	290	
HD625-30	25,000	40,000	14.4	30	6	20	80	1,100	3,481	52,150	48,160	8	379	323	
HD625-36	25,000	40,000	14.4	36	6	20	80	1,100	3,481	52,150	48,160	8	412	356	CNC Hor & Ver-Axis
HD625-42	25,000	40,000	14.4	42	6	20	80	1,100	3,481	52,150	48,160	8	445	389	
HD625-48	25,000	40,000	14.4	48	6	20	80	1,100	3,481	52,150	48,160	8	478	422	

Figure E-1: Axial Drive Life Calculation.

And finally for the semi-dedicated system as shown in Figure 7-4,

Ver-Axis → Operates 2,343 mm/cycle which corresponds to 704,683 cycles between failures. This contributes 6.41 sec/cycle (@ 14.40 in/sec).

Hor-Axis → Operates 1,824 mm/cycle which corresponds to 905,166 cycles between failures. This contributes 5.99 sec/cycle (@ 14.40 in/sec).

Feed-Axis → Operates 818 mm/cycle which corresponds to 2,018,633 cycles between failures. This contributes 30.55 sec/cycle (@ 21.34 in/sec).

Total Cycle for CNC after including three 10 second and tool changes and 15 seconds for part exchange = 88.55 sec. One would need four machines under this setup to match the production of one dedicated station.

Similar methodology is applicable for spindle bearings (spindle packs), fixture components, and all the other elements which make up a station.

Table F-1: Cost calculation of "Dedicated System".

Process Step Evaluation WorkSheet

a) Report Card - Dedicated System

FR1 = Achievable Production Rate {Achievable}	156	[JPH]
FR2 = Capital Cost	$600,000	[$ - USD]
FR31 = Operation Cost: Labor	$0.02	[CPU - USD]
FR32 = Maintenance Materials	$0.06	[CPU - USD]
FR33 = Operation Cost: Utilities	$0.25	[CPU - USD]
FR4 = Change Over Cost & Agility (Losses included in $)	$253,531	[$ - USD]
	5.32	[time - days]
	$0.25	[CPU]

$253,530.55	[$ - Tot. Incl. Prod. Loss]
$0.26	[CPU - per Sched. changeover]

FR51 = % of Strategic Level Flexibility Implementation	20%	[%]
FR52 = % Equipment Utilization (current Plane)	50%	[%]

Estimated Operation CPU	$0.59	
Changeover Time [Days]	5.32	[days]
Changeover Capital & loss CPU	$0.25	
Overrall CPU	$0.84	

Oeperational Policies

i =	5%	0.4167%
N =	60	[months]
(A/P, *i*, N) =	0.018871	
A =	$11,322.74	

T =	20 [hrs /day]
U =	5 [days/week]
V =	4 [week/month]

b) Work Sheet - Dedicated System

FR1 = TARGET PRODUCTION RATE [JPH]

DP12 = No of Parallel Machines in Cell — 1

DP111 = Station Cycle by design {JPH} — 161

Station Cycle — 22.3 sec

DP11211 = Tool Life {frequency of tool changes}

Tool A - MBC Drill	[cycles]	5,000
Tool B - Oil Pan Drill	[cycles]	5,000

DP11212 = Cycle to change a tool

*** Number of tools changed

Tool A - MBC Drill		10
Tool B - Oil Pan Drill		10
Tool A - MBC Drill	[min, ea]	2
Tool B - Oil Pan Drill	[min, ea]	2

FR11221 = Unsched. Prod. Loss - Availabiltiy — 0.9793

(for i components of the system station)

		MTTF [cycles]	MTFR [min]	Qty
Axis [feed axis]	Axis Drive	7,772,020	1440	1
	Slide System	11,658,030	4320	1
Spindles	Spindle pack/bearings	2,706,767	120	20
	Spindle head (Gears Box)	5,413,534	7200	1
	Motor	4,060,151	420	1
Fixtrues	Trasfer bar sytem	1,200,000	1440	1
	Pads & Locator	100,000	120	1
	Clamping system	1,200,000	2880	1

Assume (Series System for components of station):

Axis — Spindles — Fixtures

FR11222 = Unsched. Prod. Loss - Scheduling — 0

Combinatorial Complexity Measure — 0

FR111 = Favorable Production Rate [JPH]	161.435
FR1121 = Sched. Prod. Loss [JPH]	1.29147982
FR1122 = Unsched. Prod. Loss [JPH]	3.3341
FR11 = Station Production Rate [JPH]	156
FR1 = Target Production Rate {Achievable} [JPH]	156

FR2 = CAPITAL COST

DP212 = Cost of Individual Prod. Equip. station	$500,000	FR21 = Cost for Production Equipment	$500,000
DP12 = No of Parallel Machines in Cell	1		
DP222 = Cost Mt'l Handling	$100,000.00	FR22 = Cost for Mt'l Handling Equipment	$100,000
DP221 = # of mat'l handling units required	1		
DP12 = No of Parallel Machines in Cell	1		
DP11222 = Combinatorial Complexity	0		

FR2 = Capital Cost [$]: $600,000

FR31 = OPERATION COST : LABOR [Cost per part produced]

DP312 = Labor cost per hr	Supervision Trades Hourly	$30.00
FR31121 = Operators [hrs]		
DP31121 = hrs of Schedule Activity		
DP11211 = Tool Life (frequency of tool changes)		
DP11212 = Cycle to change a tool		
FR31122 = Tool Management [hrs]		
DP31122 = Tool Reconditioning Effort [hrs]		
DP11211 = Tool Life (frequency of tool changes)		
FR31123 = Mtce Trades [hrs]		$0.00
DP31123 = Avg Number of trades req'd per repair		2
DP11221 = Cell Availability		0.9793
FR3111 = Indirect Labor		
DP3111 = Fraction of supervision per supervised hrs FR31121, FR31122, FR31123		

FR311 = Labor Hours [min per part]: 0.00069

FR31 = Operation Cost: Labor [CPU]: $0.02

FR32 = Operation Cost: Mtce Materials [Cost per part produced]

FR321 = Fixtures Repairs/ Replace	
DP3211(a) = Number of Transfer Bars	1
DP3212(a) = Cost of spare parts (new/repaired)	$10,000
DP3213(a) = MTTF of Transfer Bars	1,200,000
DP3211(b) = Number of Pads & Locators sets	1
DP3212(b) = Cost of spare parts (new/repaired)	$1,500
DP3213(b) = MTTF of Pads & Locator Sets	100,000
DP3211(c) = Number of Clamping Systems	1
DP3212(c) = Cost of spare parts (new/repaired)	$15,000
DP3213(c) = MTTF of Clamping System	1,200,000
FR322 = Axial Drives Repair/ Replace	
DP3221(a) = Number of Axis Drives	1
DP3222(a) = Cost of axis drive components (repair/new)	$10,000
DP3223(a) = Axis Reliability (MTTF)	7,772,020
DP3221(b) = Number of Axis Slides	1
DP3222(b) = Cost of axis slides (repair/new)	$50,000
DP3223(b) = Axis Slide Reliability (MTTF)	11,658,030
FR323 = Spindle Repair/ Replace	
DP3231(a) = Number of Spindles Packs (bearing & Shafts)	20
DP3232(a) = Cost of new/repaired pack (Bearings & Shaft)	$700
DP322322(a) = Spindle Pack Reliability (MTTF)	2,706,767
DP3231(b) = Number of Head (gear box)	1
DP3232(b) = Cost of new/ repaired head (gear box)	$50,000
DP322322(b) = Head Gear Box Reliability (MTTF)	5,413,534
DP3231(c) = Number of Motors	1
DP3232(c) = Cost of new/ repaired Motor	$10,000
DP322322(c) = Motor Reliability (MTTF)	4,060,151

FR321 = Fixtures Repairs/ Replace [CPU]: $0.04

FR322 = Axial Drives Repair/ Replace [CPU]: $0.01

FR323 = Spindle Repair/ Replace [CPU]: $0.02

FR32 = Operation Cost: Mtce Materials [CPU]: $0.06

FR33 = Operation Cost: Utilities [Cost per part produced]

FR331 = Cost of kWhr	$0.08
FR3321 = Fixture Consumption	
DP33211 = Power function for Clamp/Unclamp per cycle	
DP33211 = Power function for rotate table per cycle	
DP3322 = Power/Motion function for each Axis per cycle	
DP3323 = Power/Motion function for each spindle per cycle	

FR332 = Power Consumption per cycle. [kW hr]: 0

FR33 = Operation Cost: Utilities [assumed]: $0.25

FR4 = Change Over Cost & Agility

FR41 = Fixtures

	[$]	[min]
DP411 = Change fixture ability to hold workpiece	$25,000	720
DP412 = Change small details, pads, and locators.	$1,500	120
DP413 = re-program logic		90
DP3211 = Number of Fixture Components		1
DP3111 = Fraction of supervision per supervised hours [%]		20%
DP31123 = Avg Number of trades req'd per repair		2
DP312 = Labor cost per hr		$30

FR42 = Axis

DP422 = re-program axis logic [min per axis]	90
DP3221 = Number of Axis Drives [qty to be worked on]	1
DP3111 = Fraction of supervision per supervised [%]	20%
DP31123 = Avg Number of trades req'd per repair	1
DP312 = Labor cost per hr	$30.00

FR43 = Spindles

	[$]	[min]
DP422= change design of clusters add/ remove spindles	$200,000	5760
Program Logic		90
DP3231 = Number of Spindles Heads		1
DP3111 = Fraction of supervision per supervised hours		10%
DP31123 = Avg Number of trades req'd per repair		5
DP312 = Labor cost per hr		$30.00

FR41 = Fixtures	$27,616	[$]
	2232	[min]
FR42 = Axis	$54	[$]
	108	[min]
FR43 = Spindles	$216,088	[$]
	32175	[min]

FR4 = Change Over Cost & Agility	[$]	$243,758	
	[time in days & $ of loss production]	5.32	
		$9,773.05	

FR4 = Change Over Cost & Agility [$ - total including loss revenue]	$253,531
[CPU budget per changeover schedule]	$0.25

Achievable JPH	156
Estimated CPU	$0.59
AVG number of Parts produced between changeover (product life)	1,000,000

Production Loss [$] = $9,773.05 [CPU * Hrs/day * JPH * loss(days)]

FR5 = Product Range

Number of Products the system can process	2
Total Number of Items on Catalog (produc family)	10
Number of independent machines necessary for each step (does not mean parallel machines for production rate gains)	2

FR51 = % of Strategic Level Flexibility Implementation	20%
FR52 = % Equipment Utilization (current Plane)	50%

Table F-2: Cost calculation of "Flexible CNC – Single Spindle".

Process Step Evaluation WorkSheet

a) Report Card - CNC 1-Spindle Flexible

FR1 = Achievable Production Rate {Achievable}	161	[JPH]
FR2 = Capital Cost	$1,600,000	[$ - USD]
FR31 = Operation Cost: Labor	$0.07	[CPU - USD]
FR32 = Maintenance Materials	$0.11	[CPU - USD]
FR33 = Operation Cost: Utilities	$0.75	[CPU - USD]
FR4 = Change Over Cost & Agility	$18,831	[$ - USD]
	0.26	[time]
	$0.02	
$19,623.89	[$ - Tot. Incl. Prod. Loss]	
$0.02	[CPU - per Sched. changeover]	
FR51 = % of Strategic Level Flexibility Implementation	80%	[%]
FR52 = % Equipment Utilization (current Plane)	100%	[%]

Estimated Operation CPU	$0.95	
Changeover Time [Days]	0.26	[days]
Changeover Capital & loss CPU	$0.02	
Overall CPU	$0.97	

Oeperational Policies

i =	5%	0.4167%
N =	60	[months]
(A/P, *i*, N) =	0.018871	
A =	$30,193.97	
T =	20	[hrs /day]
U =	5	[days/week]
V =	4	[week/month]

b) Work Sheet - CNC 1-Spindle Flexible

FR1 = TARGET PRODUCTION RATE [JPH]

DP12 = No of Parallel Machines in Cell: 7

DP111 = Station Cycle by design {JPH}: 26

Station Cycle: 140.35 sec

DP11211 = Tool Life {frequency of tool changes}

Tool A - MBC Drill	[cycles]	5,000
Tool B - Oil Pan Drill	[cycles]	5,000

DP11212 = Cycle to change a tool

*** Number of tools changed

Tool A - MBC Drill		1
Tool B - Oil Pan Drill		1
Tool A - MBC Drill	[min, ea]	2
Tool B - Oil Pan Drill	[min, ea]	2

FR11221 = Unsched. Prod. Loss - Availabiltiy: 0.9303568
(for i components of the system station)

		MTTF [cycles]	MTFR [min]	Qty
Axis	Axis Drive [feed]	792,103	1440	1
	Slide System [feed]	1,188,155	4320	1
	Axis Drive [Hor]	905,166	1440	1
	Slide System [Hor]	1,357,749	4320	1
	Axis Drive [Ver]	1,093,377	1440	1
	Slide System [Ver]	1,640,066	4320	1
Spindles	Spindle pack/bearings	915,032	120	1
	Spindle head (Gears Box)	1,830,064	7200	1
	Motor	1,830,064	420	1
Fixtrues	Trasfer bar sytem	1,200,000	1440	1
	Pads & Locator	100,000	120	1
	Clamping system	1,200,000	2880	1

Assume (Series System for components of station):
Axis — Spindles — Fixtures

FR11222 = Unsched. Prod. Loss - Scheduling: 0

Combinatorial Complexity Measure: 0

FR111 = Favorable Production Rate [JPH]	25.650
FR1121 = Sched. Prod. Loss [JPH]	0.02052013
FR1122 = Unsched. Prod. Loss [JPH]	1.7864
FR11 = Station Production Rate [JPH]	23
FR1 = Target Production Rate {Achiavable} [JPH]	161

FR2 = CAPITAL COST

DP212 = Cost of Individual Prod. Equip. station	$200,000
DP12 = No of Parallel Machines in Cell	7
DP222 = Cost Mt'l Handling	$200,000.00
DP221 = # of mat'l handling units required	1
DP12 = No of Parallel Machines in Cell	1
DP11222 = Combinatorial Complexity	0

FR21 = Cost for Production Equipment	$1,400,000
FR22 = Cost for Mt'l Handling Equipment	$200,000
FR2 = Capital Cost [$]	$1,600,000

FR31 = OPERATION COST : LABOR [Cost per part produced]

DP312 = Labor cost per hr	Supervision Trades Hourly	$30.00
FR31121 = Operators [hrs]		
DP31121 = hrs of Schedule Activity		
DP11211 = Tool Life (frequency of tool changes)		
DP11212 = Cycle to change a tool		
FR31122 = Tool Management [hrs]		
DP31122 = Tool Reconditioning Effort [hrs]		
DP11211 = Tool Life (frequency of tool changes)		
FR31123 = Mtce Trades [hrs]		$0.00
DP31123 = Avg Number of trades req'd per repair		2
DP11221 = Cell Availability		0.9304
FR3111 = Indirect Labor		
DP3111 = Fraction of supervision per supervised hrs FR31121, FR31122, FR31123		

FR311 = Labor Hours [min per part]	0.00232
FR31 = Operation Cost: Labor [CPU]	$0.07

FR32 = Operation Cost: Mtce Materials [Cost per part produced]

FR321 = Fixtures Repairs/ Replace	
DP3211(a) = Number of Transfer Bars	1
DP3212(a) = Cost of spare parts (new/repaired)	$10,000
DP3213(a) = MTTF of Transfer Bars	1,200,000
DP3211(b) = Number of Pads & Locators sets	1
DP3212(b) = Cost of spare parts (new/repaired)	$1,500
DP3213(b) = MTTF of Pads & Locator Sets	100,000
DP3211(c) = Number of Clamping Systems	1
DP3212(c) = Cost of spare parts (new/repaired)	$15,000
DP3213(c) = MTTF of Clamping System	1,200,000
FR322 = Axial Drives Repair/ Replace	
DP3221(a) = Number of Axis Drives [feed]	1
DP3222(a) = Cost of axis drive components (repair/new)	$20,000
DP3223(a) = Axis Reliability (MTTF) [feed]	792,103
DP3221(b) = Number of Axis Slides [feed]	1
DP3222(b) = Cost of axis slides (repair/new) [feed]	$50,000
DP3223(b) = Axis Slide Reliability (MTTF) [feed]	1,188,155
DP3221(a) = Number of Axis Drives [Hor]	1
DP3222(a) = Cost of axis drive components (repair/new)	$20,000
DP3223(a) = Axis Reliability (MTTF) [Hor]	905,166
DP3221(b) = Number of Axis Slides [Hor]	1
DP3222(b) = Cost of axis slides (repair/new) [Hor]	$50,000
DP3223(b) = Axis Slide Reliability (MTTF) [Hor]	1,357,749
DP3221(a) = Number of Axis Drives [Ver]	1
DP3222(a) = Cost of axis drive components (repair/new)	$20,000
DP3223(a) = Axis Reliability (MTTF) [Ver]	1,093,377
DP3221(b) = Number of Axis Slides [Ver]	1
DP3222(b) = Cost of axis slides (repair/new) [Ver]	$50,000
DP3223(b) = Axis Slide Reliability (MTTF) [Ver]	1,640,066
FR323 = Spindle Repair/ Replace	
DP3231(a) = Number of Spindles Packs (bearing & Shafts)	1
DP3232(a) = Cost of new/repaired pack (Bearings & Shaft)	$5,000
DP322322(a) = Spindle Pack Reliability (MTTF)	915,032
DP3231(b) = Number of Head (gear box)	1
DP3232(b) = Cost of new/ repaired head (gear box)	$50,000
DP322322(b) = Head Gear Box Reliability (MTTF)	1,830,064
DP3231(c) = Number of Motors	1
DP3232(c) = Cost of new/ repaired Motor	$30,000
DP322322(c) = Motor Reliability (MTTF)	1,830,064

FR321 = Fixtures Repairs/ Replace [CPU]	$0.04
FR322 = Axial Drives Repair/ Replace [CPU]	$0.03
FR323 = Spindle Repair/ Replace [CPU]	$0.05
FR32 = Operation Cost: Mtce Materials [CPU]	$0.11

FR33 = Operation Cost: Utilities [Cost per part produced]

FR331 = Cost of kWhr	$0.08
FR3321 = Fixture Consumption	
DP33211 = Power function for Clamp/Unclamp per cycle	
DP33211 = Power function for rotate table per cycle	
DP3322 = Power/Motion function for each Axis per cycle	
DP3323 = Power/Motion function for each spindle per cycle	

FR332 = Power Consumption per cycle. [kW hr]	0
FR33 = Operation Cost: Utilities	$0.75

FR4 = Change Over Cost & Agility

	[$]	[min]
FR41 = Fixtures		
DP411 = Change fixture ability to hold workpiece	$15,000	120
DP412 = Change small details, pads, and locators.	$1,500	90
DP413 = re-program logic		30
DP3211 = Number of Fixture Components		1
DP3111 = Fraction of supervision per supervised hours [%]		20%
DP31123 = Avg Number of trades req'd per repair		2
DP312 = Labor cost per hr		$30
FR42 = Axis		
DP422 = re-program axis logic [min per axis]		30
DP3221 = Number of Axis Drives [qty to be worked on]		1
DP3111 = Fraction of supervision per supervised [%]		20%
DP31123 = Avg Number of trades req'd per repair		1
DP312 = Labor cost per hr		$30.00
FR43 = Spindles	[$]	[min]
DP422= change design of clusters add/ remove spindles	$2,000	15
Program Logic		30
DP3231 = Number of Spindles Heads		1
DP3111 = Fraction of supervision per supervised hours		10%
DP31123 = Avg Number of trades req'd per repair		1
DP312 = Labor cost per hr		$30.00

FR41 = Fixtures	$16,788	[$]
	576	[min]
FR42 = Axis	$18	[$]
	36	[min]
FR43 = Spindles	$2,025	[$]
	49.5	[min]

FR4 = Change Over Cost & Agility	[$]	$18,831
	[time in days & $ of loss production]	0.26
		$793.14

[$ - total including loss revenue]	$19,624
FR4 = Change Over Cost & Agility [CPU budget per changeover schedule]	$0.02

Achievable JPH	161
Estimated CPU	$0.95
AVG number of Parts produced between changeover (product life)	1,000,000

Production Loss [$] = $793.14 [CPU * Hrs/day * JPH * loss(days)]

FR5 = Product Range

Number of Products the system can process	8
Total Number of Items on Catalog (produc family)	10
Number of independent machines necessary for each step (does not mean parallel machines for production rate gains)	1

FR51 = % of Strategic Level Flexibility Implementation	80%
FR52 = % Equipment Utilization (current Plane)	100%

Table F-3: Cost calculation of "Flexible CNC –with Dedicated Adapter".

Process Step Evaluation WorkSheet

a) Report Card - CNC w/ Dedicated Adapter

FR1 = Achievable Production Rate {Achievable}	144	[JPH]	36
FR2 = Capital Cost	$1,200,000	[$ - USD]	2
FR31 = Operation Cost: Labor	$0.10	[CPU - USD]	
FR32 = Maintenance Materials	$0.10	[CPU - USD]	
FR33 = Operation Cost: Utilities	$0.50	[CPU - USD]	3
FR4 = Change Over Cost & Agility	$31,831	[$ - USD]	4a
	0.26	[time]	4b
	$0.03		
$32,406.86 [$ - Tot. Incl. Prod. Loss]			
$0.07 [CPU - per Sched. changeover]			
FR51 = % of Strategic Level Flexibility Implementation	80%	[%]	5
FR52 = % Equipment Utilization (current Plane)	100%	[%]	6

Oeperational Policies

i =	5%	0.4167%	
N =	60	[months]	
(A/P, i, N) =	0.018871	T =	20 [hrs /day]
A =	$22,645.48	U =	5 [days/week]
A/N =	$0.0262	V =	4 [week/month]

Estimated Operation CPU	$0.77	
Changeover Time [Days]	0.26	[days]
Changeover Capital & loss CPU	$0.03	
Overall CPU	$0.80	

b) Work Sheet - CNC w/ Dedicated Adapter

FR1 = TARGET PRODUCTION RATE [JPH]

DP12 = No of Parallel Machines in Cell 4

DP111 = Station Cycle by design {JPH} 41

Station Cycle 88.55 sec

DP11211 = Tool Life {frequency of tool changes}

Tool A - MBC Drill	[cycles]	5,000
Tool B - Oil Pan Drill	[cycles]	5,000

DP11212 = Cycle to change a tool

*** Number of tools changed

Tool A - MBC Drill		1
Tool B - Oil Pan Drill		1
Tool A - MBC Drill	[min, ea]	2
Tool B - Oil Pan Drill	[min, ea]	2

FR11221 = Unsched. Prod. Loss - Availabiltiy 0.90350498

(for i components of the system station)

		MTTF [cycles]	MTFR [min]	Qty
Axis	Axis Drive [feed]	704,683	1440	1
	Slide System [feed]	1,057,025	4320	1
	Axis Drive [Hor]	905,166	1440	1
	Slide System [Hor]	1,357,749	4320	1
	Axis Drive [Ver]	2,018,633	1440	1
	Slide System [Ver]	3,027,950	4320	1
Spindles	Spindle pack/bearings	1,571,194	120	1
	Spindle head (Gears Box)	3,142,388	7200	1
	Motor	3,142,388	420	1
Fixtrues	Trasfer bar sytem	1,200,000	1440	1
	Pads & Locator	100,000	120	1
	Clamping system	1,200,000	2880	1

Assume (Series System for components of station):

Axis — Spindles — Fixtures

FR11222 = Unsched. Prod. Loss - Scheduling 0

Combinatorial Complexity Measure 0

FR111 = Favorable Production Rate [JPH]	40.655
FR1121 = Sched. Prod. Loss [JPH]	0.032524
FR1122 = Unsched. Prod. Loss [JPH]	3.9230
FR11 = Station Production Rate [JPH]	36
FR1 = Target Production Rate {Achievable} [JPH]	144

FR2 = CAPITAL COST

DP212 = Cost of Individual Prod. Equip. station	$250,000
DP12 = No of Parallel Machines in Cell	4
DP222 = Cost Mt'l Handling	$200,000.00
DP221 = # of met'l handling units required	1
DP12 = No of Parallel Machines in Cell	1
DP11222 = Combinatorial Complexity	0

FR21 = Cost for Production Equipment	$1,000,000
FR22 = Cost for Mt'l Handling Equipment	$200,000
FR2 = Capital Cost [$]	$1,200,000

FR31 = OPERATION COST : LABOR [Cost per part produced]

DP312 = Labor cost per hr — Supervision Trades Hourly	$30.00
FR31121 = Operators [hrs]	
DP31121 = hrs of Schedule Activity	
DP11211 = Tool Life {frequency of tool changes}	
DP11212 = Cycle to change a tool	
FR31122 = Tool Management [hrs]	
DP31122 = Tool Reconditioning Effort [hrs]	
DP11211 = Tool Life {frequency of tool changes}	
FR31123 = Mtce Trades [hrs]	$0.00
DP31123 = Avg Number of trades req'd per repair	2
DP11221 = Cell Availability	0.9035
FR3111 = Indirect Labor	
DP3111 = Fraction of supervision per supervised hrs	
FR31121, FR31122, FR31123	

FR311 = Labor Hours [min per part]	0.00322
FR31 = Operation Cost: Labor [CPU]	$0.10

FR32 = Operation Cost: Mtce Materials [Cost per part produced]

FR321 = Fixtures Repairs/ Replace	
DP3211(a) = Number of Transfer Bars	1
DP3212(a) = Cost of spare parts (new/repaired)	$10,000
DP3213(a) = MTTF of Transfer Bars	1,200,000
DP3211(b) = Number of Pads & Locators sets	1
DP3212(b) = Cost of spare parts (new/repaired)	$1,500
DP3213(b) = MTTF of Pads & Locator Sets	100,000
DP3211(c) = Number of Clamping Systems	1
DP3212(c) = Cost of spare parts (new/repaired)	$15,000
DP3213(c) = MTTF of Clamping System	1,200,000
FR322 = Axial Drives Repair/ Replace	
DP3221(a) = Number of Axis Drives [feed]	1
DP3222(a) = Cost of axis drive components (repair/new)	$20,000
DP3223(a) = Axis Reliability (MTTF) [feed]	704,683
DP3221(b) = Number of Axis Slides [feed]	1
DP3222(b) = Cost of axis slides (repair/new) [feed]	$50,000
DP3223(b) = Axis Slide Reliability (MTTF) [feed]	1,057,025
DP3221(a) = Number of Axis Drives [Hor]	1
DP3222(a) = Cost of axis drive components (repair/new)	$20,000
DP3223(a) = Axis Reliability (MTTF) [Hor]	905,166
DP3221(b) = Number of Axis Slides [Hor]	1
DP3222(b) = Cost of axis slides (repair/new) [Hor]	$50,000
DP3223(b) = Axis Slide Reliability (MTTF) [Hor]	1,357,749
DP3221(a) = Number of Axis Drives [Ver]	1
DP3222(a) = Cost of axis drive components (repair/new)	$20,000
DP3223(a) = Axis Reliability (MTTF) [Ver]	2,018,633
DP3221(b) = Number of Axis Slides [Ver]	1
DP3222(b) = Cost of axis slides (repair/new) [Ver]	$50,000
DP3223(b) = Axis Slide Reliability (MTTF) [Ver]	3,027,950
FR323 = Spindle Repair/ Replace	
DP3231(a) = Number of Spindles Packs (bearing & Shafts)	1
DP3232(a) = Cost of new/repaired pack (Bearings & Shaft)	$5,000
DP322322(a) = Spindle Pack Reliability (MTTF)	1,571,194
DP3231(b) = Number of Head (gear box)	1
DP3232(b) = Cost of new/ repaired head (gear box)	$50,000
DP322322(b) = Head Gear Box Reliability (MTTF)	3,142,388
DP3231(c) = Number of Motors	1
DP3232(c) = Cost of new/ repaired Motor	$30,000
DP322322(c) = Motor Reliability (MTTF)	3,142,388

FR321 = Fixtures Repairs/ Replace [CPU]	$0.04
FR322 = Axial Drives Repair/ Replace [CPU]	$0.04
FR323 = Spindle Repair/ Replace [CPU]	$0.03
FR32 = Operation Cost: Mtce Materials [CPU]	$0.10

FR33 = Operation Cost: Utilities [Cost per part produced]

FR331 = Cost of kWhr	$0.08
FR3321 = Fixture Consumption	
DP33211 = Power function for Clamp/Unclamp per cycle	
DP33211 = Power function for rotate table per cycle	
DP3322 = Power/Motion function for each Axis per cycle	
DP3323 = Power/Motion function for each spindle per cycle	

FR332 = Power Consumption per cycle. [kW hr]	0
FR33 = Operation Cost: Utilities	$0.50

FR4 = Change Over Cost & Agility

	[$]	[min]
FR41 = Fixtures		
DP411 = Change fixture ability to hold workpiece	$15,000	120
DP412 = Change small details, pads, and locators.	$1,500	90
DP413 = re-program logic		30
DP3211 = Number of Fixture Components		1
DP3111 = Fraction of supervision per supervised hours [%]		20%
DP31123 = Avg Number of trades req'd per repair		2
DP312 = Labor cost per hr		$30
FR42 = Axis		
DP422 = re-program axis logic [min per axis]		30
DP3221 = Number of Axis Drives [qty to be worked on]		1
DP3111 = Fraction of supervision per supervised [%]		20%
DP31123 = Avg Number of trades req'd per repair		1
DP312 = Labor cost per hr		$30.00
FR43 = Spindles	[$]	[min]
DP422= change design of clusters add/ remove spindles	$15,000	15
Program Logic		30
DP3231 = Number of Spindles Heads		1
DP3111 = Fraction of supervision per supervised hours		10%
DP31123 = Avg Number of trades req'd per repair		1
DP312 = Labor cost per hr		$30.00

FR41 = Fixtures	$16,788	[$]
	576	[min]
FR42 = Axis	$18	[$]
	36	[min]
FR43 = Spindles	$15,025	[$]
	49.5	[min]

FR4 = Change Over Cost & Agility	[$]	$31,831
	[time in days & $ of loss production]	0.26
		$576.11

FR4 = Change Over Cost & Agility [$ - total including loss revenue]	$32,407
[CPU budget per changeover schedule]	$0.03

Achievable JPH	144
Estimated CPU	$0.77
AVG number of Parts produced between changeover (product life)	1,000,000

Production Loss [$] = $576.11 [CPU * Hrs/day * JPH * loss(days)]

FR5 = Product Range

Number of Products the system can process	8
Total Number of Items on Catalog (produc family)	10
Number of independent machines necessary for each step (does not mean parallel machines for production rate gains)	1

FR51 = % of Strategic Level Flexibility Implementation	80%
FR52 = % Equipment Utilization (current Plane)	100%

VITA AUCTORIS

Gabriel Gonzalez Gillis was born in 1979 in Acapulco Mexico. He completed his studies until grade 11 from Colegio La Salle Acapulco and graduated from Assumption High School in 1998 where he finished the senior year. From there he went on to the University of Windsor Ontario where he obtained a B.Sc. in Honours Mechanical Engineer/Automotive Option. He is currently a candidate for the Master's degree in Industrial and Manufacturing Systems Engineering at the University of Windsor and hopes to graduate in summer 2008.