A Decomposition-Based Approach to Linking Strategy, Performance Measurement, and Manufacturing System Design

by

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ABSTRACT

The ability to understand the impact of lower-level design decisions on the achievement of higher-level strategic objectives is critical for the effective design of manufacturing systems. Furthermore, the development of a set of performance measures in alignment with these strategic objectives is necessary to ensure that ongoing design improvement activities result in better manufacturing system performance with respect to the goals of the firm. This thesis investigates how manufacturing systems can be designed to achieve the unique high-level strategic objectives of an organization and how performance measures can be derived to ensure that future system improvements support the firm's manufacturing strategy.

A model of the manufacturing system design process is developed using the principles of systems engineering. This system design process begins with the identification and prioritization of relevant dimensions of manufacturing performance (cost, quality, delivery performance, etc.). Next, performance measures are developed concurrently with various possible models of system behavior and structure (i.e., design alternatives). Trade-offs among these design alternatives are examined, enabling designers to select the most appropriate feasible alternative and to identify opportunities for improvements.

A structured process for trade-off analysis is developed to aid designers in identifying and analyzing the strengths and weaknesses of alternative system designs. An axiomatic design decomposition of a general set of functional requirements (FR's) and design parameters (DP's) for a manufacturing system is used to guide designers through this trade-off analysis as well as through the development of a preliminary set of performance measures. Matrices are formed to express the relationships between strategic objectives, FR's and DP's, and the design alternatives. Combination of these matrices results in the generation of a comparison matrix showing the relative strengths and weaknesses of each design alternative. A software tool is developed to assist designers in managing, visualizing, and communicating the information required for this trade-off analysis. Examples of the application of this process to the design of manufacturing systems at an automotive component supplier are reviewed.

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Committee Member: Professor Timothy Gutowski
Committee Member: Professor Deborah Nightingale
Committee Member: Professor Shahram Taj

This thesis and the associated software tool are available from http://www.geocities.com/jim_duda/

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As my time here at MIT has neared its end, another concern began to surface: what to do next. I'd like to thank the good people at i2 Technologies for helping me to clarify that and for providing me with an exciting opportunity to explore some new areas in the world of manufacturing. Plus there was no greater motivation for me to finish up my work here than to realize exactly what it was costing me to stay.

Finally, I'd like to thank you, the reader, for taking the time to read at least this much of what I've written. Hopefully you'll venture a bit further, maybe read a chapter or two, and find something valuable herein.

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List of Acronyms

AGV: Automated Guided Vehicle

AHP: Analytic Hierarchy Procedure

CI: Consistency Index

CNC: Computer Numerically Controlled

CR: Consistency Ratio

DP: Design Parameter

FMS: Flexible Manufacturing System

FR: Functional Requirement

IDEF: Integrated computer-aided manufacturing DEFinition

JIT: Just-In-Time

MRP: Manufacturing Resource Planning

MSD: Manufacturing System Design

MSDD: Manufacturing System Design Decomposition

MTTF: Mean Time to Fail

MTTR: Mean Time to Repair

PM: Performance Measure

QFD: Quality Function Deployment

ROI: Return On Investment

SPC: Statistical Process Control

TPS: Toyota Production System

TQM: Total Quality Management

Chapter 1 Introduction

In today's manufacturing environment, particularly in the automotive industry, there is a growing need for both managers and engineers to better understand how even low-level manufacturing system design decisions can impact a firm's ability to compete in an ever-changing market. In recent decades, manufacturing firms have seen a growing emphasis placed on being responsive to the needs of the customer. Production costs must be kept low, but customers are also demanding higher levels of quality, on-time delivery, and product variety. At the same time, product design life cycles are shortening, further increasing the need for responsive manufacturing system designs. As a company develops strategies for competing in a changing market environment, it must also develop the ability to design its manufacturing systems such that the manufacturing function will support the goals of the firm. Doing so can, however, be very difficult.

A manufacturing system can be defined as a collection of components (machines, equipment, people, etc.) bound by common material and information flow and working together to transform raw materials into marketable goods (adapted from Chryssolouris, 1992 and Wu, 1992). A typical automotive component manufacturing system includes a wide variety of operations, from metal forming processes to both manual and automated assembly operations. Integrating this variety of operations into one unified system that is capable of meeting all of the required demands requires effective communication among multiple disciplines and a methodology that enables the system designers to understand how design details interact and affect overall system performance.

1.1 Motivation: Problems in Existing Factories

Unsatisfactory manufacturing system performance often evolves as the result of a system design focus that is too localized, that is too narrow in scope, that is overly simplistic, that is on the means and not the ends, or that is otherwise not aligned to the firm's overall manufacturing strategy. Historically, manufacturing systems and factories have tended to be designed in a somewhat ad hoc fashion, with each sub-system designed independently of all others. For example, in a factory involving both machining and assembly operations, it is frequently the case that the machining department was designed and implemented by a completely different set of engineers and managers than those who might have designed and built a line to assemble the machined products. Furthermore, the machining department might be broken up into functional areas (i.e., a turning area, a grinding area, etc.) each of which is designed and managed by a separate group of people, possibly working under a different set of assumptions and goals. Shigeo Shingo stresses that such division leads to thinking with a limited view and to the optimization of operations rather than of the system as a whole (Shingo, 1988; Robinson, 1990). He emphasizes the value of systems-level thinking as a key contributor to successful manufacturing system design. Hopp and Spearman (1996) present a similar argument, describing this focus on local activities as a reductionist approach, where the focus is on breaking a complex system into its more simple components and then analyzing each component separately. They go on to point out that "too much emphasis on individual components can lead to a loss of perspective for the overall system," and that a more holistic approach can lead to better overall system performance.

The scope of different variables considered by the design team can critically impact system performance. In the previous example, each set of designers might only be thinking of optimizing their design in terms of local, easily measurable costs such as materials and direct labor. The result is that even though each sub-system might be designed to have a very high isolated efficiency or cost-effectiveness, the system as a whole could suffer from poor overall performance. This situation is sometimes referred to as the "Productivity Paradox," (Skinner, 1986) where performance measures for each department are increasing while the company's profitability declines.

Because of these problems, much effort has gone into trying to understand how to design manufacturing systems in a way that will result in the many subsystems and components working together to achieve the overall goals of the firm. Unfortunately, the difficulties inherent in designing a manufacturing system are sometimes dealt with through the proposal of seemingly simple solutions. For example, Zipkin (1991) describes the "romantic" view often taken towards the design of manufacturing systems. Terms such as "Just-in-time," "kanban," "lean," and "agile" are used to represent generic solutions to contemporary manufacturing problems. These solutions are often presented as being simple, trade-off-free systems that can quickly and profoundly improve all aspects of operations. Schonberger (1990) describes kanban as "something that can be installed between any successive pair of processes in 15 minutes, using a few containers and masking tape." However, efforts to implement such systems have often met with much resistance and even complete failure and rejection in industry. Although a kanban system can, perhaps, be installed in 15 minutes, designing the manufacturing system in a way that will allow the kanban system to produce the desired results can be much more time-intensive and challenging.

This tendency towards buzzword solutions rests on the belief that there exists one "right" manufacturing and performance measurement system design solution, and that once this "best" practice is implemented, the firm's problems will be solved. In some cases, a small set of design "rules" is generated to describe this "best" practice. As a result, the focus often is placed on implementing specific "tools" and following the "rules," while the reasons why these tools are useful get lost or are not effectively communicated or even understood (Zipken, 1991; Hopp and Spearman, 1996; Cochran, 1999).

The work proposed in this thesis takes the view that designing a multi-disciplinary system with several interacting components in a way that supports a specific set of strategic objectives is not a simple task and is not a task that can be accomplished by following just a few simple rules. The view taken here is that trade-offs will always exist in manufacturing system design, and that the best a firm can do is to clearly define a manufacturing strategy (i.e., a plan for how to create and maintain a competitive advantage) and then carefully and consistently make decisions and trade-offs that are consistent with this vision. The work herein is aimed at developing an approach to help managers and engineers better understand the relationships between a firm's manufacturing strategy, its performance measurement system, and its manufacturing system design in order to facilitate the design of manufacturing systems aligned to high-level objectives.

1.2 Relation of Performance Measurement to Manufacturing System Design

Often, the design difficulties described above can be traced to the discrepancy between an organization's manufacturing strategy and its system for performance measurement. The importance of effective performance measures in a manufacturing environment is well documented. Measures of performance are critical to a company's success, as these measures not only monitor how well that company has performed, but also determine the direction of the company's future. Engineers will focus on making changes that will improve system performance relative to these measures, and it is therefore critical that these performance measurements be aligned with the company's overall manufacturing strategy. In this way, performance measures function as a means for communicating strategic objectives throughout the organization. As a result, there exists a strong link between performance measurement and system design. Unfortunately, as the conditions in which manufacturing organizations operate have changed, methods for measuring system performance have often remained static.

Even when an organization desires to align its performance measurement with its manufacturing strategy, it is not always clear how to do so. Traditionally, managers have made manufacturing system design decisions based on attempts to quantify all performance factors in terms of costs. Financial measures such as return on investment and net present value can then be used to compare various alternatives. However, trying to accurately calculate such a figure can be extremely difficult and subject to debate. Factors such as quality and inventory can be particularly hard to quantify in terms of dollar figures. What is the cost of business lost due to poor quality or long lead times? How much new business would be gained with increased responsiveness and predictability? With the recognition of these challenges has come a tremendous increase of interest in developing more complete systems for performance measurement, with many measures remaining in non-financial terms. However, decision-making based on traditional cost accounting methods disregards such "intangibles" in favor of more easily measured financial data such as labor costs (Maskell, 1991). As a result, there is a need to understand how both financial and non-financial performance measures can be incorporated into the decision-making process, so that systems can be designed to meet the goals of the company.

1.3 Problem Statement

To summarize, there is a need among manufacturing firms to ensure that manufacturing system design decisions are made so as to support the overall objectives of the firm. Doing so requires that

- Performance measures are aligned to the firm's strategic objectives
- Trade-offs regarding the performance of multiple design alternatives relative to these objectives and measures are understood

Regardless of what a firm's specific manufacturing strategy might be, it is critical that this strategy be communicated effectively and consistently across all levels of the organization.

The performance measurement system used plays an important role in this communication. Once a company determines its competitive strategy (i.e., the basis on which it plans to compete: lowest cost, highest quality, excellent customer responsiveness, etc.), all decisions made at lower, operational levels (i.e., decisions regarding the details of the manufacturing system design) must support these high-level objectives. By better understanding how changes in the manufacturing environment and in the firm's manufacturing strategy create the need for changes in the manufacturing system design, and, correspondingly, how changes in the manufacturing system design can either facilitate or prevent achievement of strategic objectives, managers and engineers will be better equipped to design and/or redesign factories to capitalize on changing market conditions.

1.4 Scope of Research

The goal of this research is to develop a design process that will enhance the ability of manufacturing managers and engineers to:

- Develop an effective set of performance measures aligned to the strategic objectives of the firm
- Assess the performance of manufacturing system design alternatives with respect to multiple evaluation criteria
- Develop both a qualitative and quantitative understanding of the design trade-offs faced
- Understand how these design decisions affect the system's ability to meet strategic objectives

In order to achieve this goal, a model of the manufacturing system design process is proposed. This model is based on a general process for the design of complex systems developed in (Oliver et al., 1997). A structured process for trade-off analysis is then developed to aid designers in identifying and analyzing the strengths and weaknesses of alternative system designs. An axiomatic design decomposition of a general set of functional requirements (FR's) and design parameters (DP's) for a manufacturing system is used to provide a formal means for relating a firm's strategy to its performance measurement system and to its manufacturing system design decisions. This manufacturing system design decomposition (shown in Appendix A-1) provides a structure for understanding the interrelationships among the many elements of a manufacturing system design and for tracing the relevance of detailed design parameters to high-level system objectives.

Matrices are formed to express the relationships between strategic objectives, FR's and DP's, and the design alternatives. Combination of these matrices results in the generation of a comparison matrix showing the relative strengths and weaknesses of each design alternative. A software tool is developed to assist designers in managing, visualizing, and communicating the information required for this trade-off analysis. Examples of the application of this process to the design of manufacturing systems at an automotive component supplier are reviewed. This software tool can help system designers to understand and to quantify the performance of different design alternatives with respect to the overall goals of the firm, allowing them to better design manufacturing systems to achieve the desired performance.

1.5 Organization of Thesis

This thesis begins with a review of background material and previous research performed in the key areas related to this work: manufacturing strategy, performance measurement, and manufacturing system design. Manufacturing strategy research is reviewed in Chapter 2 to show how manufacturing strategy fits in with the overall objectives of a company and to define a set of competitive priorities that comprise a strategy. Research on performance measurement for manufacturing is then reviewed in Chapter 3, with a focus on the characteristics of an effective performance measurement system, the process for developing a system for performance measurement, and the characteristics of effective measures. Next, in Chapter 4, a generalized process for engineering design is reviewed. The application of this process to the design of manufacturing systems is discussed and observations are made regarding manufacturing system design practices observed in industry.

The next part of the thesis (Chapter 5-Chapter 9) presents a systems engineering-based approach to manufacturing system design, using an axiomatic design-based decomposition to link manufacturing strategy, performance measurement, and system design. First, the development of this decomposition is discussed (in Chapter 5) including a review of similar frameworks and the axiomatic design process used to develop it. The upper levels of this decomposition are then reviewed. Chapter 6 proposes a general model of the manufacturing system design process based on a systems engineering process model. The general systems engineering process is reviewed and its specific application to manufacturing system design is presented. The role of the manufacturing system design decomposition is then discussed in Chapters 7 and 8, with a particular emphasis on how the decomposition can be used to aid designers in thinking about manufacturing strategy, in developing a set of performance measures that will be consistent with this strategy, and in examining the trade-offs among design alternatives. Chapter 9 then presents detailed examples of the application of the proposed manufacturing system design process to illustrate its use and the role of the decomposition as a decision support tool.

Chapter 10 concludes the thesis, summarizing the work performed, the manufacturing system design process proposed, and the utility of the manufacturing system design decomposition as a decision support tool. Future research areas are identified and discussed.

Chapter 2 Manufacturing Strategy

2.1 Overview

This thesis will draw from several areas of prior study, including applications of systems engineering and optimization, performance measurement, and manufacturing system design. All of this work can, however, be seen as just a small part of a much larger whole in the research on manufacturing strategy. This chapter will begin by reviewing manufacturing strategy as a larger context for this research. Although a large body of work exists in each of the previously mentioned fields, a unified look at the connections between manufacturing strategy, performance measurement, and manufacturing system design is lacking. This chapter provides a summary of research in manufacturing strategy. The following two chapters will review the relevant literature in performance measurement and engineering design.

2.2 Introduction

Manufacturing strategy has been an important area of research since the publication of Wickham Skinner's 1969 paper on the subject. Although a great deal of work has been done since then in terms of understanding manufacturing strategy and the critical role it can play in the success or failure of a company, many issues remain unresolved. Consensus has been reached in the literature with regard to some aspects of manufacturing strategy while other aspects remain open to much debate. This chapter seeks to review the existing body of research on manufacturing strategy and to present a unified framework for thinking about its different components, in terms of both process and content. Additionally, it is hoped that this chapter will enhance the reader's understanding of how the research presented in this thesis fits into and contributes to the field of manufacturing strategy as a whole.

It would be useful to start by providing a definition of strategy in the context of manufacturing. Unfortunately, no clean and simple definition has been settled upon in the literature. Many authors note that the word strategy is used so often and so generally that it has lost much of its specific meaning. In efforts to define manufacturing strategy, researchers often choose to list its characteristics and to describe its nature. Hayes and Wheelwright

(1984) describe the following five characteristics as being representative of a strategy in a business or manufacturing setting:

Time horizon:	Strategic activities involve an extended time horizon in terms of both implementation and impact.
Impact:	Strategic decisions will have a significant impact, although it may take a long time to materialize.
Concentration of effort:	An effective strategy requires focusing on a limited set of pursuits, implicitly implying a reduced focus on other activities.
Pattern of decisions:	Most strategies require that a series of a certain type of decisions be made over time. These decisions must be supportive of each other and follow a consistent pattern.
Pervasiveness:	A strategy involves a wide range of activities, requiring that all levels of an organization act in a mutually reinforcing manner.

Others (e.g., Fine and Hax, 1985 and Porter, 1996) describe the goal of a strategy: the development and securing of a long-term, sustainable competitive advantage. With this rather vague definition in mind, this chapter first presents some ideas on the process of strategy formation followed by a more detailed discussion on the content of a manufacturing strategy and a framework for thinking about manufacturing strategy as part of a firm's overall strategy.

2.3 Hierarchy of Strategies

Historically, beginning with the work of Skinner (1969), manufacturing strategy formation has been viewed as a hierarchical, top-down process. This process has been described as an "ends-ways-means" approach (Hayes, 1985) in that it starts with defining the ends to be achieved (i.e., the corporate-level objectives) then defines a plan or strategy (i.e., the "ways") for achieving these objectives, and concludes by determining the appropriate "means" for implementing the strategy. Examples of this basic top-down approach abound in the literature (Porter, 1980; Fine and Hax, 1985; etc.). One of the more widely recognized examples of a top-down approach to manufacturing strategy development is that developed by Hayes and Wheelwright (1984) and shown in Figure 2-1.

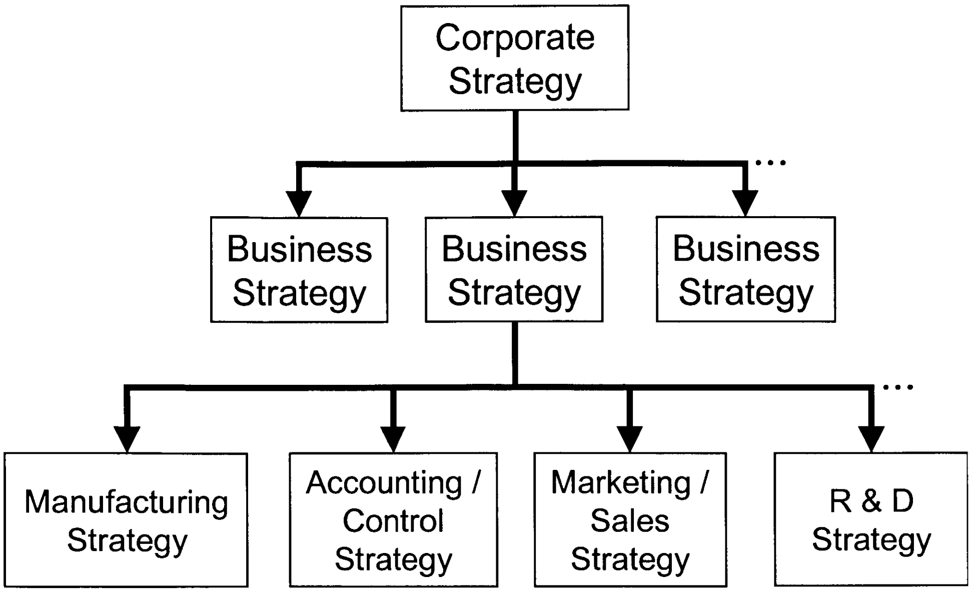


Figure 2-1: Levels of strategy (adapted from Hayes and Wheelwright, 1984)

2.3.1 Corporate Strategy

Top-down approaches such as the one shown in Figure 2-1 generally begin with the definition of a corporate strategy. Andrews (1980) describes corporate strategy as “the pattern of decisions in a company that determines and reveals its objectives, purposes, or goals. [It] defines the businesses in which a company will compete, preferably in a way that focuses resources to convey distinctive competencies into competitive advantages.” Creating such a strategy involves defining the mission of the firm, the range of business it is to pursue, and the nature of the contribution it intends to make to its various stakeholders. Corporate objectives may also be defined with respect to company growth, survival, profit, return on investment, or other financial measures (Hill, 1994).

2.3.2 Business Strategy

At the middle level of the hierarchy are the strategies for each business unit within the firm. These business strategies define (1) the scope of the business (what segments of the market will be addressed) and (2) the basis on which the business will achieve and maintain a competitive advantage. The second part of business strategy, defining the business’ competitive position, involves deciding on a position relative to several competitive priorities. Porter (1996) describes strategic positioning as emerging from three distinct but possibly overlapping sources: variety, needs, and access. Variety-based positioning is positioning based on the choice of products or services to be offered. Needs-based positioning focuses instead on providing goods and/or services to meet the needs of a particular subset of customers. Access-based positioning segments customers based on various dimensions of product or service accessibility (geographical, internet-based, rural/urban, etc.).

Essentially, Porter and many others argue, the key to defining a position of strategic advantage lies in making decisions regarding the trade-offs among the various dimensions of competition. Porter uses the concept of the production frontier to illustrate this point (see Figure 2-2). This "frontier" represents the maximum value that a company can deliver at a given cost. A desirable strategic position would represent one point on this frontier. Shifting from one point to another would represent a change in strategy based on a change in the relative importance of cost and non-price value (Porter, 1996).

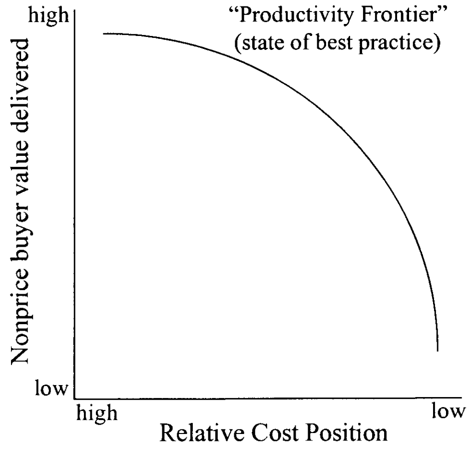


Figure 2-2: Non-price value - cost frontier (adapted from Porter, 1996)

In reality, the problem of positioning is somewhat more complex, as there exist more than two dimensions to think about. Although it seems that each researcher defines his or her own set of competitive priorities to consider, there is a large degree of agreement regarding the key areas of importance. A literature survey by Leong et al. (1990) revealed a consensus on an appropriate set of five categories of competitive priorities: cost, quality, delivery performance, flexibility and innovativeness. Table 2-1 presents an overview of these five categories and some of the sub-categories discussed in the literature (Miltenburg, 1995; Fine and Hax, 1985; Hayes and Wheelwright, 1984; Miller and Roth, 1994; Rudberg, 1999).

Table 2-1: Competitive priorities (adapted from Rudberg, 1999)

Category of Competitive Priority	**Sub-categories**
Cost	
Quality *Manufacturing products with high conformance and performance*	
Delivery Performance	Dependability Speed of delivery
Flexibility *Primary emphasis is on volume and product mix flexibilities*	Volume Product mix Change-over Modification Rerouting Material Sequencing
Innovativeness *Ability to quickly introduce new products/processes*	Product Process

Once competitive priorities have been determined, a firm must decide how to configure its resources so as to best support this position. Although defining the relative importance of the various dimensions allows for an infinite number of possibilities, empirical studies have shown that most businesses can be classified as having a configuration selected from a very limited set of 3-10 choices (see, for example, Miller and Ross, 1994; Ward et al., 1996; Richardson et al., 1985; or Kotha and Orne, 1989). Even though each researcher presents a different set of configurations, there are some basic trends across the literature. Configurations can be divided into three basic categories, as presented by Stobaugh and Telesio (1983): technology-driven, market-intensive, and low cost. With a technology-driven configuration, the firm's focus is on providing high-tech products using the newest process technology. In these firms, time-to-market and strong research and development groups are of the highest importance. With a market-intensive configuration, the firm aims to keep a particular group of customers happy. This is achieved with superior delivery performance, high conformance quality, and some degree of process, product, and volume flexibility. Finally, with a low-cost configuration, the company focuses on minimizing production costs with less emphasis on product variety and process flexibility. Each configuration results from a set of decisions made on how to develop capabilities and allocate resources so as to compete in a specific portion of the market. Choosing a configuration primarily involves selecting a limited set of competitive priorities (i.e. 1 or 2) to focus on above all others.

2.3.3 Functional Strategies

At the third level of Hayes and Wheelwright's hierarchy of strategies lie the functional strategies. Potential areas for functional strategies include marketing and sales, manufacturing, R&D, distribution, field maintenance, etc. In the traditional top-down approach, the role of the functional strategies is to support the decisions made at higher levels. As with higher-level strategies, a functional strategy requires a consistent pattern of decisions, and a central idea is that different business strategies will necessitate different patterns of decisions. In other words, trade-offs exist among the various possible decisions, and no one solution can satisfy the requirements of all possible strategies (Porter, 1996). Before discussing in more detail the content of a manufacturing strategy, it is important to note that linkages exist among the various functional strategies. The result is that functional strategies cannot be developed in isolation of one another. Instead, a strategic fit should be sought among different functional areas (Porter, 1996). Porter defines three levels of strategic fit: consistent, reinforcing, and optimization of effort. These levels of fit represent the degree to which activities are aligned across an organization. A consistent fit "ensures that the competitive advantages of activities cumulate and do not erode or cancel themselves out. It makes the strategy easier to communicate to customers, employees, and shareholders, and improves the implementation through single-mindedness in the corporation." (Porter, 1996) With a reinforcing fit, activities in some functional areas are designed to support activities in other areas. For example, decisions might be made in marketing to steer demand towards the mix of products that manufacturing is most adept at producing. In the ideal case, a firm would achieve optimization of effort, where functional groups work together to reinforce behavior and activities leading towards the achievement of strategic objectives.

2.3.4 Manufacturing Strategy

As described previously, the manufacturing function is viewed as one potential area of competitive advantage, and a manufacturing strategy is therefore an important functional element of a company's strategy. Once the higher-level steps of market positioning and business configuration have been considered, a firm can focus on defining what each functional area must do to achieve the desired strategic fit. In the case of the manufacturing functional area, Skinner (1969) refers to this step as defining the "manufacturing task," where doing so involves describing what must be accomplished by manufacturing in order to compete. Reinforcing the existence of trade-offs in manufacturing system design, Hayes and Wheelwright state that an effective manufacturing strategy is not necessarily the one promising maximum production efficiency, but is the one that best supports the business strategy. Recognizing that manufacturing encompasses a wide range of decisions, Abernathy, Clark, and Kantrow (1981) developed a framework (shown in Figure 2-3) for viewing the challenges faced by manufacturing managers.

Hayes and Wheelwright build upon this framework, stating that effective manufacturers focus their efforts on making improvements at the "micro" level (i.e., quadrants 3 and 4) rather than trying to blame problems on factors in quadrant 1 or 2. Additionally, they state that although quadrant 3 issues usually receive the most attention, several companies have leveraged quadrant 4 strengths to create a lasting competitive advantage. They go on to refine the "micro" level decisions into the categories shown in Table 2-2.

The "structural" categories shown in Table 2-2 are generally viewed as being long-term, high-impact decisions that require a significant investment and effort to implement. "Infrastructural" decisions are regarded as being more "tactical" in nature as they typically involve a myriad of smaller ongoing decisions. Shi and Gregory (1998) added seven new categories to this list. New structural categories included geographic dispersion, horizontal coordination, and vertical coordination. New infrastructural categories presented were dynamic response, transfer of knowledge, management information system, and network capability building. Clearly, interactions exist among the various decision categories, and a good manufacturing strategy is defined as being one that is *consistent*, both internally (decisions do not conflict with one another) and externally (decisions support higher-level strategies). Good manufacturing strategies are also measured by their ability to *contribute* to business strategy, directing attention to opportunities and providing the needed capabilities.

	Structure ("hardware")	Infrastructure ("software")
Macro (country)	1. Fiscal/tax policies Monetary policies Trade policies Industrial policies Capital markets Political structure Organized labor	2. Culture Traditions Religion Values Social behavior
Micro (company)	3. Business Market Selection Plant and equipment decisions Capacity Facilities Process technology Vertical Integration	4. Measurement and control systems Workforce policies Vendor relationships Management selection and development policies Capital budgeting systems Organizational structure

Figure 2-3: Key elements of manufacturing competitiveness (Abernathy, Clark, and Kantrow, 1981)

Table 2-2: Manufacturing strategy decision categories (adapted from Hayes and Wheelwright, 1984)

Decision Category	Decision Variables
Structural	
Capacity	Amount, timing, type
Facilities	Size, location, focus
Process Technology	Equipment, automation, linkages
Vertical Integration	Direction, extent, balance
Infrastructural	
Manufacturing planning and control	Computerization, centralization, sourcing
Quality	Defect prevention, monitoring, intervention
Organization	Structure, reporting levels, control
Workforce	Skill level, wage policies, employment security

2.4 A Unified Framework for Strategy

Reviewing the recent literature, it becomes clear that several different perspectives exist regarding manufacturing strategy. Researchers discuss capabilities, activities, configurations, positioning, fit, marketing, operational effectiveness, and a variety of other topics. While on the surface it may seem that some of these ideas are contradictory, these views can also be seen as complementary components of a larger framework. This framework, illustrated in Figure 2-4, was developed to bring together the disparate views found in the literature and to unite them with a common structure and vocabulary (Duda et al., 1999b).

The framework for strategy shown in Figure 2-4 was developed based on that of Hayes and Wheelwright (1984, see Figure 2-1) with some key modifications made to reflect additional concepts in manufacturing strategy. Although the top-down flow of strategies is preserved, this framework also shows the feedback necessary for the iterative nature of the strategy development process. This framework also emphasizes the importance of achieving strategic fit across the many different and separate functional areas.

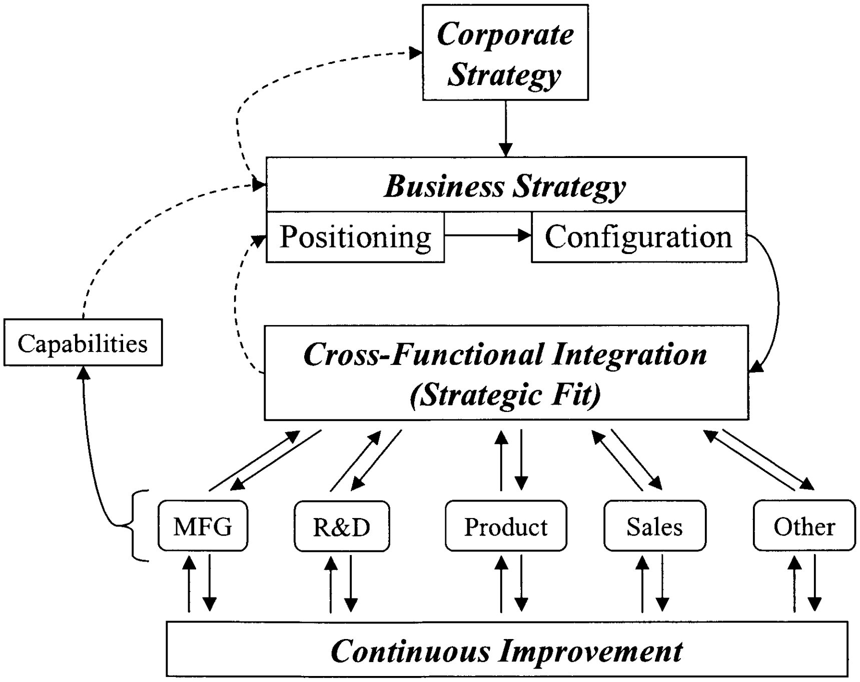


Figure 2-4: Framework for strategy (Duda et al., 1999b)

As with Hayes and Wheelwright's framework, the framework shown in Figure 2-4 represents a process beginning with the development of a corporate level strategy to determine the overall objectives of the company and, at a high level, how it intends to compete in its various businesses. With a corporate strategy in place, a more specific strategy for each business unit can be developed. Although Figure 2-4 shows only one business strategy, a large corporation might be split into several business units, each with its own distinct strategy. As described previously, developing a business strategy involves defining a desired market position in terms of trade-offs among factors such as cost, conformance quality, product features, delivery performance, flexibility, etc. Choosing such a position leads naturally to the definition of a basic business configuration and an organizational structure aimed at meeting the business' strategic objectives. At this level, a firm might decide, for example, that it wants to build an organization capable of providing a specialized product or service with a focus on a particular subset of customers. Alternatively, a firm might decide to offer a very wide range of products to a much larger segment of the market. In either case, the key is that the company chooses the basis on which it will compete and aligns its organizational structure according to this decision. The next step in the top-down process described in Figure 2-4 is the development of a cross-functional fit across activities performed in various branches of the business. In the context of this thesis, the focus will be on the manufacturing area and how decisions made here can support business-level objectives.

One important feature of this framework is that it highlights the roles of continuous improvement and capabilities development in the overall strategy development process. Although some might claim that continuous improvement is a strategy in and of itself, several researchers argue that continuous improvement is most valuable to a company when it is focused on supporting a well-defined business strategy (Pilkington, 1998; Hayes and Pisano, 1994). In other words, continuous improvement activities should be performed to support and build upon a business' strategic objectives. This process of improving manufacturing and increasing competitive advantage leads naturally to the development of improved internal capabilities. By developing strong internal capabilities, some companies have been able to maintain an advantage over competitors in the same market position simply by executing that same strategy more effectively (Hayes and Upton, 1998). Hayes and Pisano (1994) stress the importance of the development of strategic capabilities within an organization, stating that focusing on a few key areas of improvement and expertise can help to provide a firm with a competitive advantage and some strategic flexibility to continue to perform well in the face of changing market conditions and an evolving business strategy. In the framework presented here, this concept is represented by the feedback from manufacturing and other functional areas to business strategy via capabilities development. The process of strategy development is iterative, and a company's strategy is sure to be re-evaluated and modified over time. Clearly, the strength of internal capabilities is an important factor to consider when contemplating a shift to a new position in the market.

2.5 Summary and Conclusions

This chapter has presented a brief review of the literature in manufacturing strategy. The focus has been on how manufacturing strategy fits in as part of a firm's top-down approach to defining overall objectives and the means to achieve them. An important topic covered was the review of different categories of competitive priorities (cost, quality, delivery performance, flexibility, and innovativeness). The relative importance and the objectives set for each of these competitive priorities are important parts of a firm's strategy. The fundamental basis of manufacturing strategy is making decisions regarding the relative importance of each competitive priority, as such decisions determine how the firm will compete in its marketplace.

There are some researchers who disagree with this view of strategy, claiming that by effectively imitating the "best practices" of lean manufacturing and the Toyota Production System a firm can overcome trade-offs and simultaneously achieve optimal performance with respect to all aspects of strategy (Schonberger, 1986; Womack and Jones, 1996; Johnson and Bröms, 2000). This debate about the existence of trade-offs stems at least in part from the difficulty in trying to separate differences in strategy and prioritization from differences in execution. For example, it has been claimed that Toyota has been able to outperform its competitors in terms of cost, quality, flexibility, and delivery performance through superior manufacturing system design (Womack et al., 1990). Toyota's outstanding performance demonstrates that it has achieved excellent execution of its manufacturing goals, but achieving a high level of performance does not mean that trade-offs have been eliminated. Could Toyota further improve its product quality at the expense of higher cost? Could costs be reduced be making sacrifices in terms of delivery performance? If so, then designers face trade-offs and must make important decisions regarding priorities among different aspects of strategy. While Toyota has demonstrated that it is possible to have good performance with respect to many different aspects of strategy, this does not mean that trade-offs do not exist.

The view taken in this thesis is that such performance trade-offs inevitably exist, and that priorities must be set to guide designers in their decision-making process. Having the corporate goal "to be the best at everything" offers little support to designers faced with difficult manufacturing system design decisions when trade-offs are observed to exist. The research in this thesis focuses on the development of a decision support process to help firms translate their high-level strategic objectives into manufacturing system designs. A software tool is developed to help designers understand the relationships between low-level decisions and the achievement of high-level objectives. The goal of this work is to create a process by which a firm can clearly define the relative importance of its competitive priorities and then can design manufacturing systems to support its strategy. In addition to designing manufacturing systems to support a strategy, a firm must also ensure that ongoing improvement activities are focused on the critical aspects of performance. The next chapter of this thesis describes the role of performance measurement in keeping manufacturing systems aligned to corporate objectives as the system evolves and improves over time.

Chapter 3 Performance Measurement for Manufacturing

3.1 Introduction

In recent years, an overwhelming amount of research has focused on performance measurement. Neely (1999) notes that between 1994 and 1996 over 3600 articles on performance measurement were published; an average of one every five hours of every working day! Countless authors have emphasized the importance of performance measurement in a manufacturing environment. Yet the realization that performance measurement can have a powerful impact on manufacturing system performance and improvement is nothing new. In 1951, General Electric formed a task force to develop a set of appropriate business performance measures. Recognition of the importance of performance measurement in manufacturing and the need for a link between strategy and measurement can be traced back to Skinner's 1969 article on manufacturing strategy.

Interest in this field increased dramatically in the 1980's, with a particular focus on how costs were measured. Neely (1999) presents an interesting look at the factors leading to this increase in interest in performance measurement. One of these key factors was the changing cost structure in manufacturing. Traditional cost accounting systems had been developed in the early 1900's, a time when direct labor represented 50% or more of the total cost of goods sold. As this percentage dropped over time to less than 10% by the 1980's, traditional accounting, and most notably its methods for allocating overhead based on direct labor, became less effective and began leading managers to make poor decisions (Maskell, 1991; Kaplan, 1983). One result of this shortcoming in traditional methods has been a focus on developing alternative cost accounting methods, such as activity-based accounting (Cooper, 1987a, 1987b) and other alternatives (see, for example, Johnson and Bröms, 2000).

Other factors identified by Neely as leading to increased interest in performance measurement stemmed from external changes faced by manufacturing firms. The globalization of manufacturing not only increased the level of competition, it also changed the nature of this competition. Firms became more interested in differentiating themselves based not only on cost, but also with respect to other, non-financial measures such as quality and responsiveness. A greater emphasis was placed on benchmarking and understanding how the firm stacked up against the competition. Firms responded to this increased competition by implementing new programs of improvement such as Total Quality Management, Computer Integrated Manufacturing, and Just-in-Time. At the same time, the development of advanced information technology made it easier to obtain data on more non-financial factors. The result has been an increase in attention to the importance of the firm's competitive position and the recognition that financial measures alone are not adequate to measure competitive advantage. This section presents a review of some of the major issues faced in developing a contemporary performance measurement system: one that includes both financial and non-financial measures to present a balanced look at the firm's manufacturing performance and to guide future improvement activities.

3.2 Function and Content of a Performance Measurement System

Neely, Gregory, and Platts (1995) define a performance measurement system as "the set of metrics used to quantify both the efficiency and effectiveness of actions," where the term metric is used to represent the measure itself plus information regarding the formula for calculating the measure, how the required data will be collected, who will be responsible for recording this data, etc. Such a performance measurement system can function as a tool to help a firm develop and maintain a competitive advantage. It does this by assessing the firm's competitive performance relative not only to past performance, but also to competitors and to the needs of the market. An effective performance measurement system should provide rapid feedback to the firm, guiding it in making consistent decisions and facilitating and motivating improvements that support the firm's strategic objectives (Wisner and Fawcett, 1991). Such a system consists of a set of performance measures spanning the organization, so that employees at all levels can understand how their daily activities relate to the firm's overall objectives. It is necessary to define not just the measures themselves, but also the means for obtaining the required data, and standards to assess how well the firm is doing.

3.3 Designing a Performance Measurement System

Many authors have presented models, techniques, or guidelines for designing systems for performance measurement (Maskell, 1991; Wisner and Fawcett, 1991; Kaplan and Norton, 1992; etc.). The nine-step process developed by Wisner and Fawcett is presented here, as it features elements common to nearly all processes. This process, shown in Figure 3-1, is similar to the strategy-development processes discussed in the previous chapter in that it begins with the determination of a firm's mission and the strategic objectives necessary to achieve it.

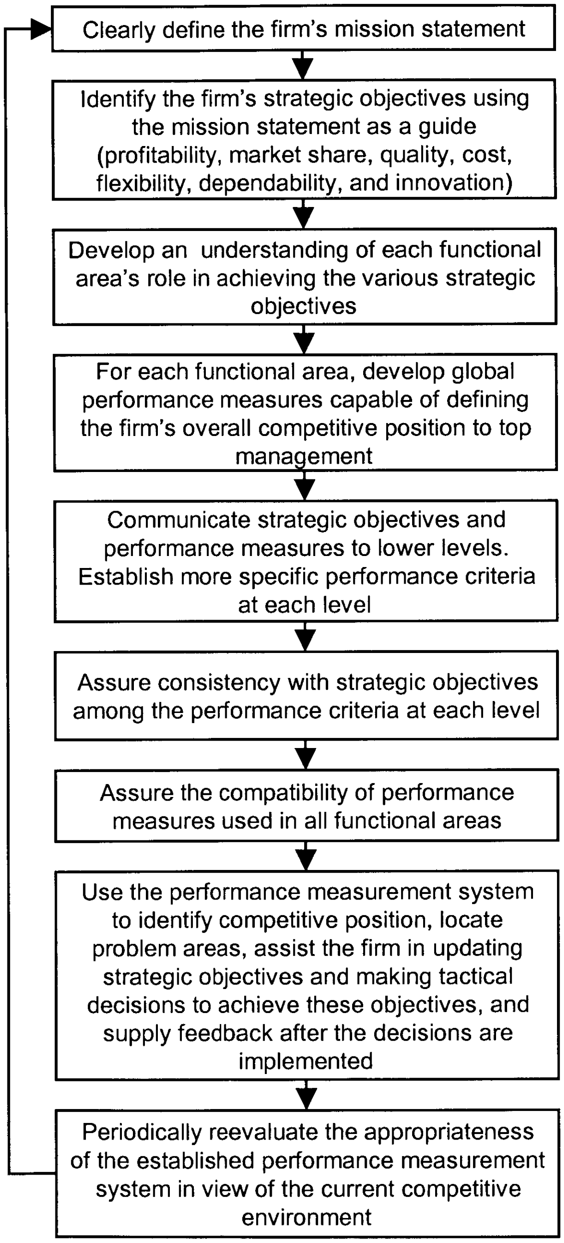


Figure 3-1: Performance measurement system design process (adapted from Wisner and Fawcett, 1991)

Once the role of a functional area (manufacturing, in this case) is understood, the next steps are to develop a set of high-level performance measurements and then to flow these requirements down to lower levels in the organization. Doing so requires dealing with three key issues: ensuring that performance measures are *consistent* from one organizational level to the next, ensuring *compatibility* among measures across a given level, and ensuring that a *complete* set of measures has been developed (i.e., the set covers all aspects of performance that are important in terms of the overall strategy). The measures themselves must be carefully selected so as to ensure consistency, compatibility, and completeness. Research in this area will be discussed in the following section. Once a set of performance measures has been defined across an organization, these measures can be used to monitor performance and to guide the firm to strategic improvements. It is also important that the performance measurement system be flexible to change over time as the firm reassesses its position in an environment of changing competition.

Although the process shown in Figure 3-1 is useful in terms of defining the steps that are involved in the design of a performance measurement system, further detail is needed to specify *how* these steps can be achieved. The research described in this thesis aims at defining techniques for developing and/or selecting performance measures, assuring consistency and compatibility among these measures, and linking the measures to the firm's strategy as well as its manufacturing system design.

3.4 Defining the Set of Performance Measures

3.4.1 Qualities of an Effective Set of Measures

A critical step in the process shown in Figure 3-1 is the definition of the performance measures themselves. As mentioned above, researchers suggest that a set of performance measures should be consistent, compatible, and complete. Consistency means that the encouraged lower-level activities support the achievement of higher-level objectives and vice-versa. An example of conflicting, or inconsistent performance measures could be if workers on the shop floor were measured based on machine utilization and their supervisor were measured on how well actual production matched the desired schedule. Measuring the workers based on machine utilization could encourage them to perform fewer changeovers, thus reducing downtime to machine setups and increasing utilization. However, the large run sizes that result would interfere with the supervisor's goal of producing the scheduled mix of parts. A consistent set of measures might include a measure of the time it takes to perform a setup, thus encouraging the operators to reduce setup times rather than to build inventory of unneeded part types. Compatibility among performance measures ensures that the various functional areas (e.g. manufacturing, marketing, research and development, etc.) are working together towards common goals. Finally, completeness ensures that the measurement system will capture sufficient data to monitor all of the important aspects of system performance and to connect the activities of employees to strategic goals. Most research on the generation and selection of performance measures focuses on this issue of completeness.

One approach for aiding in the design of a complete set of performance measures is to create a taxonomy or classification scheme for the measures. Different categories of performance measures are defined, and performance measurement system designers can then map their measures to these categories and identify any important unrepresented areas. White (1996) developed a taxonomy (based on a literature survey and compilation of 125 performance measures) to help designers think about *what* will be measured and *how* it will be measured. The question of what to measure is answered in terms of the firm's competitive priorities. Similar approaches are presented in (Neely et al., 1995; Wisner and Fawcett, 1991; and Maskell, 1991), with the primary idea being that a firm should measure performance with regard to every important aspect of its strategy. Although traditional performance measurement systems focused only on one aspect, cost, it has become accepted, in the literature if not completely in industry, that other non-financial measures must be included as well. Table 3-1 lists some representative examples of performance measures from these sources for each category.

Table 3-1: Performance measures for each competitive priority

Category of Competitive Priority	Performance Measures
Cost	Cost relative to competitors Manufacturing cost Total factor productivity Direct labor Inventory
Quality *Manufacturing products with high conformance and performance*	Perceived relative quality performance Reputation Number of complaints Warranty returns Percentage scrap Vendor quality Percent reduction in time between defect detection and correction
Delivery Performance	Percentage on-time delivery % reduction in purchase lead time System throughput time Vendor delivery time Response time Distance traveled
Flexibility *Primary emphasis is on volume and product mix flexibilities*	Set-up time Smallest economical volume Percentage workforce cross-trained % increase in multipurpose equipment How quickly plant responds to product mix changes How well plant adapts to volume changes
Innovativeness *Ability to quickly introduce new products and/or processes*	% reduction in material travel time between workstations % increase in annual number of new product introductions % increase in common parts per product

While the dimensions of manufacturing strategy or competitive priorities are quite common across the literature, the categories for how these priorities should be measured are less well established. White (1996) focuses on four issues:

Data source: internal or external

Data type: subjective or objective

Reference: benchmark or self-referenced

Process orientation: input or outcome

White's research showed that a majority of the performance measures used in industry are internal (data is generated entirely within the firm), objective (can be measured quantitatively), self-referenced (targets are set based on internal data), and outcome-oriented (measures the output of some internal process). He points out, however, that additional value can be obtained by including measures that focus on data that may be external or subjective or input-oriented, and by comparing the firm's performance to that of its competitors. Other classification schemes, such as those presented in (Flapper et al., 1996), consider the following issues:

Decision type: strategic (long term), tactical, or operational (short term)

Level of aggregation: overall or partial

Measurement unit: monetary, physical, or dimensionless

Level in organizational hierarchy

3.4.2 Qualities of an Effective Measure

Other research has focused on the qualities of effective performance measures, developing guidelines for use in the development and selection of appropriate measures. Globerson (1985), Neely et al. (1997), and Maskell (1991) present lists of guidelines and/or recommendations for developing effective measures. Table 3-2 shows several guidelines drawn from these and other works. These guidelines provide a wide range of suggestions for designing effective performance measures. However, it can also be seen that some issues remain unresolved within the literature. For example, Maskell proposes using only non-financial measures, while most researchers argue that financial measures still have an important place in a complete performance measurement system. Globerson recommends using criteria which can be measured objectively whenever possible, while White advocates the inclusion of subjective measures when necessary to measure aspects of performance that are abstract and difficult to measure qualitatively, but that are important none the less. Nevertheless, most researchers fundamentally agree on the principal qualities of a "good" measure, recognizing that an effective measure is one that can communicate relevant information in a timely manner to stimulate improvements that will improve the firm's competitive position.

Table 3-2: Guidelines for effective performance measures

Guideline	**Source**
Performance measures should be:	
directly related to the firm's manufacturing strategy	Maskell, 1991
non-financial	Maskell, 1991
simple and easy to use	Maskell, 1991
selected through discussions with the people involved	Globerson, 1985
designed to stimulate improvement rather than simply monitor	Maskell, 1991
based on quantities that can be influenced or controlled	Globerson, 1985
based on trends rather than snapshots	Lynch and Cross, 1991
aligned with the manufacturing system design	Cochran et al., 2000
Performance measures should:	
provide fast feedback	Maskell, 1991
have a clear purpose	Globerson, 1985
reflect the business process – i.e. involve both the supplier and the customer	Lynch and Cross, 1991
Ratio-based performance criteria are preferred to absolute numbers	Globerson, 1985
Objective performance criteria are preferable to subjective ones	Globerson, 1985
It should be recognized that measures vary between locations – one measure is not suitable for all departments or sites	Maskell, 1991
It should be acknowledged that measures change as circumstances do	Maskell, 1991

3.5 A Note on the Balanced Scorecard

One of the most well-known and widely used systems for business performance measurement is the balanced scorecard approach developed by Kaplan and Norton (1992). It is important to note that the balanced scorecard approach takes a higher-level look at performance measurement than the work previously discussed; it is meant to be a model for the entire firm's measurement system and not just that of manufacturing. Figure 3-2 shows the basic structure of the balanced scorecard. The fundamental goal of this approach is to focus attention on areas that are critical to the success of a business. The balanced scorecard is built upon the belief that although financial measures are a necessary component of any performance measurement system, they alone are not sufficient to guide the behavior of a contemporary business. In fact, no single measure can provide a clear performance target. Instead, the balanced scorecard seeks to help a firm answer the following four basic questions:

How do customers see us?
What must we excel at?
Can we continue to improve and create value?
How do we look to shareholders?

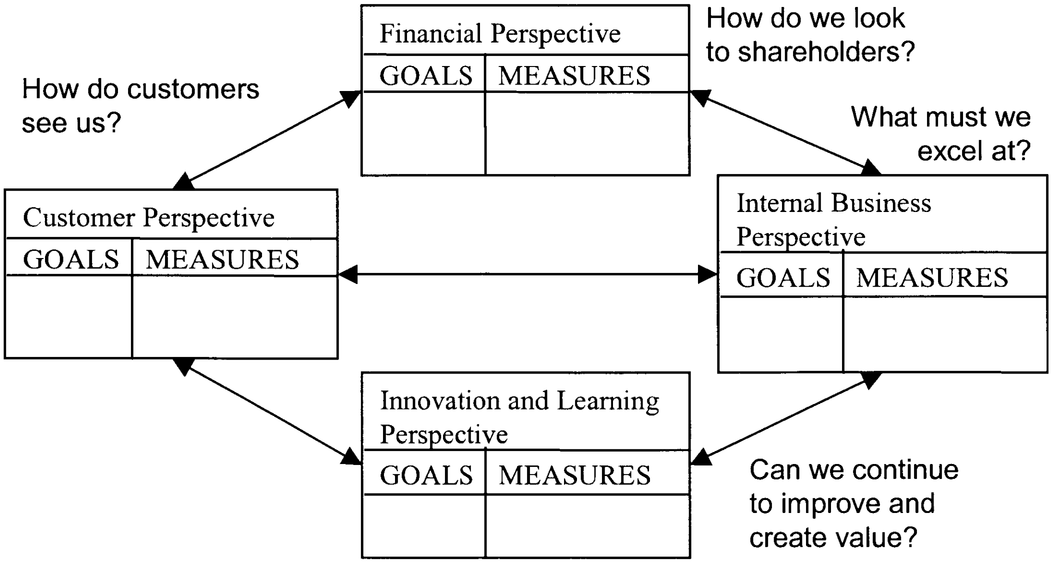


Figure 3-2: The balanced scorecard (adapted from Kaplan and Norton, 1992)

Figure 3-2 shows how these four questions lead to the following four "perspectives" on the performance of a company: financial, customer, innovation and learning, and internal business. From here, the balanced scorecard approach is quite similar to the performance measurement system design approach presented in Figure 3-1. Like the work discussed in the previous section, the balanced scorecard approach seeks to create a consistent, compatible, and complete set of performance measures for use throughout all levels of an organization. A central goal is to have workers at every level participate in the development in their own measures and to understand how their activities relate to the overall success of the firm.

3.6 Summary

This chapter has presented a review of the nature of performance measurement, with a focus on its application to manufacturing systems. This has been a subject of tremendous interest both in academia and in industry over the last twenty years, as it has been recognized that measures drive the daily activities of employees and that competitive success can only be achieved when these daily activities are aligned to the strategic objectives of the firm. In the modern manufacturing environment, traditional, exclusively financial measures of performance are no longer sufficient. As a result, research has focused on the process for designing a performance measurement system as well as the qualities of effective individual measures. The balanced scorecard approach has begun to emerge as one of the most well-known and frequently applied systems of measurement and incorporates many of the key ideas from the literature. Still, many open issues remain. Little work has been done regarding analysis of the consistency and completeness of a set of performance measures, and much work remains in terms of defining an operational process for developing and implementing an effective performance measurement system.

Chapter 4 Manufacturing System Design Methods

This chapter seeks to review prior work in the design of manufacturing systems, with a focus on the methods observed to be in practice. The chapter begins with a review of the engineering design process in general and then discusses how this process can be applied to the design of manufacturing systems. Observations of specific approaches to manufacturing system design are also included. Next, a brief review of the more holistic approaches to the design of complex systems is presented. The chapter concludes with a review of this prior work and the motivation for the research presented in this thesis.

4.1 Engineering Design Applied to Manufacturing Systems

The process of design has received much attention in engineering literature (see, for example, Pahl and Beitz, 1996; Suh, 1990; Pugh, 1991; Altshuller, 1988). Many definitions of design and models of the design process have been proposed. Although all definitions and models have their own individual features, some traits are common. Most agree that the process of design begins with the identification of a need, and that the act of designing involves taking this need and creating some sort of product that satisfies it. How this is done involves a combination of creativity, analysis, testing, and iteration. The product being designed is often a physical object, such as a gear or a transmission system, but it could just as well be something less concrete, such as an educational system or a quality improvement program. Regardless of the ultimate product, the fundamental design process remains basically the same. Figure 4-1 shows a general model of the design process. This model is based on several of the design processes proposed in the engineering literature (Norton, 1998; Ullman, 1992; Shigley and Mischke, 1989). Although this model illustrates the process as being a set of events occurring in series, iteration is always part of any design process and is expected to occur at many stages of the process. A review of the activities in each stage of the process follows, including a description of how each step relates to current practices in manufacturing system design.

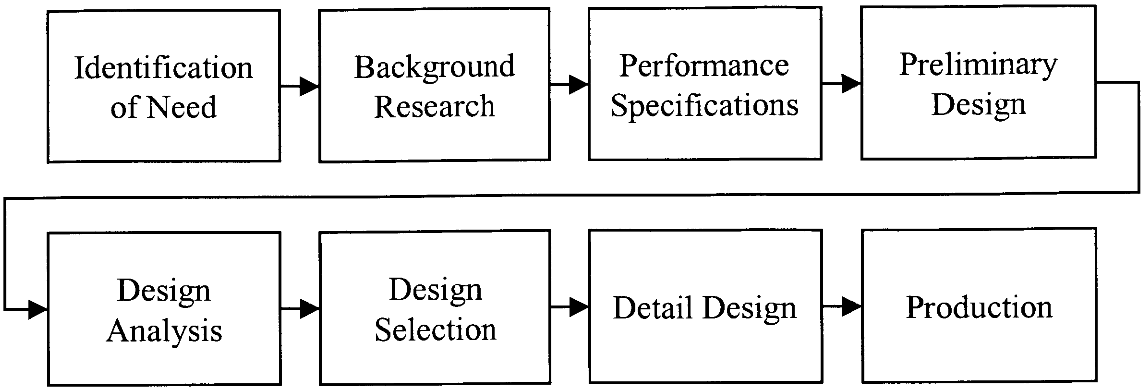


Figure 4-1: General model of the engineering design process

4.1.1 Identification of Need

The design process begins with the recognition and identification of a need or the desire for a new capability. At this stage, it is not necessary to consider how this need will be fulfilled. Instead, it is important to focus on identifying the most fundamental performance characteristics that are desired.

In the case of manufacturing system design, the identification of a need to manufacture a product essentially originates from an enterprise's corporate strategy. Manufacture of a product might be important in terms of the company's ability to meet the changing needs of a particular set of its customers, to establish or maintain a position of technological leadership, to meet growing demand for an existing product, or to grow the business by expanding into a new market. Alternatively, the need might be to improve or modify an existing system to better achieve changing strategic objectives, such as a need for increased responsiveness to changes in customer demand.

4.1.2 Background Research

An important next step in the process is to perform background research to investigate if / how similar needs have been addressed elsewhere. This can involve developing an understanding of what is "state of the art" in the relevant areas of interest.

In terms of manufacturing system design, this process generally includes competitive analysis and benchmarking. Beginning in the late 1970's, manufacturing firms have become increasingly aware of the value of benchmarking. This process can motivate learning and innovation, help to identify new sources of improvement, and enable a company to critically assess its own operations and define meaningful reference points for goal-setting and performance measurement. The benchmarking process begins with careful planning, including the identification of objectives and critical success factors. Once suitable partner sites have been identified, the team can begin to observe and analyze the partners' processes and systems, understanding and identifying not just the levels of performance achieved, but also the means for their achievement (Andersen and Pettersen, 1996).

Critics of benchmarking point out that the process is fundamentally backwards looking and history-based and is, at best, a "catch-up" strategy. This can, in fact, be the case, such as when firms seek to be "best-in-class" purely by identifying and copying the successful techniques (JIT, MRP, TQM, etc.) of industry leaders. However, benchmarking is not meant to be a strategy in itself, but instead should be viewed as an important step in the system design process, enabling a company to learn more about its competitors and the potential of its own operations.

4.1.3 Performance Specifications

By this stage, the design problem and its context should be clearly understood. Now, a more specific and detailed set of performance requirements can be drawn up. Again, it is important to focus on what is to be achieved, rather than the means that will be used to achieve it.

The means for developing an effective set of performance specifications or requirements for manufacturing system design is not often addressed in the literature. Performance specifications are often assumed to be "given," or it is assumed that these specifications and requirements are obvious or can be generated intuitively. The definition of this set of requirements is, however, a critical step in the process of designing a manufacturing system, as it is absolutely necessary to have a clear, well-defined, common understanding of the sought-after goals throughout the system design process. In a complex system such as a manufacturing system with a variety of different but interrelated elements, this requires significant communication and coordination among the various resources involved.

The formal methods for system specification and requirements generation that do exist are often presented as part of a general design process, such as Quality Function Deployment (QFD), Axiomatic Design, or Systems Engineering. The application of such methods to the generation of manufacturing system design specifications will be discussed in more detail in section 4.2 and in Chapter 5.

4.1.4 Preliminary Design

With the performance requirements in mind, the designer or design team can begin to develop design concepts. This stage of the process involves the generation of several design concepts and checks for feasibility.

At the highest level of abstraction, decisions must be made regarding how to organize the overall manufacturing system. This includes breaking the overall manufacturing system into various subsystems (if necessary) and defining the interfaces among these subsystems. For example, in an automotive vehicle manufacturing system, typical subsystems would include stamping, painting, and assembly. In automotive component manufacturing, separate subsystems are often used for machining and assembly operations, as assembly operations can require a cleaner environment than can practically be achieved in the presence of machine tools. Other considerations include the flow of materials, information, and other resources among the various subsystems. Rother and Shook (1998) describe "value stream mapping," a system used at Toyota to help capture and visualize the system design information at this high level. This process involves taking a "big picture" look at the sequence of processes needed to take a part from raw material all the way to the customer. Value stream mapping also requires initial decisions regarding the process plan, or sequence of manufacturing operations, necessary to create the final product. Decisions regarding the process plan to be used and the value stream concept can have a tremendous impact on final system cost and performance, as they drive machine design and purchasing decisions, the level and complexity of automation, and the role of direct and indirect production workers in the system. Once the desired value stream has been identified, designers can focus on the configuration of each subsystem. Different configurations considered could include: transfer lines, synchronous or asynchronous assembly lines, job shops, batch flow systems, "lean" cells, flexible manufacturing systems, etc. Requirements will be placed on each subsystem based on its interfaces with other subsystems and the desired overall system behavior. Decisions at this stage are often guided by high-level perceptions about important system requirements such as system capacity and product flexibility.

Figure 4-2 shows a well-known framework for thinking about the relationship between product and manufacturing system characteristics. The rows of the matrix represent different configurations of manufacturing systems, ranging from a job shop system to one based on continuous flow of material (Note: Hayes and Wheelwright refer to these as "process structures"). The columns represent product structures, or sets of defining product characteristics (primarily volume and variety). Hayes and Wheelwright (1979) point out that positions along the diagonal of this matrix represent "natural" configurations, but that a company might seek to differentiate itself and gain a competitive advantage by pursuing an off-diagonal position. A similar, extended version of this matrix was developed by Miltenburg (1995) and will be reviewed in Chapter 9.

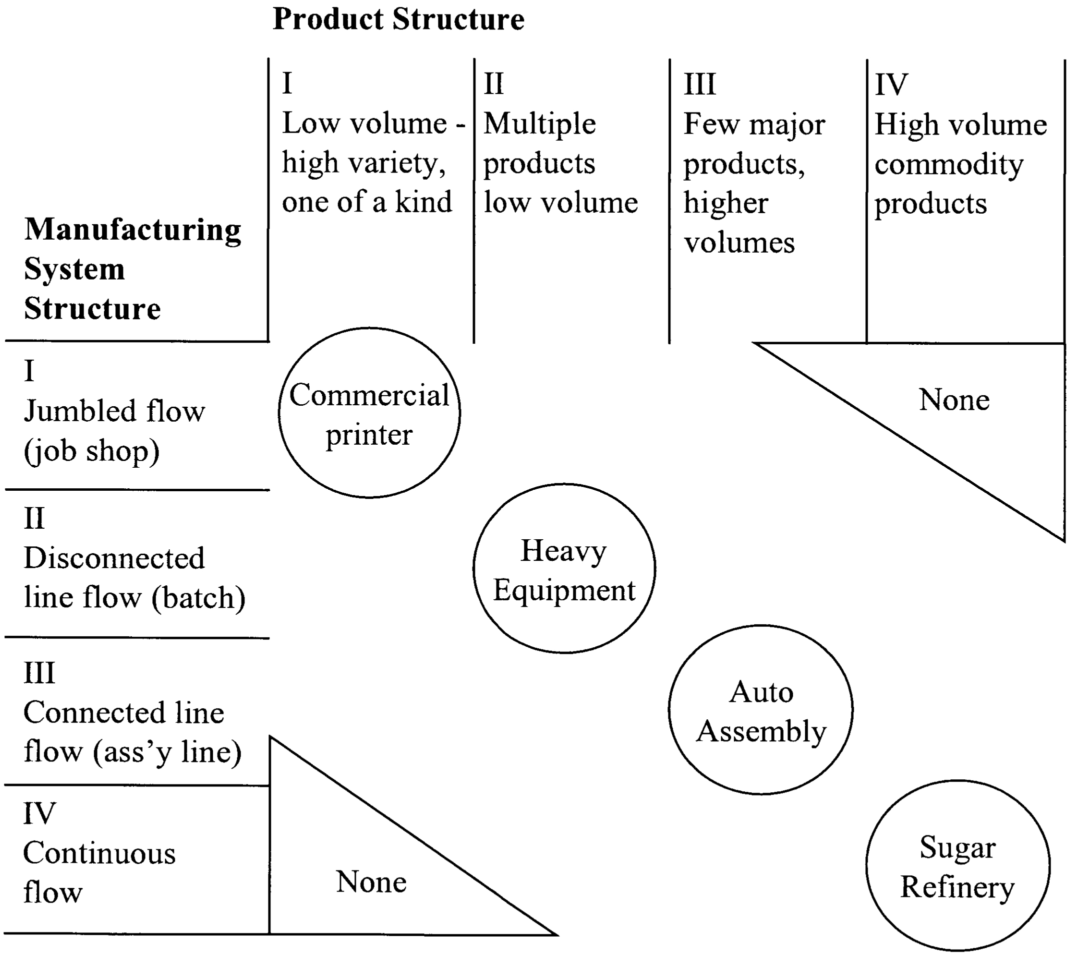


Figure 4-2: Manufacturing system - product matrix (adapted from Hayes and Wheelwright, 1979)

4.1.4.1 Observations on Preliminary Manufacturing System Design in Practice

In practice, these decisions on system configuration are often not made as part of any formal process. Observations of the preliminary design of manufacturing system designs at a variety of automotive component suppliers in the U.S. showed that, although each case was unique, the processes for making decisions regarding manufacturing system design configuration (layout, preliminary machine design, level of automation, etc.) could be grouped into the following broad categories:

Replication and improvement of a similar existing system
Decision to “go lean”
Incomplete system specification
Examination of multiple configurations

The result of these preliminary design processes was a high-level understanding of the possible system design(s), usually including basic information regarding equipment requirements, system layout, level of automation, and the role of operators. This information generally needed to be sufficient to generate an approximation of expenses and savings meaningful enough to be submitted as part of a request for project funding. Further descriptions of the four observed processes follow.

Replication and improvement of a similar existing system

Imitation of a familiar, often in-house manufacturing system design was the most frequently observed method for selecting a configuration for a new system. In the observed cases, a very similar line for a similar or identical product was already in place. The need for a new line was based on either an increase in demand for an existing product, or on demand for a new part with similar features and geometry but significant differences in terms of tooling and/or fixturing requirements caused by changes in either geometry or material properties. In such situations, preliminary design consisted mainly of imitation of the existing system with the potential for improvements if troublesome aspects of the existing system had been identified (stations with poor ergonomics or reliability, disappointing process capabilities, etc.). This method of selection was most commonly observed in situations where the company was generally satisfied with the performance of its existing manufacturing systems. The new system would be likely to have similar performance to the existing system, with the potential for some improvement based on lessons learned since the last system design iteration.

Decision to "go lean"

Essentially, this process represents an a prioiri decision to implement a particular type of manufacturing system that is significantly different from what that company has traditionally done in similar situations. In contrast to the previous scenario, plants using this method were generally dissatisfied with the performance of their existing manufacturing systems for similar products. In recent years (and in all of the observed cases falling into this category), this dissatisfaction and motivation for change has been motivated by upper-level managers reading and hearing about dramatic improvements in factory performance achieved by the conversion to "lean" manufacturing. The term "lean manufacturing" came about as a result of an international study of automotive manufacturing, described by Womack, Jones, and Roos in *The Machine that Changed the World.* This study found that certain automotive manufacturers, particularly Toyota, had implemented practices that were substantially different from the practices common in the U.S. and elsewhere, and that these practices resulted in superior performance. For more information on "lean" manufacturing and the Toyota Production System, the reader is directed to the work of Ohno (1988), Shingo (1988, 1989), and Womack (Womack and Jones, 1996; Womack et al., 1990). Practitioners, consultants, and academics who purport the benefits of just-in-time or lean often present these ideas as the ideal solution to all manufacturing problems and situations. This view is characterized by the following quote from *The Machine That Changed the World* (Womack et al., 1990):

> "Lean production is a superior way for humans to make things. It provides better products in wider variety at lower costs. Equally important, it provides more challenging and fulfilling work for employees at every level, from the factory to headquarters. It follows that the whole world should adopt lean production, and as quickly as possible."

When this view that trade-offs among manufacturing system designs no longer exist has been accepted, the preliminary design step is no longer necessary: the solution is automatically to implement a "lean" system. However, recent empirical evidence seems to indicate that system design is not so simple and that, although there is compatibility among some types of performance, trade-offs do still exist in manufacturing system design (Fillippini et al., 1998; Pilkington, 1998). The decision to "do lean" cannot, therefore, be assumed to be a universally optimal choice. Perhaps more importantly, this "just do it" approach has often led to a focus on imitating specific aspects or tools of lean manufacturing (e.g. kanban, u-shaped cells, etc.) without first understanding the system objectives and how these "lean" elements can help to achieve them, as was discussed in section 1.1. Hayes and Pisano (1994) note that companies trying to improve their competitiveness by implementing a program such as Just-in-Time (JIT) or Total Quality Management (TQM) seldom achieve the desired results, as the firms focus on these generic approaches rather than on developing their own unique competitive strategy.

Incomplete system specification

In the two situations just described (replication of existing systems and "going lean"), preliminary manufacturing system design consisted of selecting a system configuration without first analyzing the unique characteristics of the new system's requirements. With incomplete system specification, the selection of a system configuration is postponed until later in the design process. Preliminary system design work instead focuses on developing a process plan and selecting equipment so as to minimize initial investment. In this situation, the system design process is viewed fundamentally as consisting of three serial decisions: selecting equipment, then deciding how to arrange it into a layout, and finally figuring out how many operators are needed and what each one will do. Preliminary design was observed to occur in this manner in cases where there was a perceived need to get project funding approved as rapidly as possible while using a very limited amount of engineering resources. In such cases it was assumed that equipment costs would represent a large majority of the total investment cost, and so this information was critical to have in order to estimate the required investment with enough confidence to submit a project for funding approval. It was also assumed that issues of system configuration, layout, and operator work routines would not significantly impact project cost, equipment design, or system performance and could, therefore, be postponed until after project funding had been approved.

Examination of multiple configurations

Finally, there are the cases in which multiple manufacturing system configurations were considered and evaluated. Observations of this process showed that it generally started off with a review of what had been done previously in similar situations, both within the factory and at other companies. This was followed by qualitative discussions on the expected pros and cons of the various system configurations. From these discussions, the two most promising configurations were identified for further investigation. Depending on the situation, this extended analysis was performed either in-house by the engineering team or was, in effect, outsourced to the machine tool suppliers. This second case occurred when engineering resources were too scarce to adequately pursue multiple designs in sufficient detail. Instead, multiple vendors were contacted to quote on an integrated line design (as opposed to quoting just on specific pieces of equipment). The specifications for each vendor were the same, with the exception that different vendors were given different direction on what type of system configuration to pursue. For example, identical information regarding capacity, product, process plan, and quality requirements was distributed, but one vendor might be asked to quote a transfer line design while another vendor worked on a quote for a flexible manufacturing system (FMS).

4.1.4.2 Summary of Preliminary System Design Observations

None of the preliminary manufacturing system design methods observed functions as suggested by design theory. In most cases, a system configuration was selected with little to no consideration of other alternatives. When attempts were made to analyze multiple possibilities, only qualitative, subjective comparisons could be made at this early stage. In many cases, particularly those in which preliminary system design was performed by one or more outside suppliers, communication of system objectives and requirements was a major issue. It is clear that it is not enough simply to tell a team of engineers to "design a lean system." Without a clear understanding of the elements of lean manufacturing, how each element contributes to system performance, and the interrelations that exist among the elements, it is extremely difficult to effectively communicate the system design objectives. A manufacturing system design decomposition, discussed in chapter 5 of this thesis, has been developed to address this need for a tool to aid designers in understanding the relationships among the elements of a manufacturing system design and understanding how these low-level elements relate to higher-level objectives.

4.1.5 Design Analysis

Evaluation and analysis of design concepts requires the establishment of a set of metrics to measure each design's performance relative to the specifications. The result of this stage is an understanding of how well each potential design is able to meet the performance specifications.

As described in the previous section, system analysis is often very qualitative and subjective during the early stages of system design. As the design process continues and the manufacturing system design becomes more concrete, this analysis can be performed with the aid of more quantitative tools developed in the field of operations research. These design analysis tools can be divided into two categories based on their functions: to evaluate system performance, or to optimize it, usually by determining the best allocation of one or more scarce resources. A great deal of literature exists on such methods and tools; only a brief review of these techniques is presented here.

4.1.5.1 Operations Research Tools for Evaluating Manufacturing System Design

This category includes the use of simulation and/or queuing models to evaluate potential designs in terms of performance and feasibility. In some cases, these tools are used only to evaluate potential designs. In other, more sophisticated examples, an iterative process of several analysis runs can be used to optimize one or more aspects of the design. In this case, the basic structure of the system is an input to the analysis model, but some aspects of the system design are treated as variables, such as buffer sizes or machine capacities. Several commercial software packages have been created specifically for simulating the performance of manufacturing systems (ProModel, Witness, Deneb's Quest, etc.). Analytical tools, also typically implemented in the form of software, have also been developed to perform similar analyses, with the advantage of not having to rely on stochastic processes and reducing algorithm runtimes. Disadvantages of analytical approaches include decreased flexibility in dealing with system variables and configurations. For example, existing analytical models are based on strict assumptions regarding product flow, variety, equipment changeover times, etc. Simulation tools are more capable of dealing with the unique properties of a non-standard manufacturing system design. Also, many simulation tools provide a graphical representation of the system's operations, which can be valuable for demonstrating the system's functionality and beginning to develop an intuitive understanding of its behavior. The use of simulation packages for manufacturing system design analysis is widely accepted in industry and was observed in several of the instances described in the previous section. Simulation tools were often used to analyze a system design in terms of capacity, product mix flexibility, and required inventory levels. Both simulation and analytical tools require that a fairly specific and detailed system design be known. Data regarding operation cycle times, reliability, changeover times, material routing, are critical inputs to such tools, and whatever results are obtained will be highly dependent on the accuracy of this input data.

4.1.5.2 Operations Research Tools for Optimal Allocation of Scarce Resources

In this case, there is a system structure in place and the question being addressed is how to best operate the system. Problems in this category include the scheduling of different part types through a job shop or FMS system, the routing of automated guided vehicles (AGV's), the allocation of workers to various tasks, the allocation of assembly operations to stations in a line, determining lot sizes, etc. In these cases, the structure of the system (i.e., that which is capital investment intensive) is generally assumed to be existing and fixed. The objective is to make the most efficient use of these resources in terms of multiple objectives (cost, quality, throughput time, etc.). In other words, the goal is to find a solution that costs little or nothing to implement, but can result in a significant increase in performance. A variety of operations research techniques can be employed to examine such problems, including several forms of linear and non-linear programming, integer programming, simulated annealing, genetic algorithms, etc.

4.1.6 Design Selection

Based on the information gathered through analysis, the designer or design team must select which design concept will be best able to fulfill the identified need(s). Because multiple performance specifications will almost always exist, making such a decision will involve the study of trade-offs among different areas of performance.

Tools developed in operations research and decision science can be used to aid in decision-making. The role of these tools is to provide an objective, quantitative means for comparing among alternative designs. In general, no design synthesis is done. Various alternative designs have been created previously, and they are treated as inputs to the problem. Operations research provides multiple criteria group decision support systems to aid in making such decisions. Iz and Gardiner (1993) provide a survey of these systems, including the Analytic Hierarchy Process (AHP) (Saaty, 1980), the Judgmental Analysis System (Islei and Lockett, 1988), and several other tools for making multi-criteria decisions when the entire set of alternative solutions is known. Other methods such as Interactive Multiple Objective Programming (Steuer and Choo, 1983) and various forms of goal programming are reviewed for cases in which the set of solutions is defined by a set of constraints but is not explicitly known.

One limitation inherent to these approaches is the subjective nature of the ranking and priority information that must be obtained. A solution is only "optimal" to the extent that the subjective judgments and comparisons are accurate and consistent. In some methods, such as the AHP, redundant judgments are obtained and used to check for inconsistencies. Other methods have been developed based on the progressive articulation of preferences, allowing the decision maker to revise his or her preference structure as more information becomes available regarding the nature of the trade-offs and the potential solutions (see, for example, Stam and Kuula, 1991).

4.1.7 Detail Design

Once a "best" conceptual design has been selected, its characteristics must be further specified to the point where it may be fully realized. For physical products, this involves the generation of a complete set of engineering drawings for all parts of the design. For less concrete systems, detailed design might also include the formal definition of various operating policies and guidelines.

In terms of manufacturing system design, detail design encompasses a broad range of activities, including the specification and design of machine tools, material-handling devices, tooling and fixturing, etc. Detail design also includes the specification of operator work content, scheduling policies, buffer sizes and locations, and other, less-tangible design details (e.g. quality procedures, maintenance policies, etc.).

4.1.8 Production

The final step in this design process is the actual creation and/or implementation of the designed product or system. This often involves pre-production of some form of model or prototype for testing prior to ramping up to full-scale production. In cases of manufacturing system design, this will involve run-offs and trials of machines and equipment in isolation and then as an integrated system. Production will generally begin at a volume or rate somewhat lower than the target and then "ramp up" to the desired level as initial problems and difficulties are identified and improvements are made.

4.1.9 Summary

This section has presented a general model of the engineering design process and given an overview of how it applies to the design of manufacturing systems. It has been observed that manufacturing system design in practice often does not function as prescribed by design theory. Tools exist to aid designers with the individual steps in the design process, but far fewer tools have been developed and accepted in industry for providing an overall design process. With this basic model of the steps of the design process in mind, the following sections will review more holistic approaches for the design of manufacturing systems. These approaches will be related back to this design process model in order to show the scope of activities which each entails.

4.2 Integrated Approaches to Manufacturing System Design

This section presents a review of design approaches that relate to several of the steps in the engineering design process shown in Figure 4-1. Two basic categories of design approaches are discussed: design based on a general, high-level philosophy of what constitutes a "good" manufacturing system design, and design based on a more formal systems engineering approach.

4.2.1 Design by Philosophy

In many industrial settings, a company-wide "design philosophy" guides designers through all stages of the manufacturing system design process. Even if not defined explicitly, a consistent and effectively communicated philosophy can have a profound impact on an organization and its manufacturing systems. In automotive manufacturing, the most famous contemporary example of this is Toyota and its Toyota Production System (TPS). Even though Toyota does not have a formal and complete written specification of its production system design, its operators and engineers share a common vision of the characteristics of an ideal system design (Spear and Bowen, 1999). The result has been that Toyota has been highly successful at designing and improving its manufacturing systems to achieve goals such as defect minimization, cost reduction, flexibility, and effective workforce utilization. This success has attracted a great deal of attention over the past twenty years as other manufacturers from a variety of industries have been eager to duplicate Toyota's well-documented achievements.

Much has been written about the Toyota and its production system (see, for example, Ohno, 1988; Shingo, 1989; Womack et al., 1990, etc.), yet few firms have been able to duplicate Toyota's results (Spear and Bowen, 1999). Although the tools of TPS (kanban, setup time reduction, mistake-proofing, etc.) are well understood and documented, it has proven to be very difficult to duplicate the overall system performance that Toyota has achieved. Many obstacles exist in terms of trying to create a firm with a shared philosophy of what the firm's objectives are and a vision of how to achieve them. In firms with existing manufacturing systems, changing the attitudes of engineers and operators can be particularly difficult. Unless all members of the organization understand the motivation for change, the new objectives that are sought, and how the proposed means fulfill these objectives, a shared philosophy of manufacturing is unlikely to develop. Similar to establishing a manufacturing strategy, creating a shared vision of how manufacturing should function requires a consistency of purpose over time. Managers must be capable of understanding what goals and levels of improvement are reasonable to expect and must set these goals in a uniform and consistent manner. If unattainable levels of performance are demanded or if the objectives and/or the prescribed means to achieve them continuously change over time, no company-wide shared vision will develop, and managers will run the risk of alienating the employees and workers. In summary, designing manufacturing systems based on an enterprise-wide philosophy of the ideal manufacturing system can be very powerful, but is extremely difficult to achieve and requires a deep understanding of the underlying objectives and the means for achieving them. This understanding must then be reflected in a consistent series of decisions over time that will serve to reinforce the ideals of the enterprise and build a shared vision among all stakeholders.

4.2.2 Systems Engineering

The field of systems engineering has grown in importance as the need to effectively design large complex systems has increased. This section provides a brief review of systems engineering concepts with an eye towards how systems engineering principles can be applied to manufacturing system design.

Most traditional design methods are based on a bottom-up approach, where a product or system is created through the combination, assembly, and/or integration of existing elements. Once such a design is generated, it is analyzed to determine how well it can satisfy the given design requirements. Further refinements are made based on this evaluation, and this process of synthesis-analysis-evaluation is iterated until an acceptable design solution has been reached. While this type of bottom-up process can be a very effective approach in some situations, it can also be problematic when applied to the design of large complex systems. A large-scale complex system will typically involve multiple, disparate disciplines. Decision making will be fragmented and will be made more difficult by the presence of some degree of risk and uncertainty regarding future events, the necessity for qualitative value judgments, and numerous interactions among the different aspects of the system design. In such cases, a systems engineering approach is needed to improve methods for defining requirements as they relate to customer needs, to address the total system from a life-cycle perspective, to consider the overall system hierarchy and interactions among system elements both across a given level and between higher and lower levels in the hierarchy, and to organize and integrate the various engineering and related disciplines (Blanchard and Fabrycky, 1998).

Systems Engineering Applied to Manufacturing System Design

The strengths of systems engineering techniques are well suited to the task of designing manufacturing systems, as integrating disparate subsystems, analyzing complex systems to assess emergent behavior, and providing a common format for communicating information are all important issues in factory design. Although applications of systems engineering approaches to factory or manufacturing system design have been limited, research has presented methods of using object-oriented and other systems engineering techniques for manufacturing system design, analysis, and simulation.

One of the earliest applications of systems engineering principles to the problem of manufacturing system design was the development of the IDEF (Integrated computer-aided manufacturing DEFinition or, simply, Integrated DEFinition) system description technique by the U.S. Air Force (Mayer et al., 1995). IDEF was developed as a tool for describing the structure of information and organization in a complex manufacturing system and consists of multiple levels ($IDEF_0 - IDEF_4$). Each level represents a technique that can be used to study a particular aspect of a manufacturing system design. For example, $IDEF_0$ can be used to create a top-down functional model of a manufacturing system. Wu (1992) presents an example an $IDEF_0$ model of the functional structure of a manufacturing system. Other levels of IDEF deal with relational database models ($IDEF_1$), simulation analysis ($IDEF_2$), and the design of manufacturing processes ($IDEF_3$) and software ($IDEF_4$). Additional levels have been added to the IDEF methodology over time to include various additional aspects of manufacturing system design. Currently, eight levels of IDEF have been defined and another seven levels are under development (Mayer et al., 1995).

These IDEF tools have proven to be useful and powerful tools for manufacturing system description and analysis, providing an effective and standardized method to communicate and examine the details of system designs. Disadvantages to the use of the IDEF methods include the substantial learning time involved, the ambiguity of implementation processes, and the lack of a unified framework to provide guidance for understanding how the many IDEF tools (i.e. levels) fit into an overall design process (Wu, 1992).

4.2.3 Conclusions on Integrated Approaches to Manufacturing System Design

The two categories of design approaches reviewed here, design by philosophy and systems engineering, are similar in that each can have a strong influence on the way in which important decisions are made in an organization. Each type of approach seeks to guide designers in understanding how to achieve the overall, high-level objectives of the firm. The means employed to achieve this are quite different, however. Design by philosophy seeks to guide design by creating a mostly qualitative shared vision of the properties of an ideal manufacturing system. Systems engineering, on the other hand, provides a more structured, scientific approach in which more quantitative analysis can be used to define system design alternatives.

The primary limitation of each approach is the ambiguity and abstractness with which it is defined. In design by philosophy, it is extremely difficult to explicitly define exactly what the properties of an ideal manufacturing system are. As a result, information remains implicitly defined and communication and knowledge transfer become significantly more difficult. In systems engineering, knowledge and information can be communicated much more explicitly.

However, the details of the approach itself remain difficult to define explicitly. The systems engineering literature presents a variety of high-level, abstractly defined design and analysis techniques, but it is not easily determined how to implement or interpret these techniques in the context of a particular manufacturing system design problem.

The research presented in the following chapters seeks to combine some of the advantages of each of these approaches with the goal of developing an overall manufacturing system design technique that can be applied more effectively in industry. The following chapter will present an axiomatic design-based decomposition that seeks to add a more formal structure to the development of the characteristics of a "good" manufacturing system. This decomposition includes explicitly defined system requirements and design parameters, including traceability from low-level design details to higher-level objectives.

Chapter 5 A Decomposition-Based Approach to Understanding Manufacturing System Design

5.1 Overview

In designing a complex entity such as a manufacturing system, many requirements will be generated at many levels. High-level requirements could include factors such as investment cost and system capacity. Lower-level requirements include those based on more concrete factors such as machine configuration and process parameters. To assist designers in understanding the relationships among these many disparate requirements, a general set of requirements and design elements for a manufacturing system design has been developed in the Production System Design Lab at MIT. This decomposition (shown in Appendix A-1) was developed based on the principles of axiomatic design. This chapter will begin with a discussion of the motivation for developing such a decomposition and a review of other, similar frameworks that have been developed both in industry and in academia. A review of the fundamentals of axiomatic design will follow, with a focus on the structured method it provides for performing the decomposition of a system's functional requirements (FR's) and design parameters (DP's). Next, the upper levels of the manufacturing system design decomposition itself will be reviewed.

5.1.1 Motivation

The manufacturing system design decomposition was developed as a part of an effort to better understand the interrelations of the many elements of a manufacturing system design. Initial work on using axiomatic design to analyze the requirements on a manufacturing system design focused on the elements of the Toyota Production System and comparing TPS to the more traditional approaches of mass production systems (Cochran, 1994). Initial versions of this decomposition and examples of its applicability to actual systems are presented in (Suh et al., 1998; Cochran, 1999; Arinez et al., 1999; and Duda et al., 1999a). Further work on the decomposition focused on making it more generally applicable to a wider range of manufacturing systems. It has been observed that the manufacturing system design decomposition can be a useful tool towards the following ends:

- Understanding the relationships between high level system objectives (increasing customer satisfaction, reducing system throughput time, etc.) and lower level design decisions (equipment design and selection, system layout, etc.)
- Understanding the interrelations among various elements of a system design including the precedence and cause-effect relations that determine a system's ability to meet high-level requirements and objectives
- Communicating this information to a group of system designers
- Aligning performance measures to the firm's high-level objectives

5.2 Other Manufacturing System Design Frameworks

Other existing methods for thinking about and communicating the interrelationships of manufacturing system design elements were reviewed as part of the decomposition's development process. These methods for relating and communicating ideas can be thought of as frameworks, or conceptual structures used to organize groups of ideas. Many companies have developed their own frameworks to summarize their own concepts and ideas about how manufacturing systems should be designed. In recent years, these frameworks have often been based on the principles of "lean manufacturing," or the Toyota Production System. In general, no American automotive company would like to say that they use Toyota's or anyone else's production system design, and so personalized versions of it have been developed (for example, the Ford Production System, Chrysler Operating System, Delphi Production System, etc.) Although a number of these system design frameworks do exist, the focus here will be on reviewing those that relate lower-level design elements and decisions (e.g. reduced changeover time or inventory) to system-level objectives such as cost and quality.

Of the frameworks reviewed, none was developed using a formal decomposition method such as Axiomatic Design or Quality Function Deployment (QFD), and only one provided a distinction between system requirements, objectives, and design parameters. That is, most of the frameworks do not explicitly distinguish between what the system design is trying to achieve (the ends) and how it will be achieved (the means). This idea of separating the means from the ends is central to the theory of axiomatic design and will be further discussed in section 5.3.1. Instead, these frameworks seek to provide structure relating various "tools" for manufacturing system design and improvement.

5.2.1 Toyota Production System Framework (Toyota Supplier Support Center)

Perhaps the most well known framework for thinking about the elements of the Toyota Production System or lean manufacturing is that shown in Figure 5-1. This framework is not so much a decomposition as it is a visual display of the key elements of the Toyota Production System (TPS) made to emphasize the supporting role that these elements play in achieving the high-level system goals. This framework shows that, at the highest level, TPS has three goals: high quality, lowest cost, and shortest lead time. The framework emphasizes that stable manufacturing processes are the foundation of a good system design, and that stability (i.e. minimized variation of process output) is a necessary condition for achieving all of the higher-level goals. Other tools such as just-in-time manufacturing and jidoka are then necessary to fully realize the goals of TPS, but they can only be successful when built upon stable manufacturing processes.

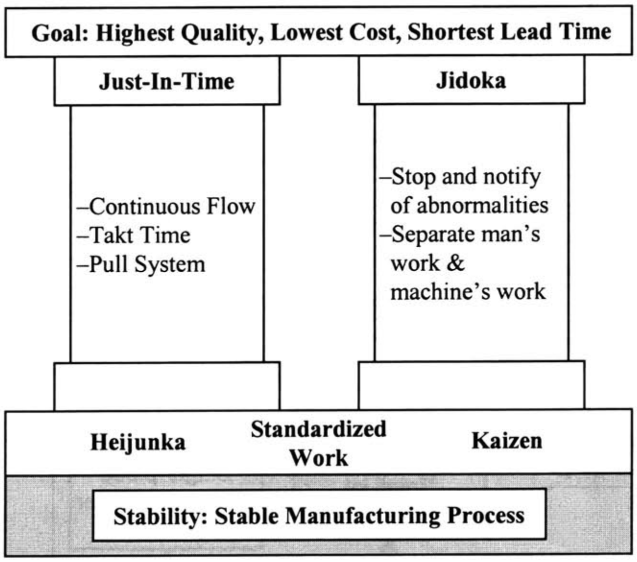


Figure 5-1: Toyota Production System framework (TSSC, 1998)

5.2.2 Toyota Production System Framework (Monden)

Another framework for understanding TPS was developed by Monden (1983, pg. 328). This framework was developed to show how the elements of TPS support the high-level objectives, and also to recommend an implementation order for these elements.

Monden's framework places improvement activities performed by the operators (i.e., kaizen) as the foundation for all other design improvements. In other words, a manufacturing system cannot be effectively improved until an effective process for making improvements is in place. The upward flow shown in the figure describes the order in which these elements can be implemented, where the lower-level elements are viewed as being prerequisites for the higher-level objectives. For example, a factory must have short setup times before it can attempt small lot production, and a company must have production smoothing before it can successfully implement a kanban system or "just-in-time" production. This type of framework is very useful in explaining why it is not enough to simply copy some aspects of TPS without first implementing others, a commonly criticized technique used by many American firms when the ideas of TPS were first becoming widely known in the 1980's.

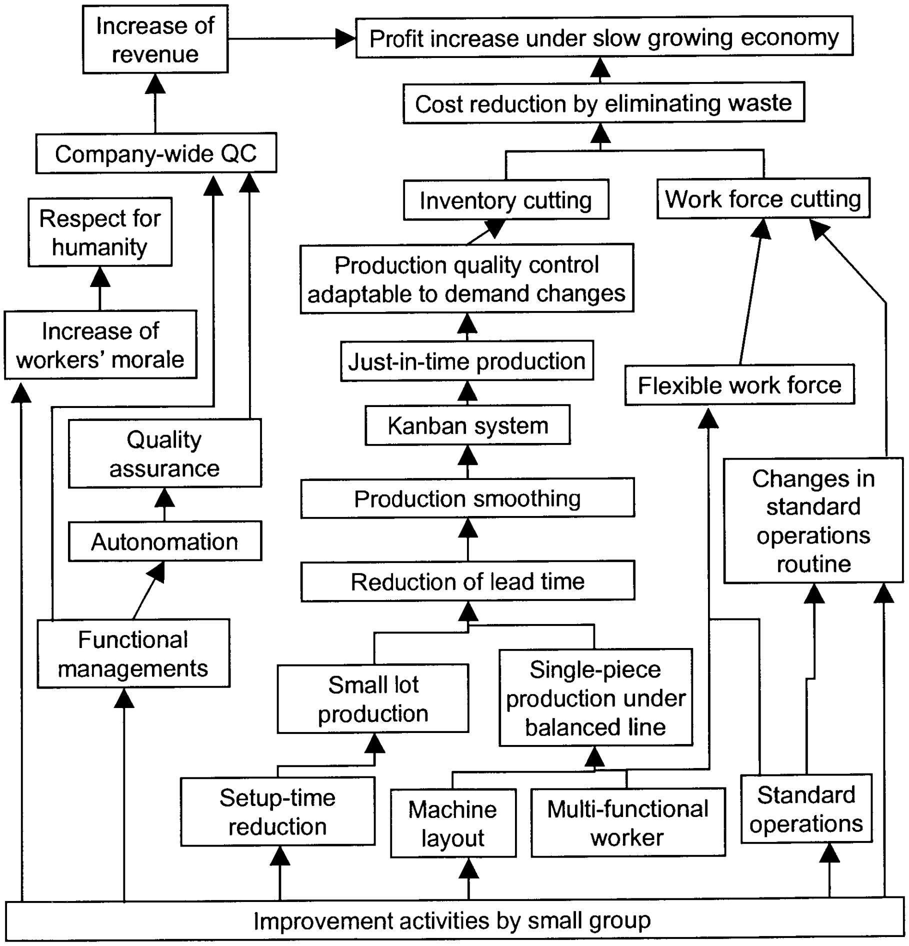


Figure 5-2: Toyota Production System framework (Monden, 1983)

5.2.3 “Lean Manufacturing Framework” (TRW Automotive)

Another framework for relating the elements of the Toyota Production System to higher-level objectives has been developed by Masafumi Suzuki of TRW Automotive in Japan (Suzuki, 1999). This framework, shown in Figure 5-3, expands upon the “pillars” of the Toyota Production System: Just-in-time production and jidoka. The framework shows the more specific design elements, or methods, that contribute to these two “pillars,” and also relates these methods to the seven types of waste defined by Ohno (1988). In this figure, a solid-line arrow indicates a strong correlation between a method and a type of waste, and a dotted-line arrow is used to show a weaker connection. According to this framework, the elimination of waste is important in terms of achieving two high-level goals: cost reduction and the improvement of productivity.

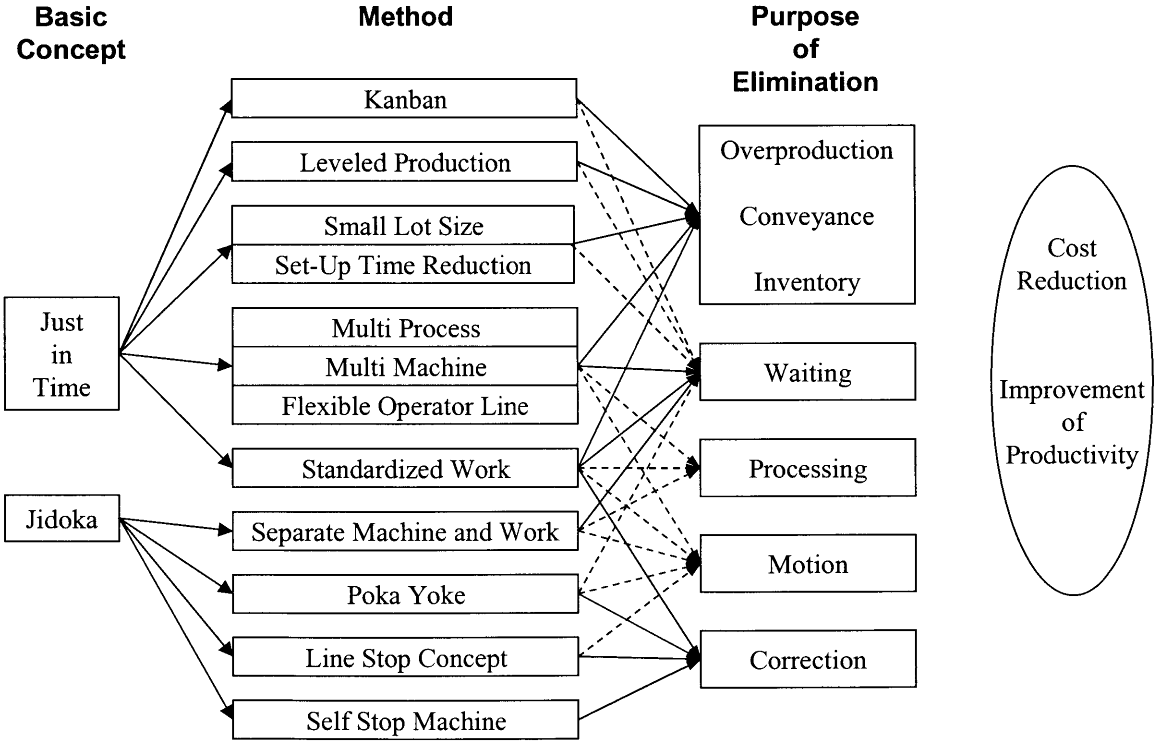


Figure 5-3: “Lean” manufacturing system framework (Suzuki, 1999)

5.2.4 Hierarchy of Manufacturing Objectives

Figure 5-4 shows a hierarchy of manufacturing system objectives developed by Hopp and Spearman (1996). This hierarchy is a more general decomposition of manufacturing system

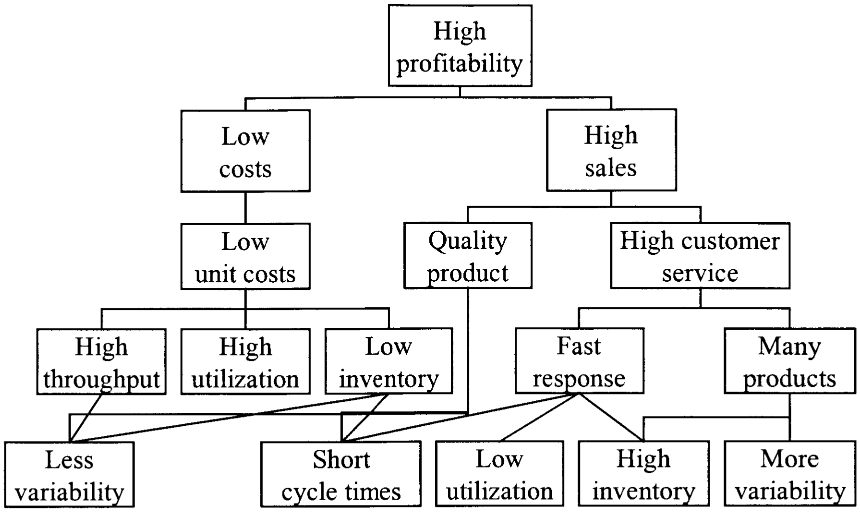


Figure 5-4: Hierarchy of objectives (Hopp and Spearman, 1996)

design requirements (not exclusively those of TPS), starting with the highest-level goal of high profitability. This goal is decomposed into lower-level objectives and finally into the means for achieving these objectives. This decomposition demonstrates that certain trade-offs exist in terms of trying to achieve "ideal" performance of a manufacturing system. For example, low levels of inventory help to lower production costs. Offering a wide variety of products could improve customer satisfaction and increase sales, but will increase the amount of inventory required in the system, thus increasing costs. Thus, trade-offs exist, and difficult decisions must be made. This framework also shows that one design element, short cycle time, contributes positively both to cost reduction and increased customer service. Note that Hopp and Spearman use the term cycle time to describe the amount of time a part spends in the system, referred to in the remainder of this thesis as throughput time.

5.2.5 Framework for Manufacturing Excellence

More closely related to the work herein is a framework proposed by Gilgeous and Gilgeous (1999) based on a study of several "Best Factory of the Year" award winners in the UK. This work sought to provide manufacturing managers with a means to identify specific operations and activities they should engage in to achieve their desired performance objectives. The resulting framework considers four manufacturing system performance objectives: quality, cost, delivery, and flexibility. Based on an examination of the award-winning factories, eight initiatives were identified, with each initiative contributing to the achievement of each performance objective. Examples of initiatives include "innovation and change," "commitment to quality," and "technology and information systems." Specific activities and enablers that facilitate the implementation of the initiatives were then identified. Some enablers, such as "training," "teams," and "continuous improvement," were found to support multiple initiatives; others were unique to a particular initiative, such as "SPC throughout" to enable the "quality commitment" initiative and "ownership given to employees" to enable "empowerment." The forty-one enablers range from shop floor activities such as mistake proofing and statistical process control (SPC) to managerial factors such as pay structures and organizational design. The resulting overall framework provides a broad view of the many low-level activities that can be pursued in a manufacturing organization to achieve high-level performance objectives. Still, many of these enablers remain conceptual in nature and represent lower-level objectives rather than the final means to achieve something. For example, "responsiveness," "flexibility," and "defect prevention" are all enablers that can be viewed as lower-level objectives that will aid in achieving higher-level goals. However, the means to achieve responsiveness, flexibility, and defect prevention are not always clear. Also, because each initiative is said to improve performance with respect to each of the four performance objectives, the framework provides only limited guidance on how to achieve any one particular objective.

5.2.6 Summary of Frameworks Reviewed

Each of these frameworks provides a means for relating the different elements of a manufacturing system design. It is interesting to note that there does not seem to be a general consensus on what the highest-level goals of a manufacturing system design are (or should be), nor is there a consensus on what the "foundation" of a good manufacturing system design is. Nevertheless, these frameworks do have much in common in terms of how they relate the elements and improvement activities to one another and to the higher-level objectives of a firm. However, two questions still arise with each of these frameworks:

- How was the framework developed?
- How can this information be used as part of the manufacturing system design process?

Monden's framework can be useful when improving an existing manufacturing system, serving as a means to identify which improvements are feasible to implement given the current state of the system. However, it is never clear exactly how to best use any of this information when designing a new system. The remainder of this chapter focuses on the development of a manufacturing system design decomposition of requirements that seeks to fulfill this need. The decomposition will be reviewed along with the ideas of axiomatic design, the structured process used to develop the decomposition. The remaining chapters of this thesis focus on how this decomposition can be used as part of an integrated approach to designing and measuring a manufacturing system so as to meet strategic objectives and fulfill the desired requirements.

5.3 Manufacturing System Design Decomposition

As described previously, the motivation for the manufacturing system design decomposition (MSDD) was the desire to have a formal structure to relate low-level activities to high-level objectives, to understand the interrelations of the elements of a design, and to communicate this information to the personnel involved in the design of new manufacturing systems. The manufacturing system design decomposition was developed based on the systematic, top-down methodology of axiomatic design. Before describing the decomposition itself, a review of the fundamental principles of axiomatic design will be presented.

5.3.1 Axiomatic Design

Axiomatic design was developed in order to provide a scientific approach for the generation and selection of good design solutions (Suh, 1990). While there are many steps in the design process (as described in section 4.1), axiomatic design theory focuses on the generation of requirements and the selection of means for achieving them. In fact, one of the most central ideas of axiomatic design is the importance of distinguishing between *what* is to be achieved and *how* it will be achieved. In axiomatic design terminology, the objectives of the design (known as functional requirements, or FR's) are expressed in the functional domain and the solutions (known as design parameters, or DP's) are expressed in the physical domain. The design process therefore becomes one of selecting the best set of DP's to satisfy the necessary FR's. Two axioms, the independence axiom and the information axiom, guide the designer in selecting the best possible set of DP's for each set of FR's. These axioms will be discussed further as the process for decomposition is reviewed. For more detail on these axioms and the axiomatic design process, the reader is directed to (Suh, 1990; Suh, 1999; and Tate, 1999).

Another key contribution of axiomatic design is that it provides a formal method for the decomposition of functional requirements and design parameters. A summary of this process is shown in Figure 5-5. The following sections present a review of these steps with an emphasis on their application to the design of manufacturing systems.

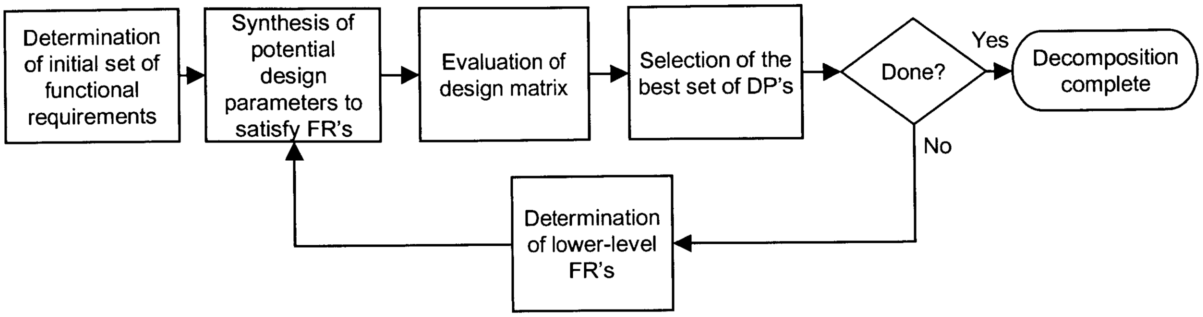


Figure 5-5: Axiomatic design decomposition process

5.3.1.1 Determination of an Initial Set of FR's

The development of the highest-level functional requirement(s) is based upon the perceived needs and desires of the customer. The goal is to develop "the minimum set of independent requirements that completely characterize the desired functions of the design" (Suh, 1999, pg. 3.8). Suh describes this process as a mapping from the customer domain to the functional domain, where the requirements should always be stated in solution-neutral terms. In the case of the MSDD, some thought was necessary to determine who the "customer" was. One alternative would have been to consider all of the relevant stakeholders (system operators, the firm itself, shareholders, the customers who would be purchasing the products, etc.) and to generate FR's for each. Instead, only the firm was considered to be the "customer" of the system, as the firm is the one who will pay for, operate, and live with the system. It is ultimately in the firm's best interest to satisfy all stakeholders to the greatest extent possible, and so FR's related to stakeholders other than the firm itself arise as means for satisfying the firm's objectives, as will be seen in the following section.

5.3.1.2 Synthesis of Design Parameters to Satisfy the FR's

This step involves determining *how* the just-determined functional requirements will be met. Synthesis of design parameters is essentially a creative process. A fundamental concept of axiomatic design is that one and only DP should be developed to satisfy an FR. At high levels, these design parameters may be conceptual in nature, describing a general system or structure for achieving an FR without yet containing enough information to be implemented.

At the lowest level, DP's should describe a solution concept in enough detail to be implemented. Typically, decomposition proceeds until all FR's and DP's have been decomposed to an operational level of detail. In the case of the manufacturing system design decomposition presented here, decomposition did not proceed to this level of detail. The goal of the MSDD was not to specify a detailed, fully implementable system design, but instead to create a design structure that would be general enough to apply in a wide variety of design situations. As a result, the design parameters are less concrete than normal, describing conceptually how the functional requirements can be satisfied without necessarily specifying all the precise details for doing so.

5.3.1.3 Evaluation of the Design Matrix

In axiomatic design, the functional and physical domains are connected by means of design matrices. That is, a vector of functional requirements can be related to its associated vector of DP's according to the equation:

$$\{\text{FR's}\} = [\text{A}]\{\text{DP's}\} \tag{5.1}$$

The elements of the design matrix indicate the effects of changes of the DP's on the FR's (Tate, 1999). In cases where the design parameters and functional requirements can be related mathematically, the matrix A can be constructed as a set of partial derivatives. However, in the case of the MSDD presented here, most FR's and DP's are more conceptual in nature and mathematical relations between them are difficult if not impossible to define. In such cases, the design matrix concept can still be applied. The elements of the matrix cannot be quantified as partial derivatives; instead the entries in the matrix show simply whether or not some relationship exists between implementing the associated DP and achieving the associated FR. As an example, consider the design equation shown below.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{5.2}$$

The elements of the design matrix, expressed as X's and 0's, indicate the presence or absence of a relationship between the FR's and DP's. X's should always be present along the diagonal, meaning that each DP affects its associated FR (e.g., a_{11}=X indicates that DP_1 affects FR_1). The X at a_{21} shows that DP_1 also affects FR_2. The following section will describe how the design matrix can be used to evaluate potential designs.

The information these matrices contain can also be represented graphically, as shown in Figure 5-6. An arrow from a DP to an FR indicates the presence of a non-zero off-diagonal element in the design matrix. For example, the figure below shows the graphical representation for the design matrix shown in equation 5.2.

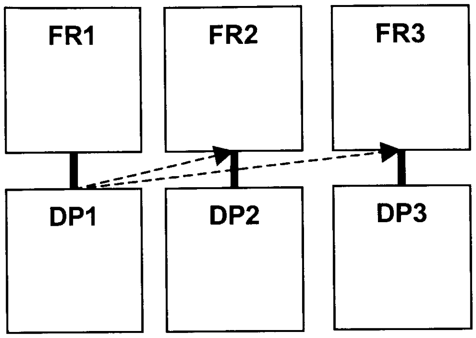


Figure 5-6: Graphical representation of design matrix

When dealing with abstract FR's and DP's, is it not always clear what it means for a DP to "affect" an FR. In the case of the MSDD, the following questions were used to determine the appropriate value for an element a_{ij} of a design matrix:

Does this particular choice for DP_j affect system performance in terms of FR_i?

Would failing to implement DP_j impede the system's ability to satisfy FR_i?

5.3.1.4 Selection of the Best Set of DP's

The two axioms of axiomatic design are used to select the best set of possible design parameters. The two axioms are as follows (Suh, 1990):

Axiom 1: The independence axiom

Maintain the independence of the functional requirements.

Axiom 2: The information axiom

Minimize the information content of the design

The first axiom states that when multiple FR's exist, the design solution must be such that each FR can be satisfied without affecting the other FR's. When this is achieved, the design matrix will be diagonal, as each DP will affect only its associated FR with no coupling occurring in the off-diagonal elements. Such a design is said to be uncoupled. In cases where independence is not achieved, two possibilities arise. In one case, the design will be partially coupled, meaning that the rows and columns of the design matrix can be rearranged such that the matrix is upper or lower triangular. In the graphical format shown in Figure 5-6, partially coupled designs are those in which all arrows point to the right. When off-diagonal elements exist and the matrix cannot be rearranged to a triangular state, the design is said to be coupled.

The information axiom states simply that simpler designs are better. Quantifying the complexity or information content of system designs can be quite difficult, however. More details on the application of this axiom can be found in (Suh, 1990; Suh, 1999; and Tate, 1999). The information axiom was not used in creating the MSDD, and thus will not be discussed further herein.

The two axioms can be used to select the best possible set of DP's when multiple options have been developed. Ideally, one would like to find a set of DP's that maintains functional independence (i.e., avoids coupling) while maintaining minimal complexity. These two goals are generally found to be consistent, as the presence of non-zero off-diagonal elements in the design matrix leads to complexity in system designs.

In developing the MSDD there were many instances where partial coupling existed between FR's and DP's. In all cases, the FR's and DP's could be arranged to create a lower-triangular design matrix (i.e. all arrows pointing to the right in the graphical representation). The information in the design matrix can be interpreted as defining the prerequisites for the achievement of each FR. When the FR's and DP's are arranged in the manner just described, the prerequisites for an FR always appear to its left. For example, looking at the third level of FR's and DP's in Appendix A-1, we can see that the prerequisites for FR113, "Meet customer expected lead time," include DP113, "Mean throughput time reduction," DP112, "Throughput time variation reduction," and DP 111, "Defect-free production." The MSDD shows that reducing or eliminating the production of defects enables the firm to have more predictable delivery and to better meet customer's expected lead time. More discussion of this notion of prerequisites will be presented in the following section when the levels of the decomposition are reviewed in greater detail.

5.3.1.5 Determination of Lower-Level FR's

Once a set of DP's has been settled upon, the next step is to determine whether or not further decomposition is necessary. As discussed previously, this would normally be done by determining whether or not the current design contained sufficient information to be operational. If so, further decomposition is not needed. In the case of the MSDD, decomposition proceeded for as long as it was possible to do so without beginning to limit the usefulness or range of applicability of the decomposition.

When further decomposition is needed, the next step is to develop the next level of FR's. By following a downward path in the MSDD, one can see this alternation back and forth between FR's and DP's as decomposition proceeds. In developing lower-level FR's for the manufacturing system design decomposition, the focus was on breaking down the higher-level FR-DP pair into its component parts. Questions asked at this stage included:

What are the components of the parent FR and/or DP?

What requirements are placed on these components?

Take, for example, the highest level FR-DP pair: "Maximize long-term return on investment" - "Manufacturing system design." In this case, the parent FR was broken down into components based on the formula for ROI:

$$ROI = \frac{\text{Revenue - Cost}}{\text{Investment}} \tag{5.3}$$

So, the components of ROI are revenue, cost, and investment over the life cycle of the system. The requirements placed on these components are that life cycle cost and investment should be minimized and revenue should be maximized in order to maximize long-term ROI. In other cases, such as FR-DP113: "Meet customer expected lead time" - "Mean throughput time reduction," the DP was broken down into its components, i.e. the different sources of throughput time, and the requirements generated were to minimize each component in order to minimize the total.

5.3.1.6 Summary of Axiomatic Design and its Use for Developing the MSDD

To recap, axiomatic design provides a structured approach for the decomposition of high-level requirements and design concepts into a more detailed state. Design axioms guide the designers in choosing the best design parameters to fulfill the functional requirements. This axiomatic design decomposition process (shown in Figure 5-5) was used to develop a decomposition of a general manufacturing system design.

Before describing the MSDD in more detail, some clarification of the role of design parameters is in order. It is important to understand the difference between design parameters and components of system structure. A design parameter describes a particular characteristic or feature of one or more system components. One physical element of a system may be affected by many DP's. Suh (1990) refers to this condition as the physical integration of multiple DP's into one physical object. Yang and Trewn (1998) go a step further, presenting an approach in which system structure is treated as a separate domain, such that a mapping process is needed to go from the design domain (i.e., the DP's) to the structure domain (i.e., the physical components of the system's structure). In the case of the MSDD, it will be shown that there are cases when one design parameter applies to many physical elements of a manufacturing system's structure, and there are cases when many DP's apply to an individual element of system structure.

In using axiomatic design to develop the manufacturing system design decomposition, a number of strengths and limitations of the approach were identified. This section reviews these advantages and disadvantages and how they were dealt with.

Strengths of the Axiomatic Design Approach

Separation of objectives from solutions: As described previously, one key advantage to axiomatic design is that it emphasizes the separation of design objectives and requirements from the solutions used to achieve them. In developing the MSDD, this separation was useful for clarifying our thought process and helping us to focus on *what* was to be achieved prior to determining how the system would be designed.

Structured approach to decomposition: Axiomatic design provides a formal process for developing a decomposition of the functional requirements and design parameters of a design. This structure was found to be useful in guiding our thinking and determining how to proceed.

Defining interrelations among functional requirements and design parameters: The use of the design matrix to relate design parameters to functional requirements provided a convenient and simple means for representing cause-effect relationships between the implementation of a particular DP and system performance relative to a given FR. This information proved to be very useful in terms of ordering the elements of the decomposition and determining a sequence for further decomposition.

Communication of design information: One important strength of the axiomatic design approach is that the resulting decomposition contains a great deal of information in a format that provides a visual representation of the hierarchical relationships between FR's and DP's from one level to the next as well as the precedence relationships that exist across a given level. The completed decomposition was found to be very useful as a tool for explaining these concepts to people previously unfamiliar with them. A detailed knowledge of axiomatic design is not necessary in order to understand the majority of the information contained in the manufacturing system design decomposition.

Limitations of the Axiomatic Design Approach

Confusing terminology and time to learn: Axiomatic design theory uses unique and sometimes counter-intuitive definitions and terminology. As a result, it can be quite confusing to newcomers to the field and learning the decomposition process well enough to perform it effectively can require a substantial investment of time. For example, the words "uncoupled" and "decoupled" are synonyms in common English; in axiomatic design, these two words have distinctly different meanings.

Application to a more abstract field: Some difficulties arose from the fact that manufacturing system design is a more abstract field than product design. While the subject of a product design process is generally a physical object, the design of manufacturing systems is more abstract. Design parameters often did not represent concrete design elements such as a valve or a housing, but were more conceptual in nature, representing information, a procedure, or characteristics that applied to an entire class of objects.

Arbitrary high-level DP's to encapsulate several ideas: Related to the last point, it was often found that non-leaf DP's (i.e. those that required further decomposition) were difficult to develop, as they represented a conceptual grouping of ideas without a meaningful physical representation. In many cases, upper-level DP's were simply restatements of the FR in a slightly different format. For example, the design parameter for the FR "Maximize long-term return on investment" is "manufacturing system design." This DP, when viewed in isolation, provides the designer with little useful information about how the objective is to be achieved. It is only by looking at its decomposition that additional insight can be gained.

Determining entries in the design matrix: In most cases, the entries in the design matrix were binary variables, taking a value of one if the DP impacted achievement of the relevant FR or a value of zero if it did not. In few cases could a more mathematical relationship be determined, due in a large part to the abstract nature of the DP's. Despite this simplification, in some cases it was still difficult to determine the proper values for the matrix entries. In cases where only a small relationship was identified between DP and FR, judgment was required to determine whether to assign a value of one or zero to the appropriate matrix entry.

Conclusions on the use of Axiomatic Design

Despite these limitations, Axiomatic Design proved to be a versatile and powerful tool for creating a decomposition of a manufacturing system's requirements and design parameters. Although other decomposition methods such as Quality Function Deployment (QFD) and IDEF$_0$ were considered, none provided as structured an approach for the decomposition process or as effective a means for connecting the "hows" of a manufacturing system design (i.e., the DP's) to the many ends these means sought to achieve.

5.3.2 Manufacturing System Design Decomposition

The complete version of the manufacturing system design decomposition (MSDD) is shown in Appendix A-1; a condensed version highlighting the upper levels is shown below in Figure 5-7. This section will review these upper levels, offering further explanations of the elements of the decomposition. Lower level FR's and DP's will be reviewed in the following chapters as examples are developed to show how the MSDD can be used as a tool for linking strategy, performance measurement, and system design decisions.

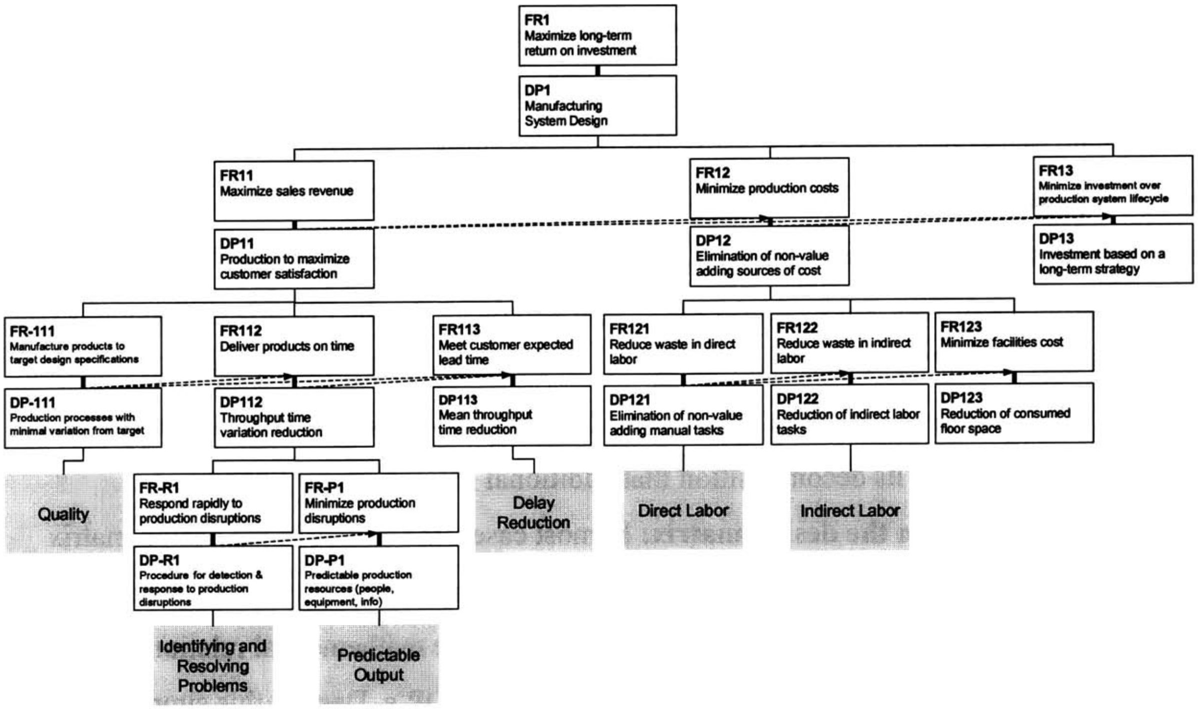


Figure 5-7: Manufacturing system design decomposition - Upper levels

5.3.2.1 Level One

The highest-level functional requirement was chosen to be "Maximize long-term return on investment." It is important to emphasize here that the goal is to maximize return on investment (ROI) over the life cycle of the system, not just in the immediate future. ROI has often been criticized as a measure of performance based on the claim that it encourages short-term thinking at the expense of long-term improvements (Johnson and Kaplan, 1987; Hayes and Wheelwright, 1979). The view taken here is that ROI does not inherently cause this behavior, it is the means often used to estimate ROI that result in a focus on the short-term. That is, the benefits of making advances such as reducing inventory, developing new products, creating a flexible system, improving customer relations, etc. can be very difficult to quantify in financial terms, and so these factors are often ignored in the calculation of the return on investment for a potential project. Although ROI may be very difficult to accurately assess, it is taken here as the highest level focus of the manufacturing function as it represents a general objective that is applicable to a wide variety of manufacturing environments and is not inherently contradictory to any accepted improvement activities.

The design parameter chosen as the means to achieve this FR is "manufacturing system design." Although other parts of a firm certainly contribute to overall performance and ROI, the focus of this work is the design of manufacturing systems, and the decomposition will be limited to those factors that a system design team will have the ability to strongly influence or control.

5.3.2.2 Levels Two and Three of the Manufacturing System Design Decomposition

As discussed in the previous section, the following three FR's must be achieved in order to satisfy FR-1 and to maximize long term ROI: FR-11, "maximize sales revenue," FR-12, "minimize production costs," and FR-13, "minimize investment over production system life cycle." Maximizing customer satisfaction (DP-11) was selected as the means to maximize revenues. This DP was then further decomposed based on the key attributes of manufacturing system performance that affect customer satisfaction: conformance quality (FR-111), on-time delivery (FR-112), and minimal lead-time (FR-113).

The prescribed means for achieving high quality is to ensure that production processes have minimal variation from the target (DP-111), as this focuses attention on improving manufacturing processes rather than trying to use final inspection to prevent the shipment of defective parts. The design matrix (shown with the arrows in Figure 5-7) shows that achieving DP-111 is critical for improving customer satisfaction. Quality variation and the production of defects makes system output unpredictable, adversely affecting FR-112, and means that more parts will have to be produced to replace these defects, adversely affecting FR-113. Thus, high conformance quality is a critical factor required to meet the high-level objectives of a manufacturing system design.

On-time delivery (FR-112) and short lead time (FR-113) are achieved by reducing the variation (DP-112) and the mean (DP-113) manufacturing throughput time. These two FR-DP pairs are based on the assumption that production is not speculative, but is based on actual demand. Variation reduction requires the ability to respond rapidly to production disruptions when they occur (FR-DP R1) and the increase of the reliability of production resources (FR-DP P1). Mean throughput time reduction is decomposed based on the various causes of delays in manufacturing systems. It is important to note the distinction made here between causes of variation in throughput time (addressed by DP-112) and causes of increases in mean throughput time (addressed by DP-113). The decomposition of DP-112 focuses on the elimination of factors that cause variation from the predicted system output; decomposition of DP-113 focuses on factors that increase throughput time but that can be accurately predicted. Thus, in a hypothetical system with no variation from what is predicted, the exact lead time for each order can be accurately predicted in advance, ensuring perfect on-time delivery performance. DP-112 is decomposed into two lower-level requirements for achieving this: FR-R1, responding quickly to unplanned disruptions such as machine breakdowns and material shortages, and FR-P1, the prevention of these disruptions.

The decomposition of FR-DP113 focuses on identifying predictable sources of delays and prescribing general solutions for their elimination. A delay is defined here as time that a part spends in the system when it is not being processed. Throughput time is defined as the total time that a part spends in the manufacturing system, from the time it enters as raw material to the time it leaves as a finished product. A fundamental relationship exists between the time a part spends in the system and the total number of parts in the system. This relationship, known as Little's Law (Little, 1961), can be expressed as follows:

$$L=\lambda * W \qquad (5.4)$$

where the variables and their units are the following:

L: Average quantity of parts in the system (i.e. total inventory) [parts]

λ: Average rate parts enter and leave the system [parts / time]

W: Average time spent in system (i.e. throughput time) [time]

This relationship assumes that the system is operating at a steady state, such that the rate parts enter the system is, on average, equal to the rate at which parts leave the system. If these rates are not equal, parts will either accumulate in the system (arrival rate > departure rate) or the number of parts in the system will go to zero (arrival rate < departure rate).

The delays identified in the MSDD include: lot delay, process delay, run size delay, transportation delay, and systematic operational delays. These delays all have root causes that can be predicted in advance. Lot delay, for example, results when parts are processed one at a time but are transported from one operation to the next in transfer batch sizes greater than one. For example, suppose that parts are transported in batches of 10. The first part processed must wait for the next nine before being transported to the next operation. The minimum amount of time each part will spend waiting for a transfer batch to be complete will be deterministic. The actual waiting time for a part may turn out to be longer due to other, stochastic occurrences (such as machine breakdowns), but the waiting time will not drop below this predicted minimum value. Section 5.3.2.3 presents a more detailed review of the various delays identified in the manufacturing system design decomposition.

The rightmost portion of the decomposition deals with reducing production and investment costs. Elimination of non-value adding sources of cost (DP-12) is the means for reducing production costs (FR-12). Three sources of waste are considered: direct labor (FR-DP 121), indirect labor (FR-DP 122), and facilities (FR-DP 123). Note that other "wastes" in manufacturing systems such as storage, transportation, and overproduction have already been considered in the decomposition as they increase throughput time as well as cost. Decomposition of DP-121 and DP-122 focuses on the effective utilization of labor, rather than on elimination of labor content and headcount reductions. Finally, FR-13, minimizing investment over the system life cycle, is achieved by making investments based on a long-term system strategy (DP-13). No further decomposition of this FR-DP pair is presented in the MSDD, as the specifics were found to be too dependent on the particular application. Decisions here might affect, for example, how flexible the system will be to changes in production volumes, or to changes in product design, or to the variety and mix of products demanded. There is no general answer as to how much flexibility is "the right amount," instead, the desired flexibility must be evaluated based on the firm's competitive environment and desired niche in the market.

One final important note on these top three levels is the information that the design matrices provide. One example, the importance of conformance quality, has already been described. It is also interesting to note the impact of maximizing customer satisfaction. The MSDD treats customer satisfaction as a prerequisite for the rest of the decomposition, meaning that it is a goal that must be achieved before costs and/or investment can be minimized. That is, the MSDD shows that minimizing running costs and investment at the expense of customer satisfaction is not a valid means for achieving the highest-level goals of the manufacturing system design. This information is consistent with related empirical and theoretical work in the literature. Ferdows and De Meyer (1990) developed a "sand cone" model, describing that manufacturing capabilities should be built by starting with quality, then focusing on dependability, then reaction speed and flexibility, and finally focusing on cost efficiency. Filippini et al. (1998) present empirical evidence to examine the existence of trade-offs among different aspects of manufacturing performance, finding that compatibility between delivery punctuality and economic performance was only observed in situations where high values of quality consistency had been achieved.

5.3.2.3 Lower Levels

As an example of the lower-levels of the manufacturing system design decomposition, the decomposition of FR-DP 113, "Meet customer expected lead time" - "Mean throughput time reduction," will be reviewed here. Other lower level FR/DP pairs will be reviewed in the remaining chapters.

As described previously, the manufacturing system design decomposition identifies five different types of delays (described by FR's T1 through T5 and their decompositions). This section will provide further details regarding each type of delay, including a definition, example, and a formula that can be used to calculate or estimate the amount of delay based on the parameters of the system design. It is important to note that these equations were derived so as to measure each delay in isolation of other factors. Each equation assumes that all unpredictable factors (e.g., machine breakdowns, quality problems, etc.) have been eliminated. A simple, two-operation manufacturing system will be used to develop examples of the different types of delays. Assume there are two processing operations (op. 10 and op. 20) necessary, each with a cycle time of two minutes, with no variability in processing time, reliability, or quality. It is also assumed that the customer of this system will demand one part every two minutes. As a result, the amount of inventory kept in the system must be sufficient to prevent the starvation of any of the operations. If an operation is idle in this scenario, demand will go unfulfilled.

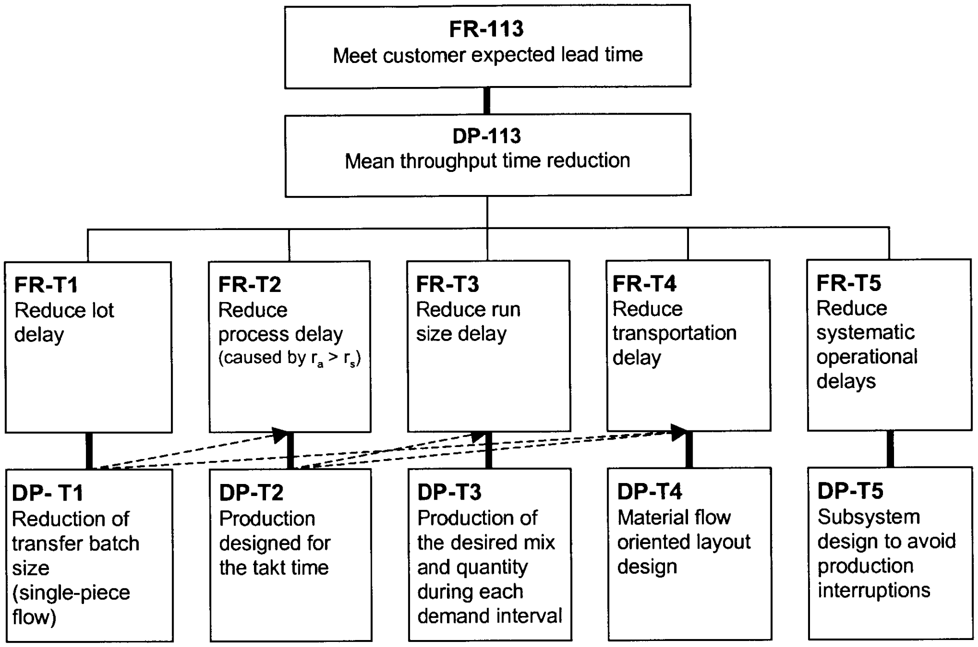


Figure 5-8: Decomposition of throughput time reduction into five delays

Lot delay

Lot delay (FR-T1) occurs when parts are transported between operations in lots (also known as transfer batches) of greater than one. While one part in the lot is being processed, all other parts in the lot must wait in storage, either before or after the operation. For the example system, suppose that parts are transported from op. 10 to op. 20 in containers that hold 20 parts each. Parts are moved only when a container is full. Thus, the first part completed at op. 10 and placed into an empty container must wait for the next 19 parts to be processed before it can be moved to op. 20. The 20th part produced and placed in the container can be moved to the next operation immediately, but upon arrival it must wait for the other 19 parts to be processed, assuming a first-in, first-out processing sequence. Other sequences (such as last-in, first-out) may be used, but the average waiting time over all of the parts in a container will be the same. Neglecting for now the time it takes to transport a full container from op. 10 to op.

20, we can see that the total number of parts stored between these operations is one less than the container size.

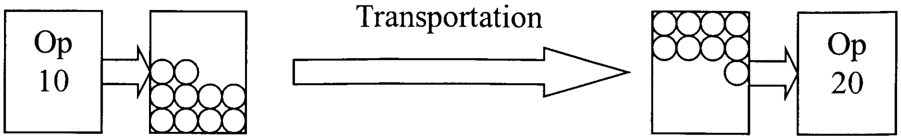


Figure 5-9: Lot delay example

(Because transportation time is neglected, part #1 could be loaded into op. 20 immediately after part #20 is completed in op. 10.)

According to Little's law, the throughput time added by this transportation lot size is given by:

$W = L / \lambda = 19 \text{ parts} / 0.5 \text{ parts/min.} = 38 \text{ minutes}$

Or, more generally,

Lot delay = (1 – Transfer batch size) / Production rate

The means for reducing lot delay is simply to transfer parts in smaller batches, ideally with a transfer batch size of one piece (DP-T1). The design matrix at this level shows that reducing transfer batch size (with the ideal goal being single-piece flow) can have an impact on the ability to reduce process delay (FR-T2) and transportation delay (FR-T4), as reducing the transfer batch size will affect the frequency and quantity of material handling from one operation to the next.

Transportation delay

Continuing with this example, let us now assume that the time to transport a container of parts from operation 10 to 20 is non-zero. In this case, additional inventory is necessary to prevent part shortages at op. 20. The transportation delay time (FR-T4) is defined as the total time from when a full transfer batch of parts is ready to be transported until these parts arrive at the downstream operation and are ready for processing. This time includes the time parts spend waiting to be transported, the time spent in transit, and any necessary loading and unloading time. The amount of inventory added to the system due to transportation time is given by:

Additional inventory = Transportation time * Production rate

The transportation delay will be equal to the amount of transportation time. Continuing with the example system and assuming that it takes six minutes to transport parts from operation 10 to 20, the amount of additional inventory will be:

6 minutes * 0.5 parts/min = 3 parts

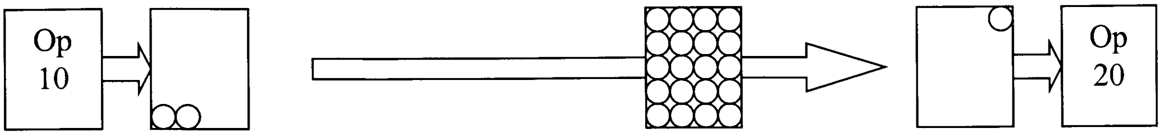


Figure 5-10: System state four minutes into the transportation time

The manufacturing system design decomposition advocates system layout design as the means for reducing transportation delays. By arranging equipment based on product flow (DP-T4) as opposed to grouping equipment by operation, transportation distance can be minimized. An alternative means for reducing transportation delay would be to speed up the means of transportation; however, this solution is not prescribed by the decomposition, as it does not address the root cause of the delay: long transportation distances. Another important factor for reducing transportation delay is ensuring that transportation resources arrive to pick up and deliver parts at the proper times. This timing aspect is covered in the decomposition of FR-T2, "Reduce process delay." This information is reflected in the design matrix by a relationship between DP-T2, "Production designed for takt time," and FR-T4, "Reduce transportation delay."

Run size delay

Run size delay (FR-T3) occurs when multiple part types are produced and the sequence of production does not match the sequence of products demanded by the customer. For example, suppose that our two-operation system produces two part types, A and B, and the customer demands 200 of part type A and 40 of type B every day. Assuming that the system runs one shift per day, five days per week, weekly demand will be 1000 of part A and 200 of part B. Suppose that, in order to reduce machine downtime due to changeovers, the system is scheduled to produce all 1000 type A parts first (requiring 2 min./part * 1000 parts / 60 min/hour / 8 hours/day = 4.2 days) and then changeover and produce part type B for the remaining 0.8 days each week. The result will be that customer demand is met on a weekly basis. However, excess inventory of each part type will have to be kept in the system in order to meet the customer's daily requirements, as shown in Figure 5-11. The upwards-sloping portions of the lines represent times when that product is being produced. The steep declines represent the daily shipment of the demanded parts to the customer. On average, an inventory of about 180 type A parts and 100 type B parts are kept in the system.

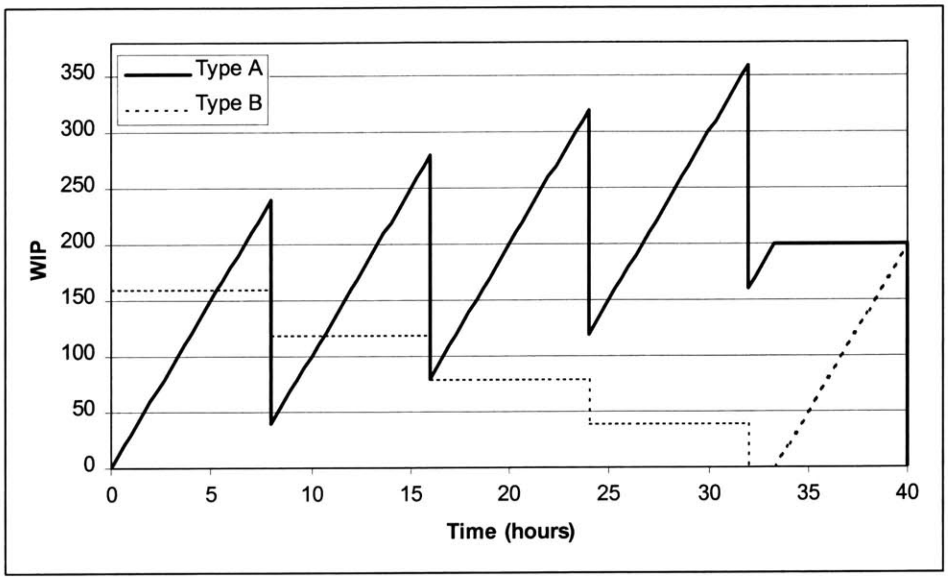


Figure 5-11: Inventory due to run size delay

To avoid run size delays, production must be matched to customer demand during each demand interval (DP-T3). The demand interval is defined here as the period of time between deliveries to the customer. In the example above, the demand interval is one eight-hour day. In practice, the length of the demand interval can vary significantly. When transportation distances are long and transportation is expensive, the demand interval might be a week or longer. When transportation distances are short and inventory reduction is critical, the demand interval might be as short as a few hours or less. In order to produce according to customer demand, demand information must be known in advance (FR-T31), requiring frequent communication with the downstream customer, and the manufacturing system must be capable of producing in sufficiently small run sizes (FR-T32). The ability to rapidly changeover equipment from one part type to the next (DP-T33) is critical for achieving this objective. Figure 5-12 shows how the WIP in the system varies throughout the week when production in the example system is matched to customer demand on a daily basis. With this case, inventory is reduced to an average of 115 of part type A and only 4 of part type B. Run size delay has, by definition, been eliminated completely. The inventory that remains in the system is due to *process* delay (FR-T2). In this example system, there is a short-term mismatch between the production and shipment rates (i.e. *during* the day parts are produced at a rate of 0.5 parts / minute, but shipped at a rate of 0 parts / minute). This process delay will be discussed further next.

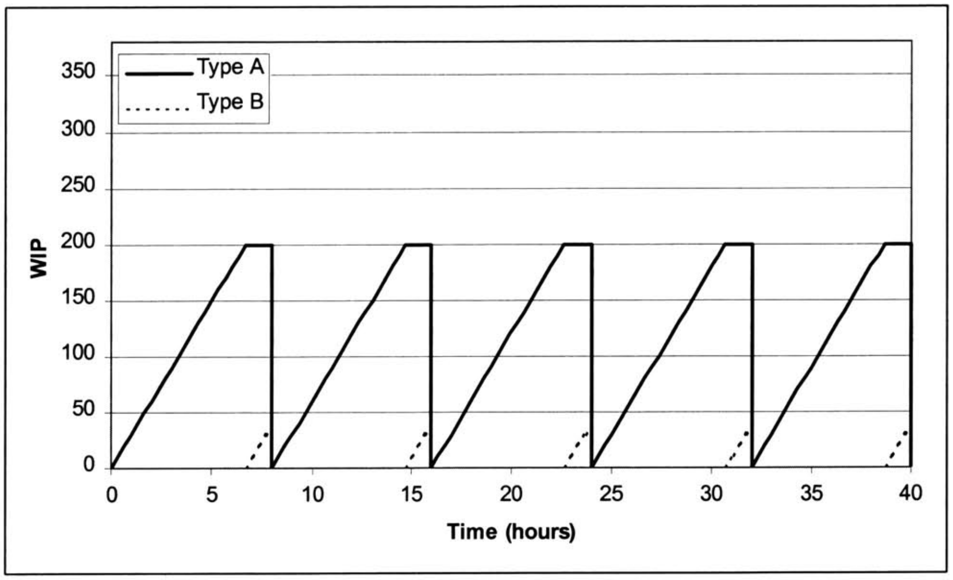


Figure 5-12: Reduced inventory – reduced run size delay

Process delay

Process delay (FR-T2) results when the arrival rate of parts, r_a, is greater than the service rate, r_s (i.e., the rate at which parts are processed). Unlike the other four types of delays described in this section, process delay cannot occur in a steady-state condition. If the average arrival rate of parts is greater than the average service rate, the amount of inventory in the system will tend towards infinity. Assuming that the long-term average arrival rate is equal to the average service rate, process delay occurs only during shorter time intervals during which $r_a > r_s$. Essentially, process delay occurs when parts are processed in excess of demand. The processed parts must then wait until they are demanded by the customer. Returning to the two-operation example described earlier, suppose we look at process delay in the context of operation 20, as shown in Figure 5-13.

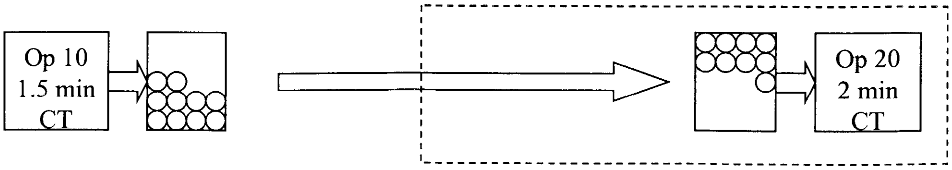


Figure 5-13: Production state at the beginning of a shift

In the previous examples, each operation had a cycle time of two minutes. Now suppose that op. 10's cycle time has been decreased to 1.5 min., and that neither operation is ever starved for parts. Customer demand remains the same at one part every two minutes, for a total of 240 parts per eight-hour shift. After six hours of operation, op. 10 will have produced the necessary 240 parts for the shift (6 hrs * 60 min/hr / 1.5 min/part = 240 parts). Op. 20, however, will have only processed 180 parts (6 hrs * 60 min/hr / 2 min/part = 180 parts), resulting in an increase in in-process inventory of 60 parts. Assuming op. 10 stops producing parts when it has met demand for the shift, op. 20 will catch up at the end of the shift, customer demand will be fulfilled, and the amount of inventory in the system will have returned to its previous level. Note that although reducing the cycle time of operation 20 could eliminate the need to run overtime, it would not reduce the amount of process delay. Instead of waiting before operation 20, the parts would simply have to wait at a point further downstream in the system. The root cause of process delay is production ahead of demand, not insufficient capacity.

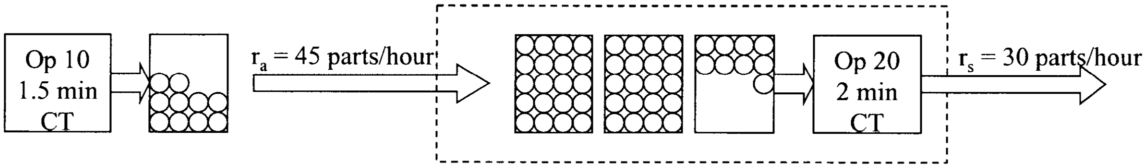


Figure 5-14: Production state four hours into the shift

The decomposition prescribes "production designed for takt time" (DP-T2) as the means to eliminate process delay. Achieving this requires that the pace of customer demand (i.e., that takt time) be defined (FR-T21) and that the service rate and arrival rate of the system be matched to this takt time (FR's T-22 and T-23, respectively). The takt time for a system can be calculated by dividing the total number of available production hours in a given time interval (e.g., one week) by the total number of parts demanded during that time. In calculating takt time, it is important that factors such as machine downtime, setup time, and worker allowances be considered in determining how many hours of production can be expected. Matching the service rate to the takt time requires that the system have sufficient capacity to meet customer demand. Overproduction is avoided by ensuring that the arrival of parts at downstream operations is balanced to takt time (DP-T23). In this way, operations producing at a pace faster than the takt time will become starved for incoming materials, and the transfer of materials from one operation to the next will serve as the means to pace production.

Systematic operational delays

Routinely occurring delays caused by interferences among resources are referred to in the manufacturing system design decomposition as systematic operational delays (FR-T5). The decomposition considers two categories of resources, production resources (workers and/or automation involved in the processing of parts) and support resources (workers and/or equipment supporting this production by supplying small purchased parts, removing chips from machine tools, etc.). Delays occur when one resource prevents another from performing its duties. The delay time is given simply by:

Systematic operational delay = Duration of interference among resources

For example, consider a workstation at which an operator manually performs several assembly tasks, including adding some screws, washers, etc. to a partially assembled product. Assuming that the operators have containers of each of these small purchased parts at their workstations, a support resource is necessary to periodically replenish the operators' supply. If this replenishment requires operators to stop working and move away from their workstations, an interference has occurred between a support resource (the material replenisher) and a production resource (the operator). The part being processed is delayed by the amount of time it takes the replenisher to refill the necessary containers. The proposed means for reducing such delays is the coordination and separation of the work and access requirements of each resource (DP's T51-T53).

5.4 Summary

This chapter has reviewed the development of a general decomposition of the objectives of a manufacturing system design. Other similar frameworks were reviewed with regard to their ability to relate low-level design activities and decisions to higher-level system objectives. The use of the principles of axiomatic design was also reviewed, with an emphasis on the structured decomposition process it provides as well as the advantages and disadvantages of this approach. The upper levels of the manufacturing system design decomposition (shown in its entirety in Appendix A) were reviewed to show how the specific FR's and DP's were selected and to describe the precedence relationships among them. The resulting decomposition has been found to be a useful tool for:

- Understanding the relationships between high level system objectives (increasing customer satisfaction, reducing system throughput time, etc.) and lower-level design decisions (equipment design and selection, system layout, etc.)
- Understanding the interrelations among various elements of a system design and the precedence and cause-effect relations that determine a system's ability to meet high-level requirements and objectives
- Communicating this information to a group of system designers

Chapter 6 Proposed Manufacturing System Design Process

6.1 Overview

This chapter proposes a core manufacturing system design process based on the principles of systems engineering and, more specifically, based on a general systems engineering design process developed in (Oliver et al., 1997). This core systems engineering process will first be reviewed and then its application to the area of manufacturing system design will be discussed. The proposed, modified version of this process will be reviewed with a focus on how it compares to Oliver's process. Next, the application of the proposed manufacturing system design process will be discussed The following two chapters will review how the manufacturing system design decomposition presented in the previous chapter can be used as an integral part of the process. More detailed examples of the use of this process will be presented in Chapter 9 to illustrate the advantages of such an approach.

6.2 A General Systems Engineering Technical Process

The manufacturing system design process proposed here is based on a general systems engineering process developed by (Oliver et al., 1997) to assist in the description, modeling, and analysis of complex systems. This section will review what Oliver calls the core systems engineering technical process (shown in Figure 6-1). This process represents the engineering tasks that support and specify a system in all phases of its life cycle. Note that three of the key steps in the process (steps 2-4) are performed concurrently, as the decisions made in each step affect one another. For example, decisions made regarding the system's structure will impact its behavior as well as the best means for measuring the system's effectiveness. The steps in this process are performed repeatedly, both over time as the system and its environment evolve and at various levels of detail such as concept analysis, subsystem design, and component design.

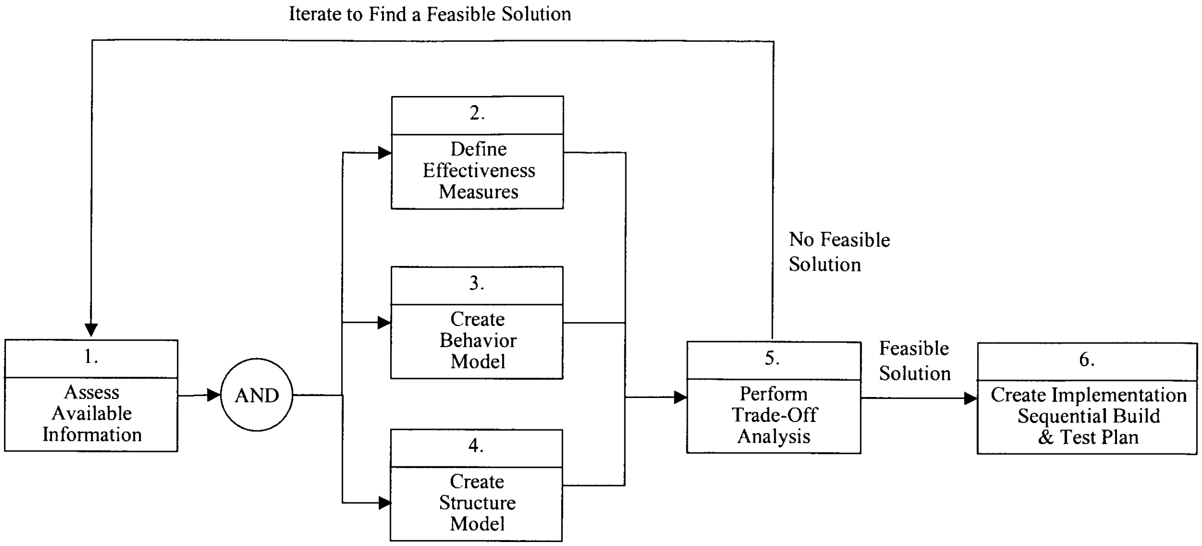


Figure 6-1: Core systems engineering process (Oliver et al., 1997)

6.2.1 Elements of Oliver's Core Systems Engineering Technical Process

A brief review of the steps in this process is presented below, with an emphasis on the creation of behavior and structure models. For a more detailed description of the activities that each step involves, the reader is directed to (Oliver et al., 1997).

Step 1. Assess Available Information

The first step involves assessing the available information: collecting it, categorizing it, and obtaining additional information if necessary. This information represents general requirements placed on the complex system being designed. It is important that this information be analyzed in order to ensure that these requirements are not redundant, contradictory, incomplete, incorrect, or unverifiable. Oliver presents a taxonomy for categorizing this information, classifying each requirement according to its origin, the work needed to be done to fix it, and its use. Work needed to fix a requirement applies to problem requirements: those that are unverifiable, inconsistent, redundant, etc. The result of this step is a complete and consistent database of requirements that represents the objectives of the system design.

Step 2. Define Effectiveness Measures

Step 2 in Oliver's core systems engineering technical process is to define the criteria by which alternative concepts and designs will be evaluated. These effectiveness measures assess how well a design performs relative to the ideal and will be used to understand the trade-offs that exist among different designs. The measures incorporate the needs and wants of the various stakeholders – users, customers, owners, operators, etc. Oliver defines three categories of effectiveness measures based on the type of work that must be done to evaluate them. Effectiveness measures can be evaluated based on the attributes of the system, a model of system behavior, or a survey of the preferences of stakeholders. For example, in the case of a manufacturing system design, investment cost can be calculated based on the attributes of the system components, namely, the cost of each component. Other effectiveness measures, such as throughput time, depend on the dynamic behavior of the system itself, requiring a model of system behavior such as a simulation to evaluate. Other, more subjective factors such as perceived product quality might require customer surveys for evaluation. Once the effectiveness measures have been defined, another important step remains: defining the priorities among them. Numerous formal methods exist for prioritizing among multiple attributes, as discussed in section 4.1.6.

Step 3. Create Behavior Model

According to Oliver et al. (1997), "Behavior for a system describes *what* the system is to do, independent of *how* the system will do it." A fully described behavior model contains sufficient information for the model to be executed and the behavior to be observed and checked for correctness. The necessary set of elements required to describe a behavior includes the following:

- Inputs and outputs
- Functions, which transform inputs to outputs
- Control operators, which define the sequencing of the functions

Text descriptions are required at all but the lowest levels to precisely define these elements. These descriptions can take the form of definitions, imperative statements (i.e., specifications or system requirements), or narrative statements. Modeling behavior in this way seeks to answer questions such as:

What inputs and outputs are involved?
What happens?
In what order?

Various methodologies have been proposed for partially representing behavior models, including functional flow block diagrams (such as the one showing the core systems engineering process) to represent functions and controls and data-flow diagrams to represent functions and inputs/outputs.

Step 4. Create Structure Model

The structural model of a system defines the elements that compose the system, determining *how* the desired behavior will be achieved. In the core systems engineering process defined by Oliver et al. (1997), creating a structure model involves three major steps: classifying and selecting objects, defining object attributes, and assigning functions to objects. Objects here can refer to physical entities such as machines, parts, or inspection devices, but objects can also be less concrete things such as flow paths, interfaces, or schedules.

Classifying and selecting objects

Classification refers to categorizing objects and defining the hierarchical nature of these categories. For example, each individual type of machine being considered can be thought of as a particular category, or class of objects (e.g., a 3 HP CNC milling machine). Different but similar classes of objects can then be grouped into higher-level classes, such as "CNC milling machines," "milling machines," or "machine tools." Another less concrete example would be to consider delays (i.e., factors that inhibit part flow) as objects. In this case, the general class of "part flow delays" could be decomposed into several lower-level classes according to cause: "storage delay," "transportation delay," "lot size delay," etc. This step results in the definition of a set containing all possible choices of objects for a system design, i.e., the design space.

The second part of this step, selecting objects, involves selecting the specific object classes that will be considered for use. This simply means choosing which objects, out of all those that are available, will be evaluated as part of a system design. The result of this step is a specific and unique design that will then be evaluated further. In the proposed model of the systems engineering process as applied to manufacturing system design, such a selection of objects is analogous to the definition of the design parameter portion of an axiomatic design-based decomposition.

Defining object attributes

This step requires that, for each object class, the relevant object attributes, or properties, be defined. In general, an object will have a great number of attributes, but only a subset of these attributes will be relevant to the system design process. The relevance of object attributes is determined based on the chosen set of effectiveness measures. All attributes that impact the system performance relative to the effectiveness measures must be considered in the analysis. Other attributes need not be monitored in the design process. For example, relevant attributes of a machine tool are almost certain to include cost and capacity. Other attributes such as changeover time or machine size may or not be relevant, depending on the effectiveness measures chosen. This will, in general, represent information beyond what would be found in the design parameter portion of an axiomatic design-based decomposition, although a specific attribute of particular importance may be specified by a design parameter.

Assigning functions to objects

The third step in creating the structure model involves the mapping of behavior onto the objects making up the system structure. That is, the designer must determine what the role or function of each object is in terms of achieving the desired system behavior.

Step 5. Perform Trade-off Analysis

Trade-off analysis evaluates the feasibility of potential designs in terms of system requirements and selects among them based on their performance relative to the effectiveness measures. Figure 6-2 shows the general process for performing trade-off analysis developed in (Oliver et al., 1997).

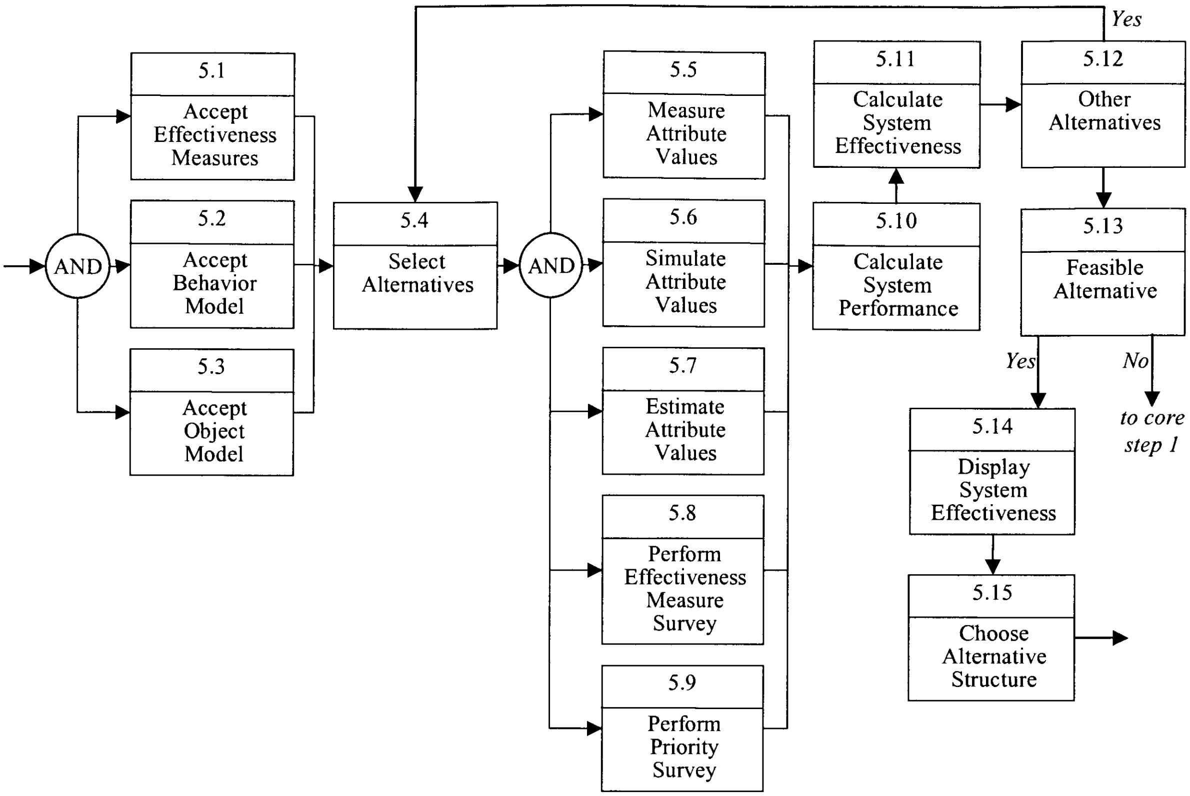


Figure 6-2: Process for trade-off analysis (Oliver et al., 1997)

This process begins with the acceptance of the effectiveness measures and the behavior and structure models developed in steps 2-4 of the core process and the selection of various design alternatives for further consideration. Next, the attribute values for each design alternative must be determined. Attribute values (i.e. the information necessary to determine whether or not the system can fulfill the requirements) can sometimes be measured directly but more often must be obtained through simulation or estimation. At this point, it might also be desirable to reassess the set of effectiveness measures and their priorities in order to reflect any changes in preference that may have developed over time as more information has been introduced. Once the alternative systems have been evaluated and the set of effectiveness measures has been settled upon, the overall system performance and effectiveness can be calculated. In this context, looking at a system's "performance" means determining whether or not it can fulfill the given requirements; a system's "effectiveness" measures the "goodness" of a design. Effectiveness is used to select among multiple designs with feasible performance relative to the requirements.

With this information in mind, the design team might decide to consider additional alternatives (step 5.12 in Figure 6-2), or to continue examining the feasible alternatives (step 5.13). If no feasible designs have been identified, then the design team must reconsider their original set of requirements. If multiple feasible designs exist, the next step is to display each system's effectiveness (5.14) in order to facilitate the selection of one alternative design to proceed with. Displaying a system's effectiveness means providing a visual display of the system's performance with regard to the multiple effectiveness measures. This might be something as simple as a series of tables, bar graphs, or spreadsheets. More sophisticated three-dimensional graphing methods might also be used if necessary. With each system's performance displayed in this manner, the design team is equipped to make a selection regarding which design alternative best meets their needs.

Step 6. Create Implementation Sequential Build and Test Plan

The final step in the process involves defining a plan for implementing the designed system, taking into account timing, budget, and resource requirements. This plan takes into account issues of time to market, technical and time-based risks that might be involved, procurement of materials and equipment, and the allocation and scheduling of resources. A more detailed description of the activities involved in this step can be found in (Blanchard and Fabrycky, 1998).

6.2.2 Summary of the Core Systems Engineering Process

The core systems engineering technical process developed by (Oliver et al., 1997) represents a structured approach to the design of complex systems. This process emphasizes the importance of the up-front definition of system requirements and the subsequent top-down approach to system design where these requirements are used as the basis for the generation of effectiveness measures and models of system behavior and structure. Once these measures and models have been defined and various system alternatives have been defined, trade-off analysis can be used to select a best choice for more detailed investigation from among the feasible alternatives. Or, if no desirable alternative has been generated, the result of the analysis can be that the original requirements need to be re-examined and the process restarted. Once a desirable alternative has been selected, the core process may be repeated at a greater level of detail, assessing the requirements placed on system components, etc. When an operational level of detail has been reached, the design team moves forward by creating a plan for system implementation. This process is intended to be general enough to apply to the design of a wide range of complex systems. The following section will show how this process can be applied to the design of manufacturing systems. More details regarding the implementation of this process will be presented in section 6.5.

6.3 Proposed Core Manufacturing System Design Process

6.3.1 Introduction

This section examines the application of the previously described core systems engineering technical process to the design of manufacturing systems. A proposed core manufacturing system design process has been developed (Figure 6-3) and will be reviewed. The steps of this process will be discussed in terms of how they relate to those in Oliver's process and how they have been modified for the specific case of manufacturing system design. The emphasis here will be on steps 2-5 of the process.

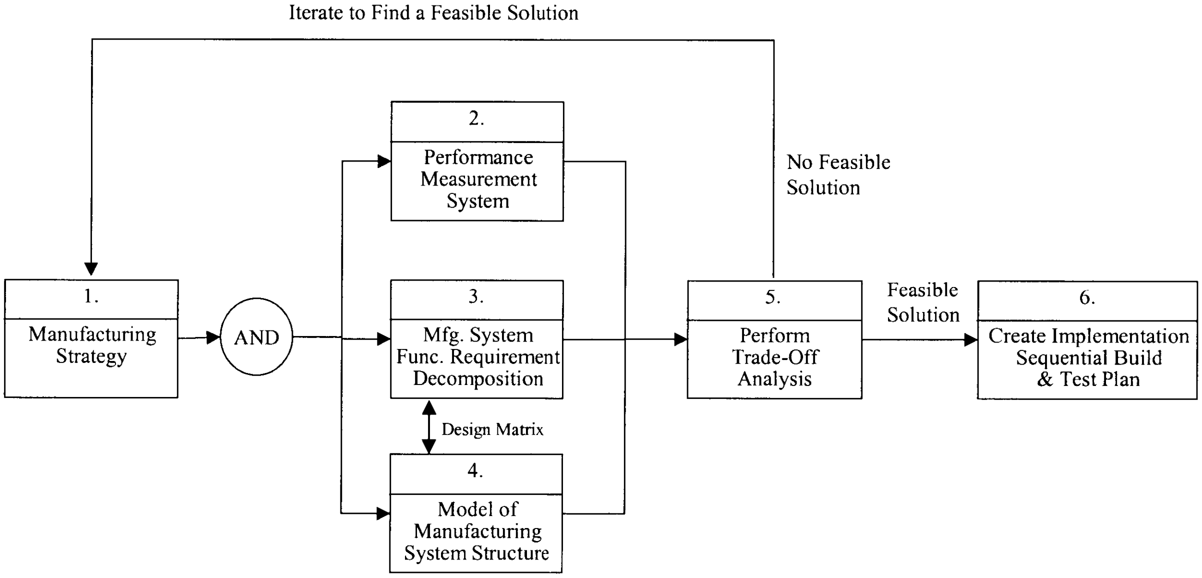


Figure 6-3: Core process applied to manufacturing system design

6.3.2 Elements of the Core Manufacturing System Design Process

As shown in Figure 6-3, the proposed process for the design of manufacturing systems has the same basic structure as the general systems engineering process shown in Figure 6-1. The process still begins with the development of an understanding of the context of the design problem and the fundamental requirements that are placed on it. Next, the system's behavior and structure are defined concurrently with a system for performance measurement. The remaining steps, performing trade-off analysis and creating an implementation plan, remain unchanged from the general systems engineering core process.

Step 1. Manufacturing Strategy and External Requirements

In general, this first step in the system design process involves gathering and categorizing information, including system performance requirements. In terms of manufacturing system design, this information can come from two sources: the firm's own manufacturing strategy and external stakeholders in the system design. In terms of strategy, this step involves defining the firm's manufacturing strategy and the resulting high-level system objectives (e.g. providing a specified variety of products at a reasonable cost with the highest possible level of service). Information from external stakeholders must also be collected and analyzed for any requirements that may be placed on the system. Sources of external requirements could include downstream customers, governmental organizations, or labor unions. Customer requirements placed on manufacturing systems will often include factors related to product quality. While manufacturing system designers do not, in general, control the *performance* quality of a product (i.e. how well the product performs its functions, it durability, reliability, etc.), manufacturing is responsible for ensuring that the products it sends to its customers are within the given design specifications. In some cases, customers might also place requirements on how quickly the system must be able to respond to production orders. This is common, for example, in cases when a system for automotive parts fabrication is located near a vehicle assembly line. The assembly line might broadcast information on the exact sequence of vehicles to be assembled and the corresponding parts requirements directly to the parts fabrication system, with the requirement that the necessary component parts be manufactured and delivered to the station on the assembly line where the component will be assembled to the vehicle. Other external requirements can involve factors such as safety, ergonomics, and environmental issues.

Step 2. Define Effectiveness Measures / Performance Measurement System

This step involves defining and prioritizing the key measures that will be used to evaluate and compare potential designs. Note that step 2 is done concurrently with steps 3 and 4, the definition of behavior and structure models. Effectiveness measures represent a small subset of the full set of system requirements, but they are what will drive the system design and improvement process. Typically, effectiveness measures number 3-15 even for large complex systems (Oliver et al., 1997). In terms of manufacturing system design, effectiveness measures can include things such as investment cost, labor costs, inventory levels, etc., as discussed in Chapter 3. These measures will serve as the means for evaluating how well a given design is able to fulfill the firm's strategic objectives and meet the necessary requirements.

The development of a set of performance measures must be done concurrently with steps 3 and 4, the specification of system behavior and structure. While some high-level measures of performance may be derived directly from the firm's strategy and external requirements, other performance measures will be dependent on the specifics of the particular design alternative. That is, no one set of performance measures is likely to be both complete and also applicable to all feasible manufacturing system design alternatives.

Step 3. Create Behavior Model

Creating a system behavior model involves defining the required outputs of the system for various combinations of inputs and defining how the system will perform so as to best satisfy the effectiveness measures. In the context of this thesis, the key element here is the decomposition of system behavior or function. This step involves the development of a detailed set of activities that can combine to provide the desired overall system behavior. As described in section 5.3.1, axiomatic design can be used to decompose high-level functional requirements into a more operational set of lower-level FR's. Axiomatic design theory states that this decomposition based on function should take place concurrently with the decomposition of system structure, such that the designer alternates back and forth between the functional and structural domains.

The functional requirement portion of the manufacturing system design decomposition can be used as a general model of desired system behavior. In creating the MSDD, two primary methods were used to decompose high-level functional requirements: identifying the *components* of the high-level requirement, or determining a *sequence* of sub-activities that achieve the higher-level function. For example, FR-R113 "Meet customer expected lead time" is decomposed by identifying five causes or components of excess lead time and prescribing that each be reduced (FR's T1 – T5), as discussed in section 5.3.2.3. An example of an FR decomposed based on a sequence of activities is FR-R1 "Respond rapidly to production disruptions." The sub FR's (FR-R11 through FR-R13) are based on the activities that take place when a production disruption occurs: recognition of the problem, communication of the problem, and problem solution. In this way, a more detailed description of the behavior required to achieve the higher level FR is generated. To respond rapidly, any or all of these lower-level activities must be performed more rapidly.

Step 4. Create Structure Model / Model of Manufacturing System Structure

A general structure model captures the possible sets of components from which to build the system. The allocation of behavior onto objects can be performed in either step 3 or step 4. In the case of manufacturing systems, the design parameter portion of an axiomatic design decomposition of a manufacturing system can be viewed as a form of a structural model, in that it categorizes various elements of a system and performs a mapping of behavioral elements (in this case, functional requirements) onto structural elements (design parameters). As discussed in the description of step 3, this decomposition of system structure must take place concurrently with the decomposition of system function. The process of decomposing high-level design parameters is essentially the process of moving from one high-level, abstract DP to a set of multiple, more concrete DP's that specify the high-level DP more completely. For example, DP-P1 "Predictable production resources" specifies a general category of appropriate resources. Lower-level DP's further specify the necessary characteristics of these resources, identifying different types of resources (information systems, equipment, workforce, and material replenishment system) and describing the important properties each must have.

6.3.3 Summary of the Core Manufacturing System Design Process

Steps 1 through 4 of the proposed core manufacturing system design process have been reviewed to explain how they have been modified from Oliver's more general systems engineering process to apply specifically to the case of manufacturing system design. Steps 5 and 6 remain unchanged from the general systems engineering process. The topology of the proposed process (i.e., the sequence and concurrency information relating the various process steps) has also remained unchanged. The names and descriptions of steps 1 through 4 have been modified to reflect the common vocabulary and techniques of manufacturing system design. The next section will explore these differences between the general systems engineering process and the proposed manufacturing system design process in greater detail.

6.4 Comparison with the General Systems Engineering Process

The proposed core manufacturing system design process described in the previous section was developed based on a general process for the design of complex systems. This section reviews the key differences between the approach as modified for this specific case and the more general process. While the two processes are quite similar, some key differences warrant further discussion, particularly in terms of the modeling of system behavior.

6.4.1 Steps 1 and 2 of the Processes

The first two steps of the core manufacturing system design process, "Manufacturing Strategy and External Requirements" and "Performance Measurement" are essentially the same as steps 1 and 2 of the general systems engineering process: "Assess Available Information" and "Define Effectiveness Measures." In manufacturing system design, the key information that needs to be considered at the beginning of the design process will come from the firm's competitive strategy and from external sources such as the downstream customer(s), and this fact is emphasized in step 1 of the manufacturing system design process. The term "performance measure" is used in step 2 as a synonym for "effectiveness measure" simply because "performance measure" is a far more widely known and accepted term in the field of manufacturing.

6.4.2 Step 3: Behavior Model

It is proposed that, in the case of manufacturing system design, an axiomatic design decomposition of a system's functional requirements can be used as a form of behavior model. This approach differs in some ways from the traditional object modeling techniques described in (Oliver et al., 1997) but answers the same fundamental question: What must the system do? The most significant departure from the typical object modeling approach is found in the focus of the behavior model. For example, behavior in the context of a manufacturing system design problem can be viewed in (at least) three different ways: in terms of the part being manufactured, in terms of the team designing the system, or in terms of the system design itself.

Part-focused view of behavior

In the first case, a part-focused view, a behavior model would focus on the process plan for making a part. The model would capture the behavior of the system as it processes a part from start to finish. Such a view would focus on the information necessary to create a simulation model of a system design: routing information, process times, labor requirements, etc. While this information is useful and necessary for understanding the dynamic behavior of a system at a low level, it is less helpful for determining a system's ability to meet higher level requirements or for examining the dependencies among multiple design decisions. Figure 6-4 shows a simple part-focused behavior model.

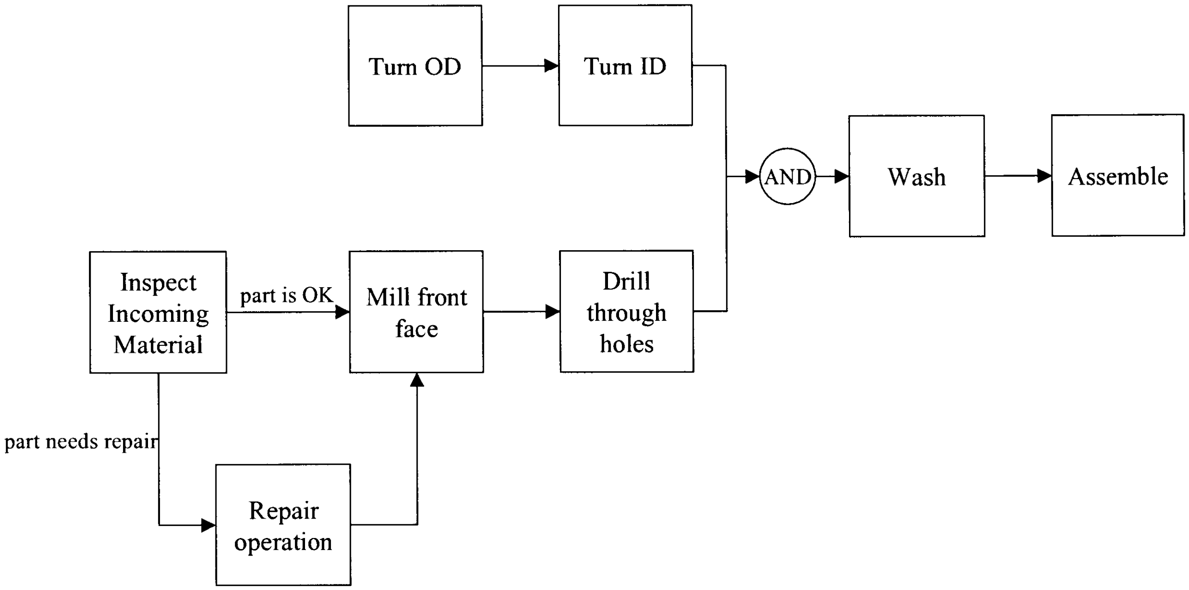


Figure 6-4: Part-focused view of behavior

Design team-focused view of behavior

In this case, the focus is on the sequence of activities carried out by the team of managers and engineers responsible for the system design. This behavior model would more closely resemble a *project* plan, detailing the various decision points and responsibilities involved in the design process as illustrated in Figure 6-5

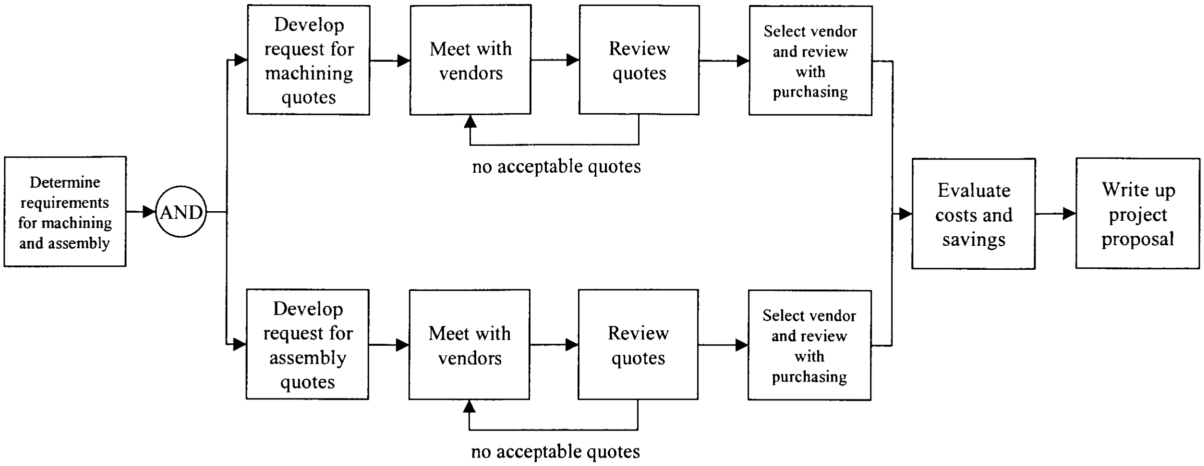


Figure 6-5: Design team-focused view of behavior

System-focused view of behavior

In this case, the focus is on the overall system and how it will be able to meet the design requirements and objectives. This approach focuses on the specific design decisions that must be made, the sequence in which they must occur, and the dependencies among them; it is a plan for meeting the objectives. Figure 6-6 presents a partial example of such a behavior model, tracing requirements for achieving customer satisfaction.

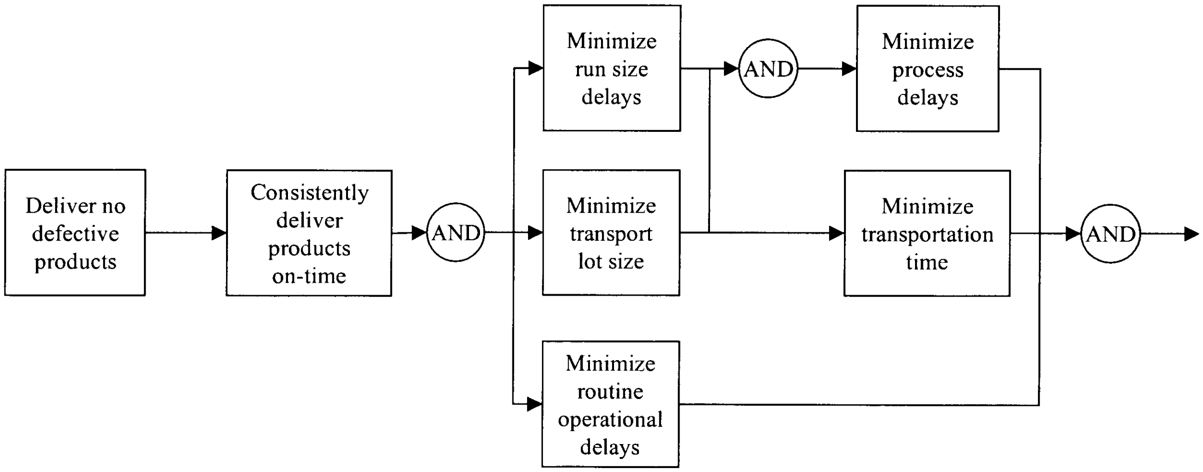


Figure 6-6: System design-focused view of behavior

In this work, axiomatic design is used to develop system-focused models of behavior. The strengths of the axiomatic design approach are its ability to show how high-level objectives can be decomposed into lower-level, more operational requirements, and to examine the interdependencies among various design requirements and decisions through the use of the design matrices. Structurally, it is a straightforward process to convert an axiomatic design decomposition of functional requirements into a functional flow block diagram as typically used with the object modeling methodology. The levels of hierarchy in the decomposition are maintained, and the ordering of functions/requirements at each level can be determined according to the appropriate design matrix. Uncoupled tasks can be done in parallel, decoupled tasks must be done sequentially, and fully coupled tasks will require iteration.

6.4.3 Step 4: Create Structure Model

The information contained in a general model of the structure of a manufacturing system is well captured in an axiomatic design decomposition. In a typical object model, information on system structure comes from definitions of classes of objects and from the combination of various specific instances of different classes of objects. In an axiomatic design decomposition, higher-level DP's (i.e., those that are further decomposed) are similar to object classes, in that the DP's contain information defining a set of possible objects. "Leaf" DP's (i.e., those that are not further decomposed) represent more specific instances of these higher-level DP's, similar to instances of a class of objects.

One difference between the general model of manufacturing system structure provided by the design parameter portion of the MSDD and a more traditional manufacturing system structure model is that the MSDD is focused on the overall ability of the design to meet the necessary objectives and requirements. That is, the MSDD focuses on the qualities of the system structure that enable it to meet these requirements and objectives. An alternative structure model would be one based on manufacturing *process*, i.e., the series of operations necessary to process a part. A process-focused model of system structure (e.g. the number and type of each necessary machine) is useful and necessary for determining how the manufacturing system will achieve its most fundamental requirement: transforming raw materials into finished goods. In fact, this process-focused model is the type of model many manufacturing engineers immediately think of when analyzing the structure of a manufacturing system. Rather than focus on the process plan, the MSDD focuses attention on issues that might be overlooked with a process-based approach, such as the means for dealing with disruptions, controlling the flow of information, minimizing the amount of time a part spends in the system, etc.

6.4.4 Steps 5 and 6: Trade-off Analysis and Implementation Plan

As described in earlier, these last two steps remain unchanged from the general systems engineering process. Designers of manufacturing systems are encouraged to identify and analyze the trade-offs that exist among multiple design alternatives. Once a design has been selected, a plan for its implementation must be developed. Developing such a plan for a manufacturing system can clearly be a difficult task; however, defining a method for doing so is beyond the scope of this thesis.

6.5 Applying the Core Manufacturing System Design Process

This section discusses the application of the proposed core manufacturing system design process. The different types of design decisions this process applies to will first be reviewed. The manufacturing system design decomposition presented in Chapter 5 represents a structured method for analyzing the requirements and design elements that make up a manufacturing system design; its use as a tool for helping system designers relate strategy, performance measurement, and design structure through trade-off analysis will be reviewed.

6.5.1 Applying the Process at Different Levels of Detail

In designing a manufacturing system, decisions must be made at many different levels of detail (as illustrated in Figure 6-7). At an abstract level, system designers must make general decisions about the grouping of operations and the flow of material and information. Decisions must be made regarding how to group customer demand, how to add capacity, at what stage(s) in production to keep inventory, etc. As an example, consider an automotive component manufacturer producing a variety of rear axles. Suppose that these axles will go to six different final assembly plants, each of which demands axles at a rate of approximately one per minute. The component plant could decide to design one high-speed assembly line that produces one axle every 10 seconds and can produce all the different types of axles, thus having the capability to fully satisfy all of the customers' demand. Alternatively, the plant might decide to install six lower-speed axle assembly lines, each aligned to a particular assembly plant. Or, the subsystems might be grouped according to the *type* of axle produced in order to reduce the required equipment flexibility. Each choice, while still abstract (few details of the design will be known at this point), will have performance implications regarding inventory, investment cost, scheduling difficulty, delivery reliability, etc.

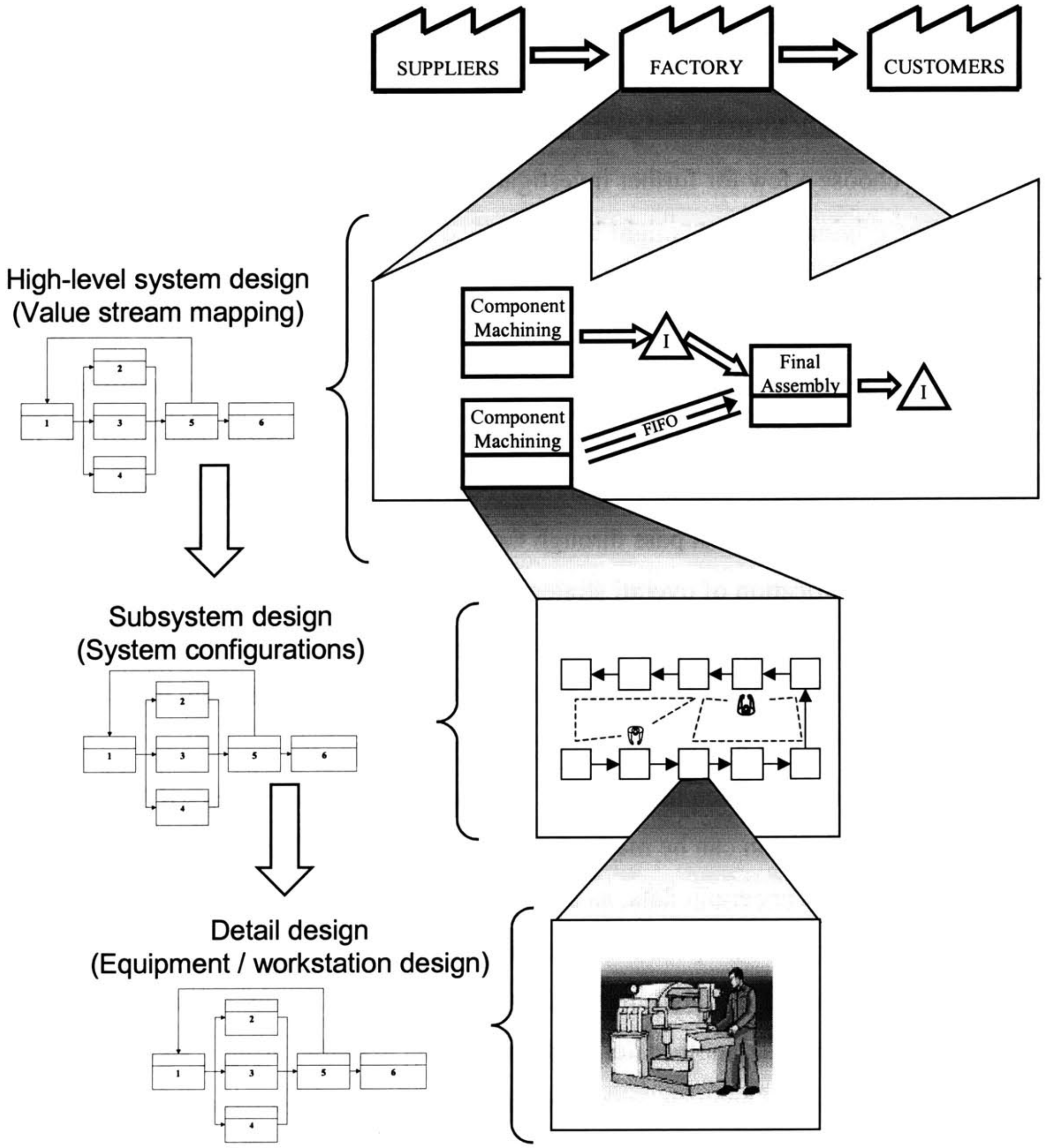


Figure 6-7: Applying the MSD process at different levels of detail

At a more detailed level, decisions are made regarding specific machine designs and configurations, system layouts, and the role of operators. To continue the previous example, suppose that the company has decided to further investigate the possibility of designing one high-speed line. Now the company's designers must examine this concept in more detail, working out a feasible process plan, finding or designing capable machines, determining how to arrange the equipment, deciding which steps to automate, estimating how much inventory will be needed, etc. Clearly, a realistic design process does not take place in one continuous pass from high-level to low-level decision-making. Instead, iteration takes place among the various levels of detail. System designers might initially examine many high-level system concepts then choose a few for further investigation. Upon further analysis at a greater level of detail, these original concepts might be abandoned or significantly modified as new ideas and improvements are generated.

In terms of the proposed core manufacturing system design process, this means that multiple passes through the process will be required in order to completely specify a system design. As more detailed design information is obtained, a better understanding of the trade-offs faced can be used to re-examine higher-level decisions. Returning to the example of the axle manufacturing plant, a first pass through the manufacturing system design process would begin with the identification of overall strategic objectives as well as requirements from the customers and other stakeholders (step 1 in the core process). Different high-level system concepts could then be analyzed (steps 2-5). Figure 6-8 shows value stream maps (as discussed in section 4.1.4) for two such design concepts.

Once the trade-offs between these design alternatives have been analyzed (step 5) at this conceptual level, a decision can be made about how to proceed. This decision will necessarily be based on somewhat uncertain data, as the details of each design have not been fully determined. Suppose now that preliminary estimates showed concept B to be the more desirable. The design of each subsystem (axle shaft machining, carrier sub-assembly, axle assembly) will now require another iteration through the manufacturing system design process at a more detailed level of analysis with new requirements and objectives being introduced based on the higher-level decisions. For example, referring again to Figure 6-8, we can see that each axle assembly subsystem will be the immediate customer of an axle shaft machining subsystem and will therefore place requirements on the machining subsystem's performance. This next iteration of the design process will likely deal with issues of layout and subsystem configuration (i.e., will the axle shaft machining subsystem be configured as a job shop, a transfer line, an FMS, etc.). Additional iterations of the design process might also be necessary to examine more detailed decisions such as equipment configuration, operator work loops, scheduling policies, etc. Applying the proposed core manufacturing system design process will thus involve multiple passes through each stage as decisions are made and design moves from the conceptual to the detailed.

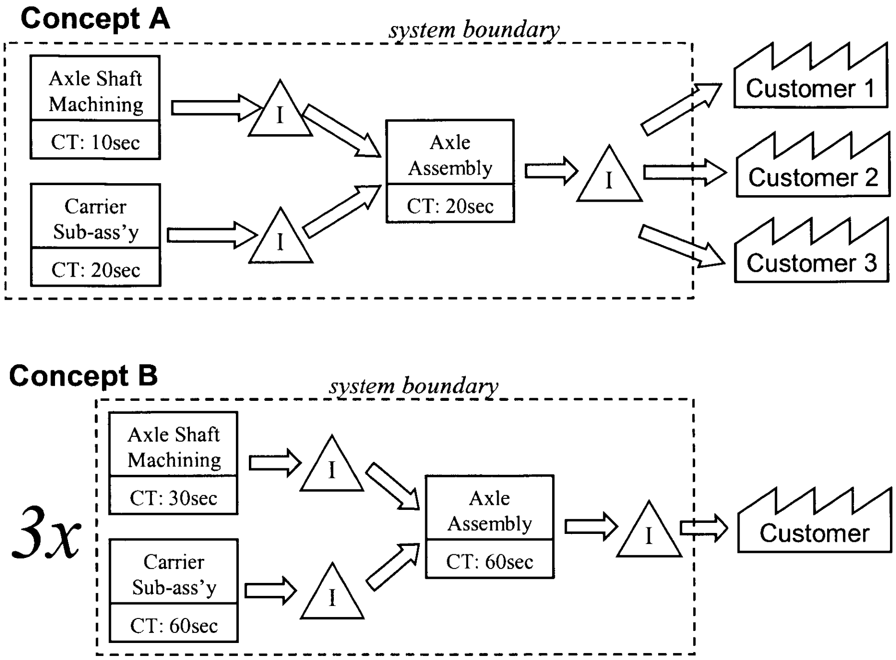


Figure 6-8: Value stream maps for two alternative system concepts

6.6 Summary

This chapter has reviewed the general systems engineering process developed by Oliver, Kelliher, and Keegan and has introduced an adapted version of this process, modified for the specific case of manufacturing system design. The general design process was developed as a high-level model of the steps needed to describe, model, and analyze complex systems. To modify this general process so that it would more specifically apply to the design of manufacturing systems, the names and descriptions of some of the steps have been changed to better incorporate the vocabulary that is common among manufacturing system designers. The fundamental nature of the process remains unchanged. That is, both the general and manufacturing system design processes begin with the determination of a feasible set of requirements and objectives. Next, potential system structures and behaviors are identified and analyzed. Concurrently, a set of measures is developed to assess system performance. With these three parallel steps completed, the trade-offs among different system designs are analyzed. If a satisfactory solution has been identified, it can be built, tested, and implemented. Otherwise, it will be necessary to re-examine the original design objectives and requirements.

Many aspects of the manufacturing system design process presented here remain abstract. The next two chapters seek to further clarify the process, explaining each step in greater detail, with a focus on how the manufacturing system design decomposition can be used to aid in linking strategy, performance measurement, and design decisions.

Chapter 7 Integrating the MSDD into the Proposed Core Process: Strategy and Performance Measurement

The manufacturing system design decomposition (MSDD) presented in Chapter 5 can serve as a useful tool at many stages of the proposed manufacturing system design process. Chapters 7 and 8 will go through the steps of the core process, describing how the MSDD can be used at each stage. The various "branches" of the decomposition will be reviewed in more detail as its use is described. This chapter will focus on the manufacturing system design decomposition's role in examining manufacturing strategy and performance measurement. Chapter 8 will then review a method for using the MSDD as a tool for the identification and analysis of trade-offs.

7.1 Relating Manufacturing Strategy to the MSDD

The manufacturing system design decomposition can serve as a common framework for linking manufacturing strategy to system behavior, structure, and effectiveness. This section discusses how the objectives of a manufacturing strategy are reflected in the decomposition. That is, how goals in terms of cost, quality, delivery performance, flexibility, and innovativeness map to the individual FR's and DP's of the design decomposition. Sections 7.2 and 7.3 will then show how the decomposition can then be used to help develop a strategy-based set of effectiveness measures and to relate information about strategy to the models of system behavior and structure (Figure 7-1). The result of these connections is that the design decomposition can be used to help system designers to understand how specific decisions regarding particular aspects of behavior and structure will impact the system's overall ability to fulfill the desired strategic objectives. In steps 3 and 4 of the core manufacturing system design process, the goal is to *identify* the key structural and behavioral decisions that will impact the system's performance relative to the strategic objectives. *Quantification* of this impact is performed as part of step 5, trade-off analysis, and will be reviewed in Chapter 8.

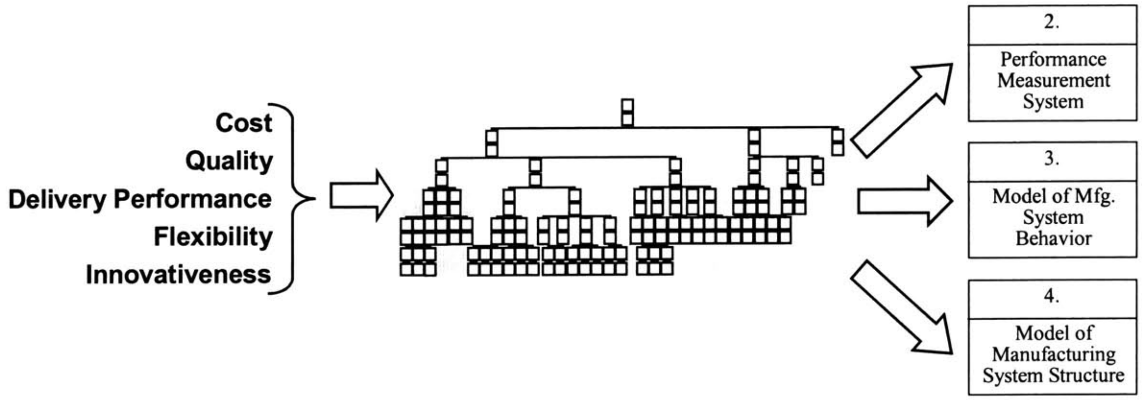


Figure 7-1: Using the MSDD to link strategy to system measurement and models

7.1.1 Cost

Clearly, many decisions made during the system design process will affect performance in terms of cost. In this broad strategic context, the word cost is used to represent investment costs as well as ongoing production costs. As a result of this broad definition, nearly every decision made will have some impact on cost performance. Figure 7-2 shows an overview of how the various FR-DP pairs affect system performance in terms of cost. (A matrix showing the leaf FR-DP's and their relationships to the different aspects of strategy is shown in Appendix B-1.) Note that in Figure 7-2 and the figures that follow, an FR-DP pair is represented by a single box. A darkly shaded box indicates that the associated FR-DP pair has a strong, direct influence on cost; less direct influences are shown with the lighter shading. Note that only "leaf" FR-DP pairs (those which are not further decomposed) are considered. If an FR-DP pair has an effect on a particular aspect of strategy, all of its parent FR-DP pairs will as well.

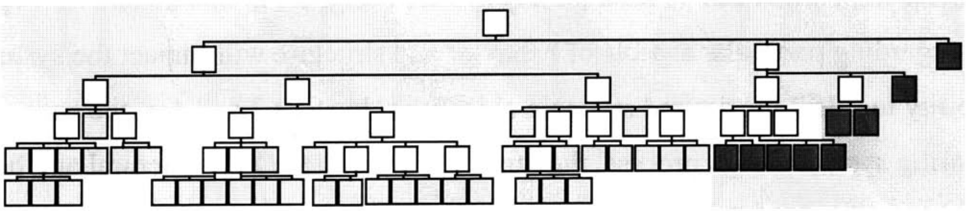


Figure 7-2: Relating the MSDD to cost

In the case of cost it can be seen that there is a strong correlation between the right-most branches of the decomposition and cost, as these branches are the decompositions of the high-level DP's "Elimination of non-value adding sources of cost" and "Investment based on a long-term system strategy.” Figure 7-2 also shows that all other FR-DP pairs have the potential to influence costs, although to a lesser extent. In the general case, it is often impossible to say whether a particular FR-DP pair will have a positive or a negative impact on cost. For example, consider FR-DP Q123: “Ensure operator human errors do not translate to defects”-“Mistake proof operations (poka-yoke).” The idea here is to implement devices, fixtures, tools, etc. that prevent the operator from accidentally performing an operation incorrectly. For example, special features might be added to a part fixture to ensure that it would be impossible for an operator to incorrectly locate a part. Creating additional features on a part fixture will incur some development costs, and possibly incur significant tooling costs as well. However, preventing defects caused by inevitable human errors will certainly reduce the costs associated with quality problems on an ongoing basis. Such situations must be examined on a case-by-case basis in order to accurately assess their overall impact on total cost.

7.1.2 Quality

Of the five dimensions of strategy reviewed here, quality maps the most easily and directly to the MSDD. The left-most branch of the decomposition deals exclusively with the aspects of quality that manufacturing system designers can directly influence, those of conformance quality. The term conformance quality is used here to represent how closely the manufactured products conform to the ideal design. That is, the goal is that all dimensions should be produced to their nominal values, not just somewhere within the specified tolerances. Figure 7-3 shows the FR-DP pairs that influence conformance quality. FR’s Q1 and Q2, “Operate process within control limits” and “Center process mean on the target,” are based on the fundamental ideas of statistical process control (SPC). FR-Q3, “Reduce variation in process output” and its decomposition are based on the ideas of robust design and making a process’s output predictable despite noise at the inputs. Thus, quality control for a process is achieved by identifying and eliminating causes of variation and by making the process output robust to the input noise that remains. Sources of variation considered at the lower levels include the equipment, operators, process plan, and materials (FR’s Q11 through Q14).

As described in section 5.3.2.2, the design matrices in the manufacturing system design decomposition show that producing products with high conformance quality is a necessary prerequisite for achieving high levels of performance in other areas such as on-time delivery, quick response, and low cost. As a result, only the left-most branch deals explicitly with quality. Meeting these goals will ensure high conformance quality; failing to meet them will have a negative impact on the achievement of objectives in all remaining portions of the decomposition.

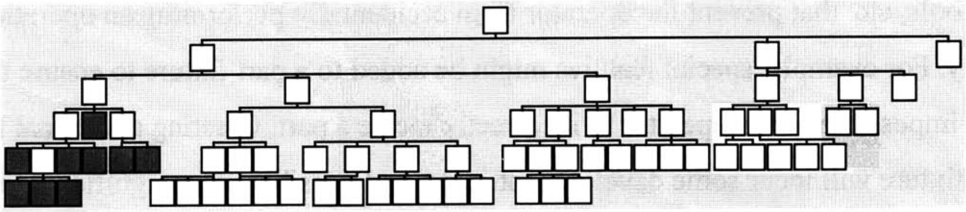


Figure 7-3: Relating the MSDD to quality

7.1.3 Delivery Performance

Two critical aspects of delivery performance can be defined: speed of delivery and dependability. These can also be thought about in terms of the mean and variance of delivery time. Manufacturing firms desire to be able to promise short order lead times to their customers (short *mean* delivery time); they also desire to have the ability to consistently deliver their products on-time (low *variance* in delivery time). Figure 7-4 shows how these strategic objectives map to the manufacturing system design decomposition. Factors affecting both dependability and speed of delivery are shaded in (dark shading for a direct relationship, lighter shading for an indirect relationship); factors affecting only the speed of delivery are indicated with diagonal cross-hatching.

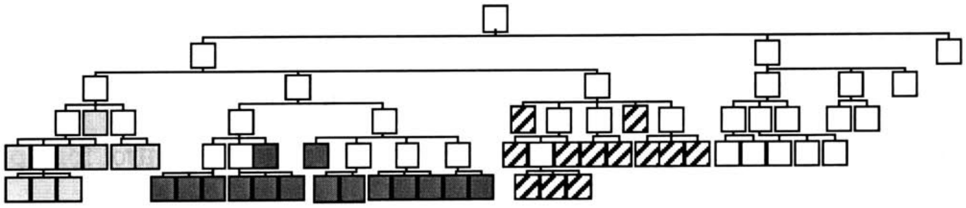


Figure 7-4: Relating the MSDD to delivery performance

Two branches of the decomposition (beginning with FR-DP's R1 and P1) address the requirements for achieving dependable delivery performance by reducing the variation in system throughput time (FR-DP 112). These branches examine production disruptions as the primary cause of variation and unpredictability in system throughput time. In this context, a disruption is defined to be any unplanned event that negatively affects the time output of the system (e.g. a machine breakdown that results in parts being delivered late). A disruption-free system would be one in which all production goes as planned.

One way to understand the impact of disruptions is in terms of the mean time to failure (MTTF) and the mean time to repair (MTTR). The isolated efficiency (also referred to as the availability) of a piece of equipment, e_i, can be expressed as:

$$e_i = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} \tag{7.1}$$

This isolated efficiency represents the fraction of time that the equipment will be available for production barring any external effects (i.e. material or labor shortages) (Gershwin, 1994). In order to improve the isolated efficiency of a piece of equipment, one can reduce the mean time to repair and/or increase the mean time to failure. In the manufacturing system design decomposition, the branch beginning with FR-R1, "Respond rapidly to production disruptions," focuses on the ability of support resources to respond rapidly when a disruption to planned production occurs (i.e. the ability to minimize MTTR). The branch beginning with FR-P1, "Minimize production disruptions," focuses on eliminating the sources of disruptions and preventing them from causing future problems, thereby increasing MTTF. These two branches (shown with the darkly shaded boxes in Figure 7-4) include factors affecting the system as a whole, not just the equipment as viewed in isolation. That is, the reliability of labor, information, and material delivery systems is considered in addition to the reliability of the equipment itself. The lower levels of these branches will be discussed in greater detail in section 7.2.4.

The design matrix for the high-level objectives affecting delivery performance is shown in Figure 7-5. As discussed previously, achieving the quality requirements is necessary in order to reduce the mean throughput time as well as its variance. Any time a part is scrapped or requires rework, variability is added to the system. This relationship is reflected in the design matrix with element X_{21}. Such unpredictable variation (due to either quality or other time-based factors) necessarily adds to the mean throughput time as well, as the minimum throughput time is achieved only when production goes according to plan. By definition, no disruptions allow quality parts to get through the system more quickly. Thus, the more variation is present, the longer the mean throughput time. This information is captured in the design matrix through elements X_{31} and X_{32}. The information in this design matrix is consistent with what many companies have learned empirically: that reducing inventory without first reducing or eliminating the sources of variability that make this inventory necessary is not a viable way to improve system performance.

$$\begin{Bmatrix} \textbf{FR: } \text{Manufacture products to target design specifications} \\ \textbf{FR: } \text{Deliver products on time} \\ \textbf{FR: } \text{Meet customer expected lead time} \end{Bmatrix} = \begin{bmatrix} X_{11} & - & - \\ X_{21} & X_{22} & - \\ X_{31} & X_{32} & X_{33} \end{bmatrix} \begin{Bmatrix} \textbf{DP: } \text{Production processes with minimal variation from the mean} \\ \textbf{DP: } \text{Throughput time variation reduction} \\ \textbf{DP: } \text{Mean throughput time reduction} \end{Bmatrix}$$

Figure 7-5: Design equation for FR 111 – FR 113

7.1.4 Flexibility

The term flexibility has been used to encompass a broad range of capabilities that a manufacturing system might possess. Upton (1994) offers the following general definition of flexibility:

> “Flexibility is the ability to change or react with little penalty in time, effort, cost or performance.”

Upton also defines a framework for characterizing flexibility in terms of its dimensions (i.e., what is being changed), its time horizon (how quickly the changes are made), and its elements: range, mobility, and uniformity. The focus here will be on the different dimensions of flexibility, primarily product mix flexibility and volume flexibility. These two types of flexibility are emphasized here because each can have a significant impact on manufacturing system design and each is often driven by the external requirements placed on the system. Product mix and volume requirements are generally determined by the customer and not by the manufacturing system designers. The design team must then determine the best way to meet the customers’ needs. Other important dimensions of flexibility include machine flexibility (i.e., the ability to modify and/or replace the machine used for a particular process) and design change flexibility (the ability to introduce new products into the system). These two dimensions of flexibility are considered here to be a part of the firm’s innovativeness and will be reviewed in section 7.1.5.

Requirements with the potential to affect a manufacturing system’s product mix flexibility appear throughout the manufacturing system design decomposition, as shown in Figure 7-6.

Many of the quality-based requirements must be considered in order to assure the desired level of product mix flexibility. Equipment must be capable of producing quality parts in the desired run sizes without lengthy periods of downtime for tool-changes and iterations between process gauging and adjustment (FR's Q11, Q13, and T32). Similarly, operators must be capable of processing the desired mix of parts (FR's Q121 and Q123), which can be problematic when the different products have similar but different manual work content. In some cases, assistance must be provided to the operators to prevent mistakes such as the addition of the wrong components to an assembly. In some such cases, a printout of the instructions for assembly may accompany each product down the line. In other cases, a barcode on the part's pallet might be used to activate a computer display of the key instructions and required components at each station. Another approach is to "mistake-proof" the process, making it impossible for the operator to perform the operation incorrectly. This approach is particularly useful when specific operator errors can be anticipated and accounted for in a cost-effective manner.

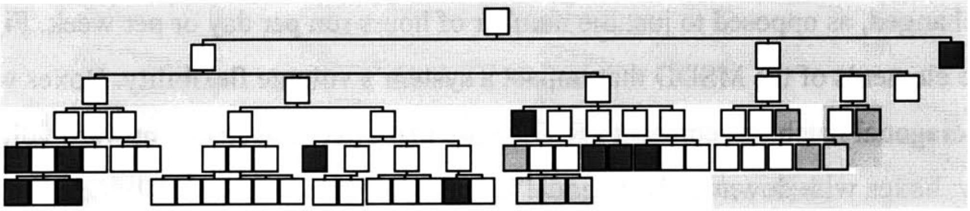


Figure 7-6: Relating the MSDD to product mix flexibility

Other requirements affecting product mix flexibility involve the design of the information flow necessary to communicate the desired product mix information to the necessary points in the manufacturing system (FR's P11, T31, and I2), the amount of work-in-process material kept between stations (FR-P141), and the associated material handling methods (FR-T1). Some auxiliary materials (nuts, bolts, washers, etc.) might be stored right at the stations. If many different products require many different components, the storage space required for all of the possibilities can become large enough to interfere with the ergonomics of the operators' work routines (FR's D22 and D23) and can create difficulties in keeping all of the components available (FR T51). If the different products have different amounts of work content (i.e. cycle time varies from one part type to the next), requirements regarding the balancing of operations become important (FR's T221, T222, T223, and D3).

Volume flexibility can be defined as the ability to alter a manufacturing system's production volume with a minimal penalty. For this investigation a distinction is made between "upward" and "downward" volume flexibility. Upward volume flexibility represents the ease with which a system can be reconfigured to produce at a faster rate. Downward volume flexibility describes how easily a system can produce at volumes less than its capacity. It is important to note that some degree of volume flexibility can often be achieved simply by changing the number of hours per day or per week that the system is run. In this way, overtime can be used to provide some degree of volume flexibility with a relatively low cost penalty for running at slightly higher or lower volumes. The limits on this approach often come from labor relations. Workers may not be willing to work sufficient overtime or an entire additional shift if volumes continue to rise. When volumes drop, the system can always be run for fewer hours per day, but labor contracts often require that operators be paid for at least a full shift, making running a line for less time than that unappealing to management. The following descriptions of volume flexibility consider cases where the *rate* of production must be changed, as opposed to just the number of hours run per day or per week. Figure 7-7 shows the elements of the MSDD that impact a system's volume flexibility. Boxes with upwards-diagonal hatching represent FR-DP pairs that affect a system's upward volume flexibility; boxes with downwards-diagonal hatching affect downward volume flexibility. FR-DP pairs that affect both upwards and downwards volume flexibility are indicated with both directions of hatching.

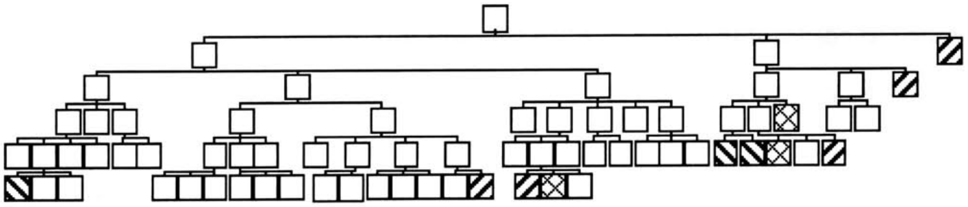


Figure 7-7: Relating the MSDD to volume flexibility

Reconfiguring a manufacturing system to increase its production rate affects functional requirements on its layout, labor, scheduling, machine design, and investment cost. Material handling systems must be capable of providing parts at the increased rate (FR-P142). All equipment must be capable of meeting the faster cycle time (FR-T221). If it is not, additional equipment must be purchased and installed, affecting investment cost (FR13), system floor space (FR123), and operators' manual work content (FR's D21, D23, and D3).

Decreasing a manufacturing system's production rate affects different requirements, mainly in terms of the operators running the system. In some cases, running the system at a slower rate means that each operator can be responsible for a greater number of machines and that fewer operators will be necessary. This could affect the amount of training an operator requires (FR-Q121) if he or she will be asked to run additional types of machines and will require the revision of manual work-loops (FR's T222, D11, D12, D21, and D3).

7.1.5 Innovativeness

Strategic requirements based on innovativeness have to do with the manufacturing system's ability to adapt to technological advances in the design of both products and processes. As described in the section on flexibility, innovativeness is dependent on the ease with which equipment can be replaced and/or modified, as well as the time it takes to introduce new types of products to the manufacturing system.

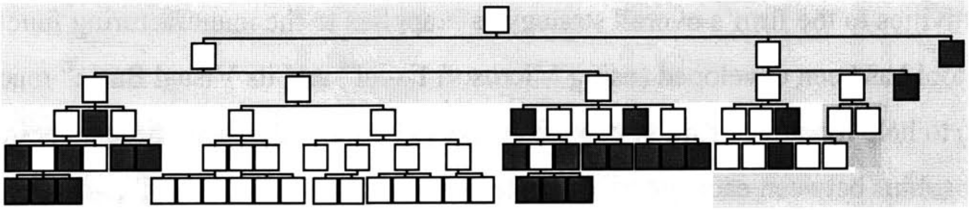


Figure 7-8: Relating the MSDD to innovativeness

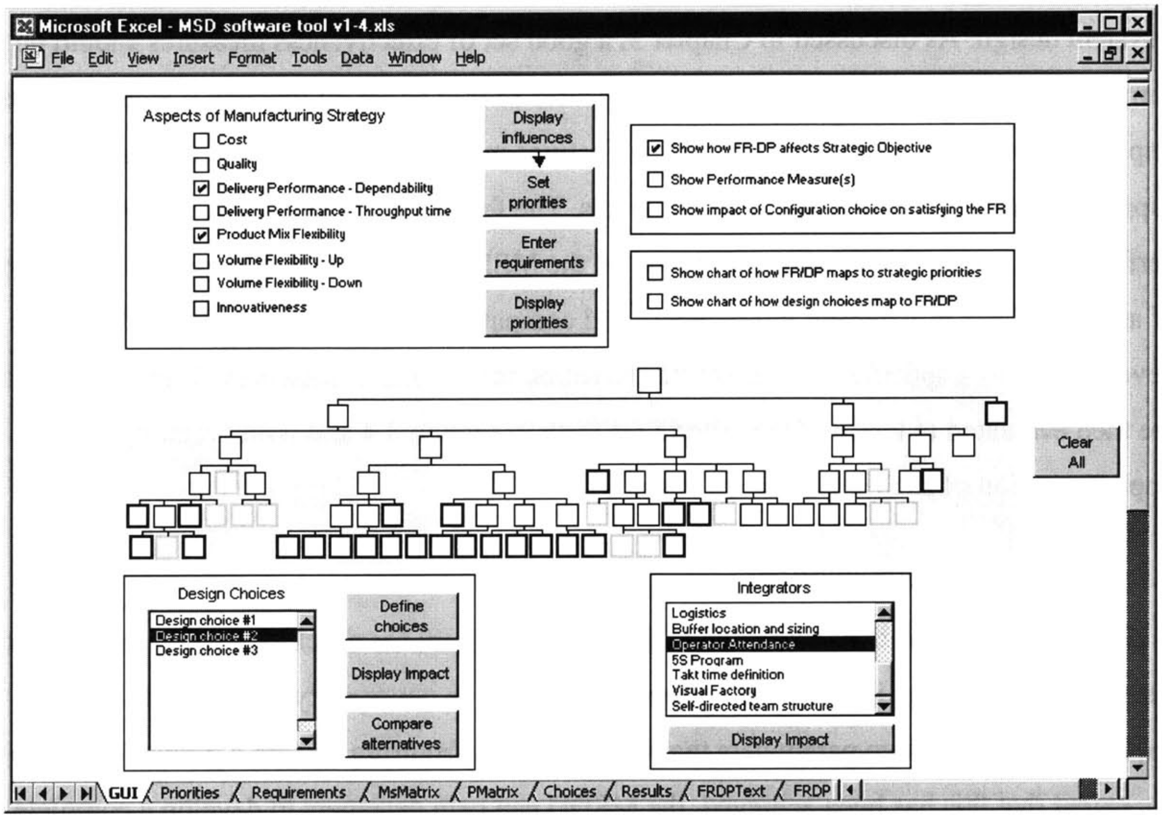
Figure 7-8 shows the FR-DP pairs that are related to a system's innovativeness. Quality issues related to automatic and manual work content are important. When introducing a new product into the system, it must be confirmed that the equipment is capable of producing it and that the operators are trained to process it. Similarly, when new equipment is introduced it must be confirmed that it is capable of processing all necessary part types and that the appropriate operators are trained in its use. The addition of new equipment or part types could also affect the system's floor space (FR-123) and manual work content (FR's D21 and D3). Depending on the flexibility of existing equipment, new or modified part designs could require significant investment for fixturing, gauging, and tooling (FR-13).

The throughput time of the system also affects its innovativeness. This relationship is a particularly important factor in environments such as computer hardware production where product designs change rapidly, making previous designs obsolete. In that case, long throughput times can be very damaging to a firm's competitive position, both in terms of the time it takes to introduce new products and in terms of the rapidly decreasing value of the inventory within the system.

7.1.6 Summary of Linking the MSDD to the Dimensions of Strategy

The prior sections have shown how the various dimensions of manufacturing strategy map to the requirements and objectives of the manufacturing system design decomposition. These mappings show that a system must achieve several lower-level functional requirements in order to excel in even one dimension of strategic performance. The mappings also show that each FR-DP pair is important to system performance with respect to two or more dimensions of strategy.

These mappings of functional requirements and design parameters to strategic objectives can be useful to designers as they perform steps 2-5 of the core manufacturing system design process. The mappings provide a structured means for linking detailed, low-level system design activities to the firm's overall strategy as it applies to the manufacturing function. A software tool has been developed (using Microsoft Excel® and its Visual Basic® macro language) to help manufacturing system designers to better understand these mappings and the relationships between each aspect of strategy and each relevant FR/DP pair. The software tool allows designers to view this mapping information graphically, as shown in Figure 7-9. Designers can choose one or more aspects of manufacturing strategy and then display the interactions between these aspects and the various leaf FR/DP pairs. Such relationships are indicated through the border thickness of the appropriate boxes. A dark, thick border indicates that achieving the associated leaf FR/DP pair will have a strong impact on the ability of the system to perform well with respect to the selected aspects of strategy. Lighter borders indicate leaf FR/DP pairs with a less critical impact on the selected aspects of strategy. Figure 7-9 shows an example where the relationships between FR/DP pairs and both delivery performance (in terms of dependability) and product mix flexibility are displayed. Clicking on a box will bring up a window displaying the functional requirement, design parameter, and a brief explanation of how that FR/DP pair relates to the selected aspects of strategy (a table containing this text is shown in Appendix B-3). As an example, Figure 7-10 shows the window displayed when the designer clicks on the box in the lower-left (i.e., the one corresponding to FR/DP Q-121). The tool provides a quick and simple way to convey the basic information linking the MSDD to strategy. The software tool can also provide assistance with other portions of the core manufacturing system design process, as will be discussed in the sections that follow.



Aspects of Manufacturing Strategy

- ☐ Cost
- ☐ Quality
- ☑ Delivery Performance - Dependability
- ☐ Delivery Performance - Throughput time
- ☑ Product Mix Flexibility
- ☐ Volume Flexibility - Up
- ☐ Volume Flexibility - Down
- ☐ Innovativeness

- ☑ Show how FR-DP affects Strategic Objective
- ☐ Show Performance Measure(s)
- ☐ Show impact of Configuration choice on satisfying the FR

- ☐ Show chart of how FR/DP maps to strategic priorities
- ☐ Show chart of how design choices map to FR/DP

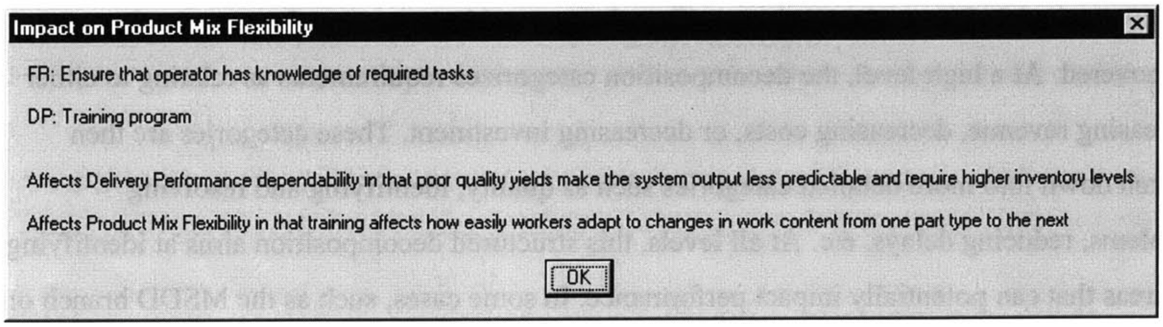
Design Choices

- Design choice #1
- Design choice #2
- Design choice #3

Integrators

- Logistics
- Buffer location and sizing
- Operator Attendance
- 5S Program
- Takt time definition
- Visual Factory
- Self-directed team structure

Figure 7-9: Software tool showing mapping of strategy to MSDD



Impact on Product Mix Flexibility

FR: Ensure that operator has knowledge of required tasks

DP: Training program

Affects Delivery Performance dependability in that poor quality yields make the system output less predictable and require higher inventory levels

Affects Product Mix Flexibility in that training affects how easily workers adapt to changes in work content from one part type to the next

Figure 7-10: Window displaying strategy information for FR/DP Q-121

The next section will review step 2, the development of a set of performance measures, and will discuss how the mappings of strategy to the MSDD can be used to help designers focus measurement on the areas of performance that are critical to achieving the high-level goals of the firm.

7.2 Using the MSDD to Define Effectiveness Measures

The structure of the manufacturing system design decomposition provides a convenient framework for the development of a system for measuring the performance or effectiveness of a system design. As discussed in Chapter 3, a good set of effectiveness measures should be complete, consistent and compatible; the measures should cover all functional areas that are important to the achievement of strategic objectives in a manner that fosters mutually supportive behavior at all organizational levels. The following sections review how a performance measurement approach based on the MSDD can assist system designers in terms of assuring the completeness, consistency, and compatibility of a set of measures. Next, the development of a specific set of measures based on the MSDD is reviewed. These measures are then evaluated in terms of the criteria set forth in section 3.4 and issues relating to the implementation of such a system are discussed.

7.2.1 Ensuring Completeness

The breadth of the decomposition makes it a useful tool for checking the completeness of a set of measures. The intent of the decomposition was to cover all types of controllable requirements and design parameters that impact a manufacturing system's performance. To the extent that this has been achieved, the MSDD can help designers to develop a complete set of effectiveness measures. While it is impossible to guarantee the completeness of a set of measures, the MSDD can be used to confirm that several key aspects of system performance are covered. At a high level, the decomposition categorizes requirements as relating to either increasing revenue, decreasing costs, or decreasing investment. These categories are then broken down into more detailed categories such as quality, identifying and resolving problems, reducing delays, etc. At all levels, this structured decomposition aims at identifying all areas that can potentially impact performance. In some cases, such as the MSDD branch on "Identifying and Resolving Problems," the decomposition is based on the series of actions that must be taken in order to achieve the objective. In other parts of the MSDD, completeness of the decomposition is based on the identification of all of the relevant categories of problems that could arise. For example, consider the decomposition of quality requirements. The decomposition categorizes quality requirements according to the following sources of variation: equipment, operators, methods, and materials. This effort to identify and classify all sources of quality problems represents an attempt at defining a complete set of factors that must be measured and monitored to ensure quality.

Because the MSDD was developed to be generally applicable to a wide range of situations and scenarios, it cannot contain a complete set of all possible requirements and objectives. Requirements based on product design or union workforce regulations, for example, are not included in the MSDD. Product design issues are beyond the scope of what is included in the manufacturing system design decomposition. Union guidelines are not included in the MSDD, as their form and presence will vary from one firm to the next. The core manufacturing system design process accounts for this lack of completeness by allowing for the definition of other external requirements, as described in section 6.3.2. It is critical that these requirements be considered in addition to those from the MSDD when a set of performance measures is being generated.

7.2.2 Ensuring Consistency at all Organizational Levels

The different levels of the manufacturing system design decomposition correspond to different levels in an organization. FR's and DP's at the lower levels tend to be factors under the control of operators and engineers. Mid-level requirements and design parameters represent factors most often controlled by mid-level managers and section supervisors, and the achievement of higher-level objectives is frequently the responsibility of top-level managers. As a result, the decomposition can facilitate the development of performance measures at all levels of the organization, allowing everyone involved in manufacturing to see how their daily activities relate to the high-level objectives of the firm. Because lower-level objectives were explicitly derived through a decomposition process that started with the high-level system requirements, there is consistency of purpose across all organizational levels and traceability from low-level activities to high-level objectives. These concepts are also discussed in terms of how the MSDD can be used to support the development of a balanced scorecard approach in (Lobo et al., 2000).

7.2.3 Ensuring Compatibility Within Manufacturing

Similarly, the information contained in the design matrices of the MSDD helps to ensure compatibility among different tasks within the manufacturing function. As discussed in the previous chapter, this design matrix information (represented graphically with arrows in the

MSDD as shown in Appendix A-1) identifies where interdependencies exist among different aspects of the system design. Although this does not guarantee that all measures will be fully compatible (i.e., will encourage mutually supportive behavior), the information is useful in terms of alerting system designers to areas in which issues of compatibility might arise. For example, looking at the 2nd level of the decomposition in Appendix A-1, we see that DP-11 ("Production to Maximize Customer Satisfaction") has an impact on FR-12 ("Minimize Production Cost") and FR-13 ("Minimize Investment over Manufacturing System Life Cycle"). Thus, actions that are taken to maximize customer satisfaction could result in higher production or investment costs. The design matrix information makes system designers aware of this relationship so that they may more easily recognize the existence of any trade-offs that may exist between various effectiveness measures. The usefulness of the MSDD for assisting with trade-off analysis will be further discussed in Chapter 8. For now, the key advantage obtained from using the MSDD to develop a set of performance measures is the ability to call attention to the relationships among design elements at an early stage in the design process so that the impact of these relationships can be monitored as different system design alternatives are considered.

7.2.4 A Set of Performance Measures Based on the MSDD

This section describes a set of performance measures (PM's) derived based on the manufacturing system design decomposition, where one or more performance measures are defined for each FR/DP pair. High-level FR-DP pairs are reviewed first; the remaining pairs are grouped according to the "branches" of the decomposition (decompositions of level three DP's). It was desired that the measures assess the system's ability to meet the functional requirements rather than evaluate whether or not the system has implemented a particular design parameter. The emphasis here is placed on the performance relative to the objective and not on the means used to achieve the objective. The goal in developing these PM's was to identify a measure for each functional requirement that would clearly link system performance to that FR and would be reasonable to measure in a factory environment. The guidelines for effective measures reviewed in Table 3-2 were used to select and create useful measures that could provide fast and meaningful feedback to system designers, managers, and operators. Specific measurement issues and difficulties that arose will be discussed as the measures are reviewed.

7.2.4.1 High-Level Performance Measures

Table 7-1: High-level performance measures based on the MSDD

Functional Requirement (FR)	Performance Measure (PM)
FR-1: Maximize long-term return on investment	PM-1: Return on investment over system life cycle
FR-11: Maximize sales revenue	PM-11: Sales revenue
FR-111: Manufacture products to target design specifications	PM-111: Process capability
FR-112: Deliver products on time	PM-112: Percentage on-time delivery, amount of lateness
FR-113: Meet customer expected lead time	PM-113: Difference between mean throughput time and customers' expected lead time
FR-12: Minimize production costs	PM-12: Production costs
FR-121: Reduce waste in direct labor	PM-121: Percentage of operators' time spent on wasted motions and waiting
FR-122: Reduce waste in indirect labor	PM-122: Amount of required indirect labor
FR-123: Minimize facilities cost	PM-123: Facilities costs
FR-13: Minimize investment over production system life cycle	PM-13: Investment over system life cycle

Although the selection of measures for these high-level requirements was straightforward, these measures are likely to be among the most difficult to quantitatively measure in practice. Financial measures such as PM-1, PM-11, and PM-13 present difficulties in that they require forecasting costs and revenues over the entire projected life cycle of the system. Uncertainty in these projections makes these results difficult to quantify with any great precision. Probability-based tools can be useful for determining expected values of forward-looking measures such as these. Another way of avoiding the measurement difficulties presented by future uncertainty is to look only into the short-term, or to base future projections heavily on past results. However, this focus on the past and short-term future is likely to divert attention from the activities necessary for long-term success (Hayes and Wheelwright, 1979). Another difficulty faced in measuring performance at this level is attempting to isolate the impact of manufacturing on these measures. This is particularly true in the case of sales revenue, where it can be very difficult to make quantifiable predictions about the impact of increased customer satisfaction on sales. Because of difficulties such as this, it is important that a firm also measure performance with respect to the critical lower-level requirements that influence important aspects of system behavior.

7.2.4.2 Quality Performance Measures

Table 7-2: Quality performance measures based on the MSDD

Functional Requirement (FR)	Performance Measure (PM)
FR-Q1: Stabilize process	PM-Q1: Number of defects per n parts with an assignable cause
FR-Q11: Eliminate machine assignable causes	PM-Q11: Number of defects per n parts assignable to equipment
FR-Q12: Eliminate operator assignable causes	PM-Q12: Number of defects per n parts assignable to operators
FR-Q121: Ensure that operator has knowledge of required tasks	PM-Q121: Number of defects per n parts caused by an operator's lack of understanding about methods
FR-Q122: Ensure that operator consistently performs tasks correctly	PM-Q122: Number of defects per n parts caused by non-standard methods
FR-Q123: Ensure that operator human errors do not translate to defects	PM-Q123: Number of defects per n parts caused by human error
FR-Q13: Eliminate method assignable causes	PM-Q13: Number of defects per n parts assignable to the process
FR-Q14: Eliminate material assignable causes	PM-Q14: Number of defects per n parts assignable to quality of incoming material
FR-Q2: Center process mean on the target	PM-Q12: Difference between process mean and target
FR-Q3: Reduce variation in process output	PM-Q3: Variance of process output
FR-Q31: Reduce noise in process inputs	PM-Q31: Variance of process inputs
FR-Q32: Reduce impact of input noise on process output	PM-Q32: Output variance / input variance

The manufacturing system design decomposition branch dealing with quality and the corresponding performance measures focus on the various potential causes of variation in process output (i.e., deviations from the targeted product design specification). At the top level of this branch (FR's Q1, Q2, and Q3) this is achieved by stabilizing each process (i.e. eliminating assignable causes of variation), centering the process, and making it robust to input noises. Achievement of these FR's can be measured by monitoring the number of defects and process means and variations. At the next level down (FR-Q11 – FR-Q14, FR-Q31 - FR-Q32), the potential sources of variation are examined individually so that the root causes of defects and process variation can be traced and monitored. Quality problems assignable to operators are further decomposed based on whether the defect occurred due to an operator's lack of understanding about what to do (FR-Q121), due to an operator's decision to follow a non-standard work routine (FR-Q122), or due simply to inadvertent human error (FR-Q123). The measures for these FR's are expressed as ratios, comparing the number of defects to the number of parts, n, made in some time interval. For example, quality data for FR-Q11 might be recorded on a per-shift basis. In that case, the value of n would be the total number of parts made during a shift, and the value of the performance measure would be the number of defective parts assignable to equipment problems that were produced during that shift divided by n. The more frequently the data are recorded (i.e. the shorter the time interval), the easier it will be to track variation to its source; however, it will also increase the amount of time necessary to record and track the data. The last FR at this level, "Reduce impact of input noise on process output" (FR-Q32), is based on the concept of robust design, with the goal being to make the process' output predictable and centered on the target despite noise in the inputs.

7.2.4.3 Performance Measures for Identifying and Resolving Problems

Table 7-3: Performance measures for identifying and resolving problems based on the MSDD

Functional Requirement (FR)	Performance Measure (PM)
FR-R1: Respond rapidly to production disruptions	PM-R1: Time between occurrence and resolution of disruptions
FR-R11: Rapidly recognize production disruptions	PM-R11: Time between occurrence of disruption and identification of what the disruption is
FR-R111: Identify disruptions where they occur	PM-R111: Time between identification of disruption and identification of where the disruption occurred
FR-R112: Identify disruptions when they occur	PM-R112: Time between occurrence and recognition that disruption occurred
FR-R113: Identify what the disruption is	PM-R113: Time between identification of where disruption occurred and identification of what the disruption is
FR-R12: Communicate problems to the right people	PM-R12: Time between identification of what the disruption is and support resource understanding what the disruption is
FR-R121: Identify correct support resources	PM-R121: Time between identification of what the disruption is and identification of the correct support resource
FR-R122: Minimize delay in contacting correct support resources	PM-R122: Time between identification and contact of correct support resource
FR-R123: Minimize time for support resource to understand disruption	PM-R123: Time between contact of correct support resource and support resource understanding what the disruption is
FR-R3: Solve problems immediately	PM-R3: Time between support resource understanding what the disruption is and problem resolution

These requirements and measures deal with the ability of the people within the manufacturing system to respond to production disruptions. The decomposition of FR-DP pair R1 is based on the sequence of events that results when such a disruption occurs. The sequence of events described in the decomposition is summarized by the timeline shown in Figure 7-11 below. It is assumed that operators are responsible for identifying problems, but that additional support resources will be necessary to resolve problems. In cases where operators can solve problems themselves, the "communicate disruption" portion of the process will be unnecessary. The corresponding measures simply reflect the time spent on each step of the problem solving process, with the goal being to identify, communicate, and resolve the problem as quickly as possible.

Identify disruption			Communicate disruption			Solve problem
Identify that a disruption has occurred	ID where disruption occurred	ID what the disruption is	ID support resource(s)	Contact support resource(s)	Communicate disruption info	

Figure 7-11: General process for problem identification, communication, and resolution

7.2.4.4 Performance Measures of Predictable Output

While the previous branch of the decomposition focused on quickly reacting to problems when they occur, this branch looks at what can be done to minimize the number of disruptions that occur and the time variation in system output that results. FR's P11 – P14 describe four sources of variation in production output: information, equipment, operators, and materials. Two approaches can be taken to monitor system performance with regard to these requirements. One approach, shown in Table 7-4, is to measure each FR directly, without regard to higher-level objectives. In this case, the focus is on the number of disruptions that occur due to each of the four sources of variation just described. A second approach, shown in Table 7-5, is to measure the achievement of the lower-level FR's (P11 – P14, etc.) in terms of how they affect the higher-level FR-P1. That is, to measure how much production time is lost due to each source of variation. These measures are referred to as being indirect as they do not directly measure performance in terms of each FR. For example, consider FR-P132: "Ensure availability of workers." A direct measure of this FR would be the number of times that workers are late at the beginning of a shift or after a break. However, assuming that the system is running at less than its maximum capacity, not all operator lateness will result in a disruption to the planned system output. Such lateness would affect the direct performance measure, but not the indirect measure.

While the indirect measures more precisely reflect the system's ability to meet the high-level requirement of predictable output, certain advantages do exist for direct measurement of the lower-level FR's. One strength of the direct measures is that they are much simpler to track in a real factory. The data they involve are counts of the number of occurrences of problems and the duration of each problem. The indirect measures are more difficult to capture. Consider, for example, the measures for FR-P12, "Ensure predictable equipment output." The direct measures are: "Number of occurrences of unplanned equipment downtime, Amount of unplanned equipment downtime," and the indirect measure is "Production time lost due to unplanned equipment downtime." When a piece of equipment fails, it is a relatively simple matter for most factories to track the direct measures, noting the occurrence and duration of the downtime. Determining how much *production* time was lost is much more difficult. One might look at how much, if any, overtime had to be run to meet the production schedule, but even this measure cannot isolate production time lost specifically due to equipment failure. A general disadvantage to using the direct measures is that they may draw attention to "problems" that are not actually affecting the system's ability to meet its high-level objectives. However, in all cases the direct measures would focus attention on making reliability improvements

Table 7-4: Direct performance measures for predictable output

Functional Requirement (FR)	Performance Measure (PM)
FR-P1: Minimize production disruptions	PM-P1: Number of occurrences of disruptions, Amount of time lost to disruptions
FR-P11: Ensure availability of relevant production information	PM-P11: Number of occurrences of information disruptions, Amount of interruption time for information disruptions
FR-P12: Ensure predictable equipment output	PM-P12: Number of occurrences of unplanned equipment downtime, Amount of unplanned equipment downtime
FR-P121: Ensure that equipment is easily serviceable	PM-P121: Amount of time required to service equipment
FR-P122: Service equipment regularly	PM-P122: Frequency of equipment servicing
FR-P13: Ensure predictable worker output	PM-P13: Number of disruptions due to operators, Amount of interruption time for operators
FR-P131: Reduce variability of task completion time	PM-P131: Variance in task completion time
FR-P132: Ensure availability of workers	PM-P132: Number of occurrences of operator lateness, Amount of operator lateness

Functional Requirement (FR)	Performance Measure (PM)
FR-P133: Do not interrupt production for worker allowances	PM-P133: Number of disruptions due to operator allowances, amount of interruption time for worker allowances
FR-P14: Ensure material availability	PM-P14: Number of disruptions due to material shortages, amount of interruption time for material shortages
FR-P141: Ensure that parts are available to the material handlers	PM-P141: Number of occurrences of marketplace shortages
FR-P142: Ensure proper timing of part arrivals	PM-P142: Parts demanded - parts delivered

Table 7-5: Indirect performance measures for predictable output

Functional Requirement (FR)	Performance Measure (PM)
FR-P1: Minimize production disruptions	PM-P1: Production time lost due to disruptions
FR-P11: Ensure availability of relevant production information	PM-P11: Production time lost due to information disruptions
FR-P12: Ensure predictable equipment output	PM-P12: Production time lost due to unplanned equipment downtime
FR-P121: Ensure that equipment is easily serviceable	PM-P121: Production time lost while machines are being serviced
FR-P122: Service equipment regularly	PM-P122: Production time lost due to inadequate amounts of maintenance
FR-P13: Ensure predictable worker output	PM-P13: Production time lost due to low operator output
FR-P131: Reduce variability of task completion time	PM-P131: Production time lost due to varying task completion time
FR-P132: Ensure availability of workers	PM-P132: Production time lost due to unavailable operators
FR-P133: Do not interrupt production for worker allowances	PM-P133: Production time lost due to worker allowances
FR-P14: Ensure material availability	PM-P14: Production time lost due to material shortages
FR-P141: Ensure that parts are available to the material handlers	PM-P141: Production time lost due to material handlers waiting for parts
FR-P142: Ensure proper timing of part arrivals	PM-P142: Production time lost due to operators waiting for material to arrive

7.2.4.5 Performance Measures for Delay Reduction

Table 7-6: Performance measures for delay reduction

Functional Requirement (FR)	Performance Measure (PM)
FR-T1: Reduce lot delay	PM-T1: Inventory due to lot size delay
FR-T2: Reduce process delay	PM-T2: Inventory due to process delay
FR-T21: Define takt time(s)	PM-T21: Has this information been provided? (Yes/No)
FR-T22: Ensure that production rate is balanced with takt time	PM-T22: Difference between production cycle time and takt time
FR-T221: Ensure that automatic cycle time <= minimum takt time	PM-T221: Has this been achieved? (Yes / No)
FR-T222: Ensure that manual cycle time <= takt time	PM-T222: Has this been achieved? (Yes / No)
FR-T223: Ensure level cycle time mix	PM-T223: Is average cycle time less than takt time in desired time interval?
FR-T23: Ensure that part arrival rate is balanced with service rate	PM-T23: Difference between arrival and service rates
FR-T3: Reduce run size delay	PM-T3: Inventory due to run size delay
FR-T31: Provide knowledge of demanded product mix (part types and quantities)	PM-T31: Has this information been provided? (Yes/No)
FR-T32: Produce in sufficiently small run sizes	PM-T32: Actual run size - target run size
FR-T4: Reduce transportation delay	PM-T4: Inventory due to transportation delay
FR-T5: Reduce systematic operational delays	PM-T5: Production time lost due to interferences among resources
FR-T51: Ensure that support activities don't interfere with production activities	PM-T51: Production time lost due to support resources interferences with production resources
FR-T52: Ensure that production activities don't interfere with one another	PM-T52: Production time lost due to production resources interferences with one another
FR-T53: Ensure that support activities (people/automation) don't interfere with one another	PM-T53: Production time lost due to support resources interferences with one another

The next section of the decomposition addresses the requirements for meeting the customers' expected lead time by reducing the mean throughput time of the manufacturing system. The five highest-level FR's in this branch (FR-T1 – FR-T5) represent five categories of delays. One result of Little's law (as presented in section 5.3.2.2) is that counts of inventory can be used to estimate system throughput time, where average throughput time is equal to average total inventory divided by the average rate at which parts enter and leave the system. So, each type of delay can be measured according to how much additional inventory must be kept in the system to account for it. For example, the inventory added due to transportation delay (time the parts spend being moved from operation to operation) can be measured by tracking the average number of parts in transit within the system at a given time. Other types of delays can be measured and improved directly (lot delay) or with a minimal amount of further decomposition (run size delay and systematic operational delay). The remaining delay, process delay, requires further decomposition based on the necessary conditions for its elimination.

7.2.4.6 Performance Measures for Direct and Indirect Labor Costs

Table 7-7: Performance measures for direct and indirect labor costs

Functional Requirement (FR)	Performance Measure (PM)
FR-D1: Eliminate operators' waiting on machines	PM-D1: Percentage of operators' time spent waiting on equipment
FR-D11: Reduce time operators spend on non-value added tasks at each station	PM-D11: Percentage of operators' time spent on non value-adding tasks while waiting at a station
FR-D12: Enable worker to operate more than one machine / station	PM-D12: Percentage of stations in a system that each worker can operate
FR-D2: Eliminate wasted motion of operators	PM-D2: Percentage of operators' time spent on wasted motions
FR-D21: Minimize wasted motion of operators between stations	PM-D21: Percentage of operators' time spent walking between stations
FR-D22: Minimize wasted motion in operators' work preparation	PM-D22: Percentage of operators' time spent on wasted motions during work preparation
FR-D23: Minimize wasted motion in operators' work tasks	PM-D23: Percentage of operators' time spent on wasted motions during work routine
FR-D3: Eliminate operators' waiting on other operators	PM-D3: Percentage of operators' time spent waiting for other operators
FR-I1: Improve effectiveness of production managers	PM-I1: Amount of indirect labor required to manage system
FR-I2: Eliminate information disruptions	PM-I2: Amount of indirect labor required to schedule system

The focus of the measures of direct and indirect labor is on eliminating non-value added tasks, rather than on eliminating the labor itself. The decomposition for direct labor (FR's D1 - D3) is based on two types of waste: waiting and wasted motions. It is desired that operators spend as little time as possible waiting either for another operator to complete his/her work (FR-D3) or waiting at a station while a machine completes its cycle (FR-D1). Elimination of workers' waiting at a station while a machine cycles is eliminated through the use of work loops, where an operator runs multiple machines, walking from one to the next. Since time spent walking between machines does not add value to the product, it is desired that this walking time and distance be kept to a minimum by locating the machines as close together as possible. Similarly it is desired that wasted motions in operators' work (FR-D23) and work preparation (FR-D22) be minimized as well. In all cases, the performance measures for eliminating waiting and wasted motions encourage reducing the portion of operators' time that is spent on these non-value adding operations.

In the case of indirect labor, the focus is on making managerial activities as efficient as possible. Other forms of indirect labor such as maintenance and quality control are not addressed in this portion of the MSDD, as it is thought that activities in previous branches of the decomposition represent the means for making efficient use of such resources. Indirect labor activities that remain are broken into two categories: supervision (FR-I1) and scheduling (FR-I2). Ideally, one would like to see a system in which the operators are capable of running and scheduling the system by themselves with a minimum of external supervision, allowing indirect workers the time to focus more on making future improvements.

7.2.4.7 Conclusions

The prior sections have suggested an extensive list of performance measures for monitoring and assessing performance in a manufacturing system. This list of measures does not, however, constitute a complete system for performance measurement. This section evaluates these measures against the standards for performance measures presented in Chapter 3 and discusses how the measures can be used as part of a firm's overall performance measurement system.

As described in Chapter 3, performance measures can be categorized by their data source (internal / external), data type (subjective / objective), reference (benchmark / self-referenced), process orientation (input / outcome), level of aggregation, level in organizational hierarchy, etc. A complete performance measurement system should make certain that no category of measures is overlooked. For the performance measures derived based on the MSDD, there is a strong correlation between the level of the decomposition from which the measure comes and its categories, particularly in the case of data source, data type, and level in organizational hierarchy. Measures derived from lower-level requirements tend to be internal, objective, and to apply to lower levels of the organization. Such measures tend to be focused on internal details of the system, such as specific sources of quality or reliability problems. As such, they clearly will be measured internally and at a shop-floor level and can usually be quantified objectively. Higher-level measures are more often external, subjective, and applicable to higher levels of the organization. With these measures, external factors such as customer expectations and satisfaction become important, making the measures more subjective. Another difficulty is that at the higher levels, it becomes difficult if not impossible to isolate *manufacturing's* contribution to the measure. For example, it is easy to measure current sales revenues, but it would be extremely difficult to objectively quantify the impact of the manufacturing system design on changes in these revenues.

The performance measures presented here can also be evaluated in terms of the guidelines for effective performance measures presented in Table 3-2. Using the structure of the manufacturing system design decomposition ensures that all measures are related to strategic objectives, are based on factors that can be influenced or controlled within the manufacturing function, have a clear purpose, and include a wide variety of non-financial factors. Only a small percentage of the measures reflect the entire business process including customers and/or suppliers, however, as the lower-level FR's tend to be internally focused. Some of the measures are based on ratios, such as the quality measures, but most are expressed as absolute numbers. However, many others could easily be converted to ratios if so desired.

The set of measures presented in this chapter is not intended to be a complete and universal system for performance measurement. Instead, individual firms using these measures have many decisions left to make, allowing the final set of measures to reflect input from the people involved. Targets for each measure must be defined, either internally or through competitive benchmarking. Lower-level measures are likely to be self-referenced, as industry-wide data will likely be very difficult to obtain. In many cases, long-term targets can be set easily as many of the measures will have target values of zero. Clearly, any firm would like to eliminate all defects, all unplanned machine downtime, etc. However, each firm will also set its own, more immediate goals based on more realistic and achievable targets. Firms might also choose to place more measurement emphasis on specific process inputs, or the specific design parameters they choose to fulfill their functional requirements. This can be particularly important when the desired performance results are not being achieved. For example, a firm might wish to measure the changeover time (DP-T32) on a particular piece of equipment that has historically required a large amount of time and resource for setups. While measuring "inputs" such as this, it is important to remember *why* the changeover time is being reduced: to enable the reduction of run sizes (FR-T3) and, ultimately, required levels of inventory and throughput time.

It is also important to note that these measures relate only to manufacturing, not to the activities of the firm as a whole. Thus they represent an important component of an enterprise-level performance measurement system, such as the balanced scorecard approach discussed in Chapter 3. Lobo, Duda, and Cochran (2000) present a more detailed look at how deriving performance measures based on the manufacturing system design decomposition can contribute to the development of an enterprise measurement system using the balanced scorecard approach.

7.3 Using the MSDD for Behavior and Structure Modeling

As described in sections 6.3 and 6.4, the FR and DP portions of the manufacturing system design decomposition can be viewed as system-focused models of behavior and structure, respectively. While these decompositions can be valuable as conceptual models, significant further work will be required in order to develop complete models of system behavior and structure. In the case of behavior modeling, this will include the development of process plans for all part types, the definition of scheduling policies, determination of part routings, etc. Developing a complete structure model will require many decisions regarding the number and type of machines to acquire, system layout, buffer locations and sizes, etc. Essentially, the data necessary to create complete models of behavior and structure is the same data that would be needed to create a complete computer simulation of the proposed system.

7.4 Summary

This chapter has presented an overview of how the manufacturing system design decomposition can be used to determine the lower-level functional requirements and design parameters that relate to a given set of high-level strategic objectives. The manufacturing system design decomposition has been shown to contain a broad and diverse set of requirements that span all major aspects of manufacturing strategy. Because of this breadth, the MSDD can also function as a useful tool for the development of a set of effectiveness measures. A list of performance measures derived from the FR/DP pairs of the MSDD was presented and reviewed. These measures can be a valuable starting point in the development of a performance measurement system and can be built upon by system designers with input from those being measured.

Chapter 8 Integrating the MSDD into the Proposed Core Process: Examining Trade-Offs

With information about strategy, requirements, effectiveness measures, and system structure and behavior in mind, designers can examine the trade-offs that exist among multiple possible design solutions. The MSDD can serve as an important tool in helping designers to identify the relevant trade-offs and to begin forming quantitative models of these trade-offs. This section reviews a process for using the MSDD to guide the analysis of trade-offs among design choices. The process begins with the creation of a formal model of the decision maker's preference structure and then uses this information to select and prioritize a set of performance measures. Next, the manufacturing system design decomposition is used as a means to relate the design alternatives being considered to the relevant aspects of performance. Finally, this information can be combined to show how the various design alternatives compare in terms of their ability to achieve the desired results. With this information, designers can identify key trade-offs for more detailed investigation, identify opportunities for improvements in one or more of the alternatives, and/or select one design choice for further study. Once a design choice is made, the performance measurement system can be revised to include details particular to the specific design choice made. An overview of this process for using the MSDD as an aid for trade-off analysis is shown in Figure 8-1. Examples of the application of this process will be reviewed in Chapter 9.

Throughout this process, matrices are used to store and process the relevant information. Table 8-1 gives a summary of the information contained in each of the different matrices used in the proposed process. A more detailed description of each of these matrices will be provided as its role in the trade-off analysis process is discussed.

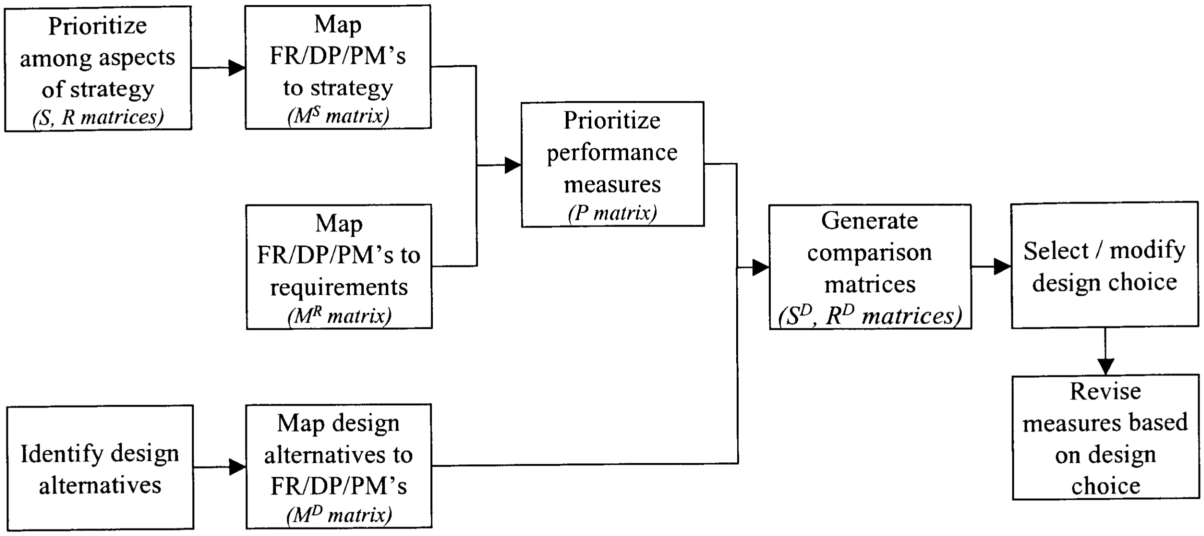


Figure 8-1: Process for using the MSDD as an aid for trade-off analysis

Table 8-1: Matrices used in the trade-off analysis process

S	Diagonal matrix containing the priority weight for each aspect of strategy
R	Diagonal matrix containing the priority weight for each requirement
M^S	Mapping matrix relating the FR/DP pairs of the MSDD to aspects of strategy
M^R	Mapping matrix relating the FR/DP pairs of the MSDD to requirements
M^D	Mapping matrix relating the design choices to the FR/DP pairs of the MSDD
P	Matrix showing the priority of FR/DP pairs relative to the strategic objectives ($=S*M^S$)
S^D	Matrix comparing the design choices in terms of the relevant aspects of strategy ($=P*M^D$)
R^D	Matrix comparing the design choices in terms of the requirements ($=M^R*M^D$)

8.1 Modeling the Decision Makers' Preference Structure

The process of examining trade-offs begins with the development of a formal model of the decision maker's preference structure. In the context of this thesis, this means developing a set of all relevant objectives and requirements and assigning priorities to each. The result of this step in the process is a prioritized set of performance measures for use in evaluating potential design solutions. It is assumed that a complete set of strategic objectives and external requirements has already been derived (in step 1 of the core manufacturing system design process). It is also assumed that an unweighted set of performance measures has been determined (in step 2 of the core process). This process of modeling the decision makers' preference structure can be performed independently of the definition of a set of design alternatives. As a result, this same preference model could be used by an organization to examine several different design questions / issues. That is, the high-level objectives and priorities of the firm should be independent of the particular details of the specific decision being investigated.

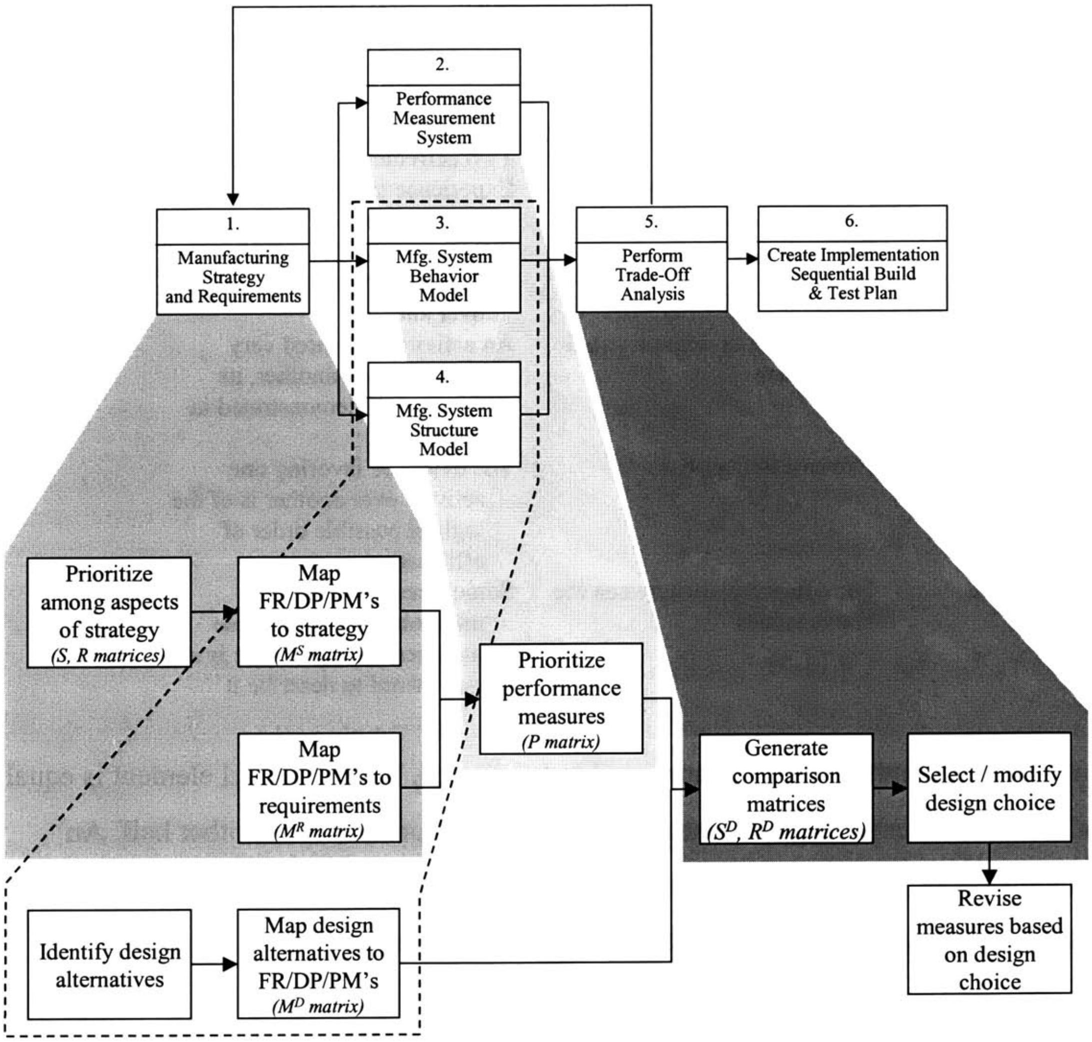


Figure 8-2: Relating trade-off analysis to the core process

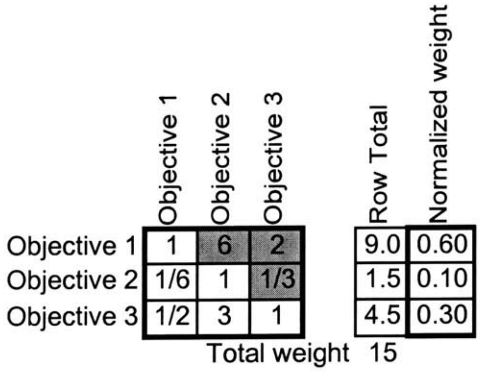
8.1.1 Prioritizing Aspects of Strategy

The analytic hierarchy process (AHP) (Saaty 1988, 1994) can be used to provide a structured process for determining weighting factors to reflect the relative importance of each objective. An n x n pairwise comparison matrix, A, is developed, where n is equal to the number of relevant strategic objectives being considered. Each entry, a_{ij}, represents the importance of objective i relative to objective j, using a scale ranging from 0 to 9. A value of 1 indicates that objectives i and j are equally important. Values greater than 1 indicate increasing importance of objective i relative to objective j, as described in Table 8-2. If objective i is less important than objective j, the reciprocal of the appropriate value is entered into the matrix. For consistency, a_{ij} should equal $1/a_{ji}$ in all cases.

Table 8-2: AHP judgment scale, adapted from (Saaty, 1994)

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong Importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another, its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	For compromises between the above values	Sometimes one needs to interpolate a compromise judgment because there is no good word to describe it

Only n(n-1)/2 elements of the A matrix need to be entered. Each diagonal element is equal to one, and half of the remaining elements are simply the reciprocals of the other half. An example of a matrix for comparing three objectives is shown in Figure 8-3, where only the shaded entries must be entered. The rest can be computed automatically.



	Objective 1	Objective 2	Objective 3	Row Total	Normalized weight
Objective 1	1	6	2	9.0	0.60
Objective 2	1/6	1	1/3	1.5	0.10
Objective 3	1/2	3	1	4.5	0.30

Total weight 15

Figure 8-3: Sample pairwise comparison matrix and weighting factors

8.1.2 Checking for Consistency

Once all elements in this matrix have been entered or calculated, a standard check for overall consistency among these priorities can be performed, as defined by Saaty (1994). For a perfectly consistent comparison matrix, A, the following relationship holds true for all combinations of entries:

$$a_{jk} = \frac{a_{ik}}{a_{ij}} \tag{8.1}$$

When the matrix A is perfectly consistent, it will have one non-zero eigenvalue, and that eigenvalue will be equal to n. If the matrix is not perfectly consistent, it will have a maximum eigenvalue, λ_{max}, greater than n. The less consistent the matrix, the greater the value of λ_{max}. The Consistency Index (CI) of such a matrix is defined as follows:

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{8.2}$$

Thus, a perfectly consistent matrix will have λ_{max}=n, and CI = 0. The less consistent the matrix is, the greater the consistency index will be. The consistency index for a comparison matrix can be compared with the Random Index (RI), which is defined as the consistency index of a similar comparison matrix (i.e., one of the same size) where the above-diagonal elements are determined randomly, the diagonal elements equal one, and the below-diagonal elements are the reciprocals of the appropriate above-diagonal entries. Table 8-3 gives the average values of the RI for different size comparison matrices.

Table 8-3: Average values of the random index

n	1	2	3	4	5	6	7	8	9	10
Random Index (RI)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

The Consistency Ratio can now be defined as:

$$CR = \frac{CI}{RI} \tag{8.3}$$

Values of CR will range from zero for a perfectly consistent matrix to one for a matrix in which the comparisons are no more consistent than a random set of numbers. Values of CR greater than one are possible but are unlikely to occur in practice. If the set of values is found to be inconsistent, values of the entries must be reconsidered and reevaluated until a sufficiently consistent set of data is obtained. Saaty (1994) recommends that inconsistency is unacceptable when the judgment error is more than 10% of the measurement values themselves (i.e. $CR > 0.1$). As described in section 4.1.6, determining values for the relative importance of each objective is an inherently subjective process, and even consistent results should be viewed as a guideline for further design work rather than an exact result.

The information in a consistent comparison matrix, A, can then be used to calculate approximate weighting values for each strategic objective as follows. First, the sum of all entries in each row is calculated. Next, each of these sums is divided by the total weight (i.e. the sum of all entries in the matrix). The result is a normalized set of weights to reflect the relative importance of the relevant strategic objectives. Strictly speaking, this technique is only perfectly accurate for a perfectly consistent matrix A. If A is inconsistent only within an acceptable amount ($CR < 0.1$) this process will produce an estimate of the relative weight of each objective. Exact results can be obtained by raising A to a large power before computing the weights (Saaty, 1994).

8.1.3 Including Requirements

The process just described for deriving normalized weighting factors considers only the relevant strategic objectives and not any external requirements placed on the system design. Because requirements specify characteristics of the system that *must* be met, they are treated differently from objectives such as minimizing cost or maximizing delivery performance when developing a preference structure model. In order to create such an overall model of the decision makers' preference structure including both objectives and requirements, the following procedure is used. All requirements are given a weighting score of one. The objectives' normalized weighting factors are then scaled so that the most important objective is given a weight of one (i.e. each normalized weighting factor is divided by the value of the largest weighting factor). The result is a set of weights that range from zero to one. Continuing with the example data shown in Figure 8-3 and assuming that there are two additional external requirements, an overall preference structure could be created as shown in Figure 8-4. This simple example is intended to illustrate the process for developing a preference structure model; a more detailed example based on a case taken from industry will be presented in Chapter 9.

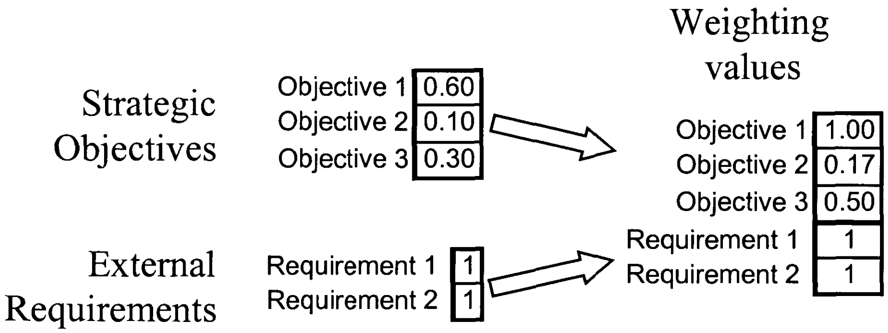
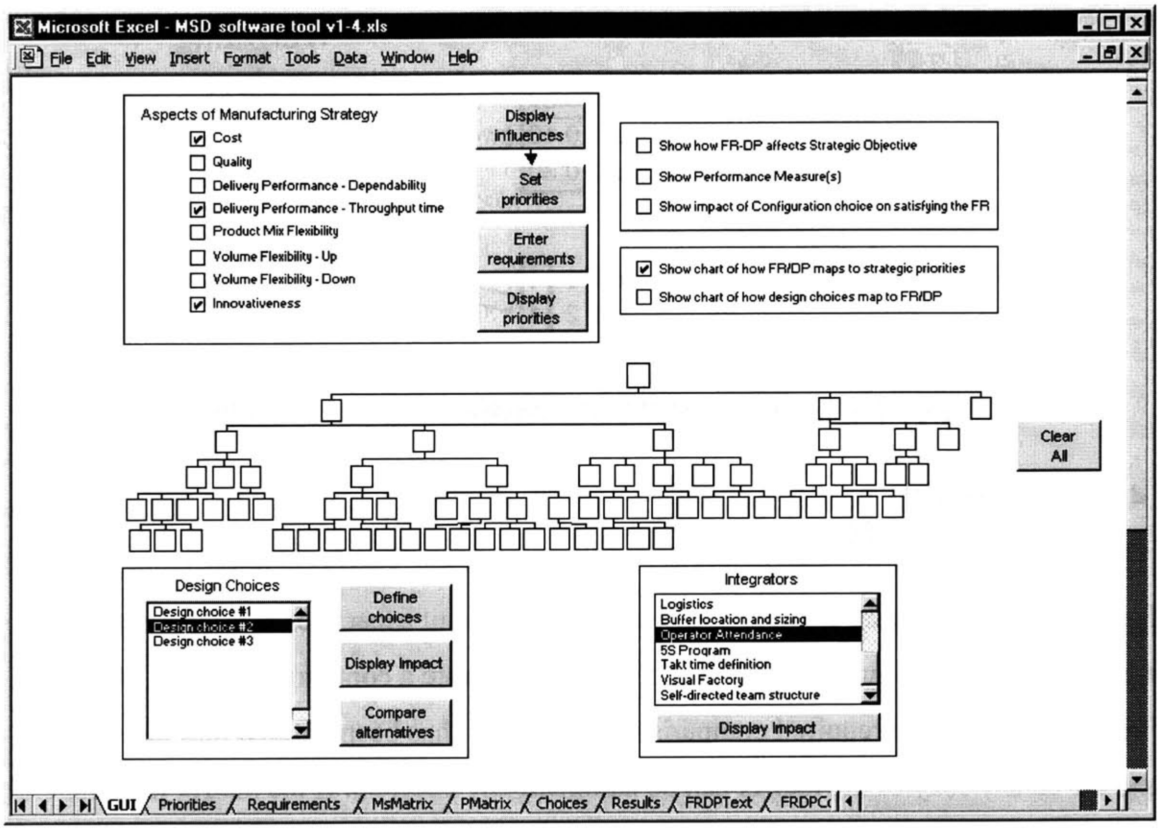


Figure 8-4: Defining weights for objectives and requirements

8.1.4 Using the MSD Software Tool

The software tool introduced in section 7.1 assists the designer(s) in developing this preference structure model. Designers can select the relevant aspects of manufacturing strategy (as shown in Figure 8-5) and automatically generate a comparison matrix (as shown in Figure 8-6). Once the required comparison information has been entered into the shaded boxes, the consistency of the matrix can be automatically checked. If the matrix is sufficiently consistent (i.e. $CR < 0.1$), then the normalized weights are calculated (as shown in Figure 8-7). If the entries in the matrix are not adequately consistent ($CR > 0.1$), the user is notified and is prompted to review and revise the comparisons until sufficient consistency is achieved.

The resulting model of the decision makers' priorities is an important tool for the remaining steps of the core manufacturing system design process, as it can help the designers to quantify performance differences and better understand trade-offs among various system alternatives. The disadvantages to the development of such a model are the time it takes to gather the necessary data, the potential difficulty at arriving at a consistent set of preferences, and the inherent subjectivity of the data.



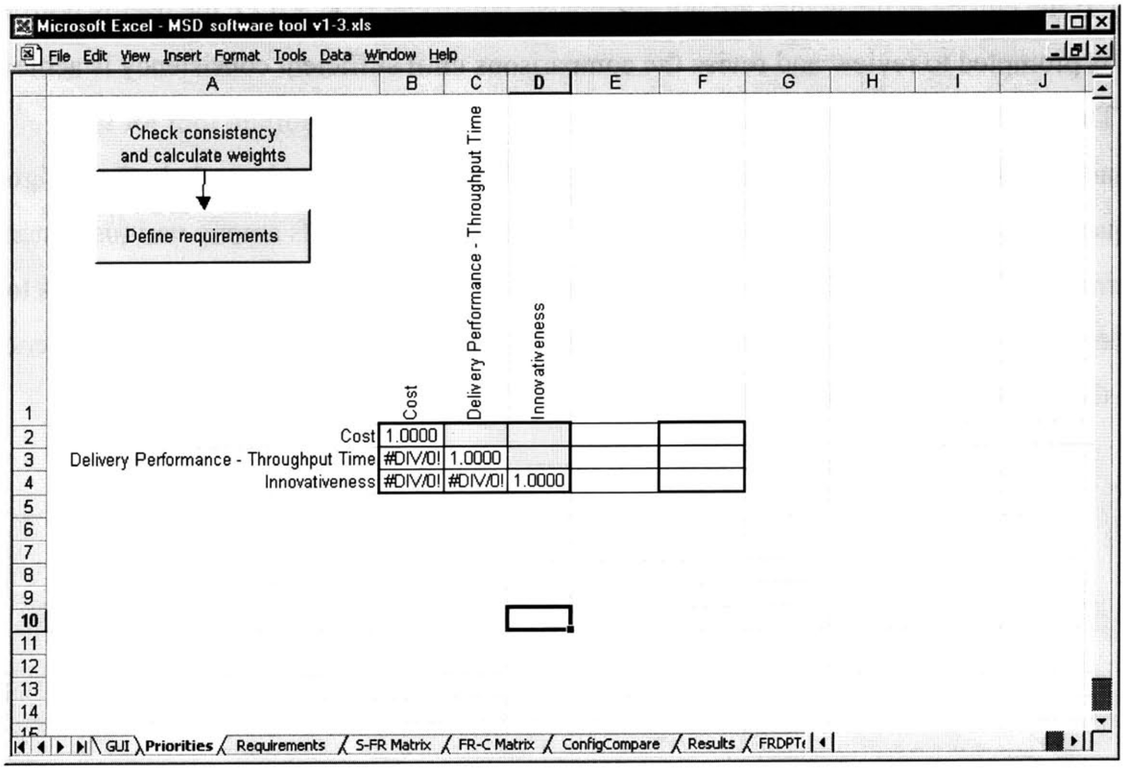
Aspects of Manufacturing Strategy

- ☑ Cost
- ☐ Quality
- ☐ Delivery Performance - Dependability
- ☑ Delivery Performance - Throughput time
- ☐ Product Mix Flexibility
- ☐ Volume Flexibility - Up
- ☐ Volume Flexibility - Down
- ☑ Innovativeness

- ☐ Show how FR-DP affects Strategic Objective
- ☐ Show Performance Measure(s)
- ☐ Show impact of Configuration choice on satisfying the FR

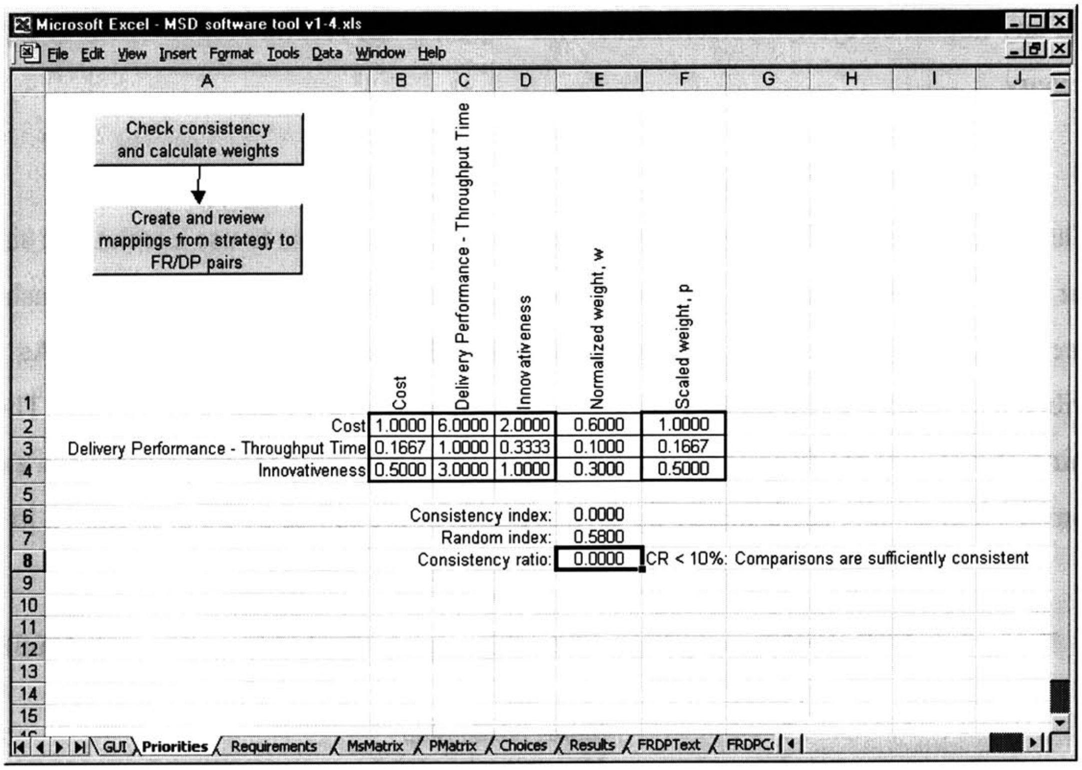
- ☑ Show chart of how FR/DP maps to strategic priorities
- ☐ Show chart of how design choices map to FR/DP

Figure 8-5: Selecting relevant aspects of strategy using the software tool



	Cost	Delivery Performance - Throughput Time	Innovativeness
Cost	1.0000		
Delivery Performance - Throughput Time	#DIV/0!	1.0000	
Innovativeness	#DIV/0!	#DIV/0!	1.0000

Figure 8-6: An automatically generated comparison matrix



	Cost	Delivery Performance - Throughput Time	Innovativeness	Normalized weight, w	Scaled weight, p
Cost	1.0000	6.0000	2.0000	0.6000	1.0000
Delivery Performance - Throughput Time	0.1667	1.0000	0.3333	0.1000	0.1667
Innovativeness	0.5000	3.0000	1.0000	0.3000	0.5000

Consistency index: 0.0000
Random index: 0.5800
Consistency ratio: 0.0000 CR < 10%: Comparisons are sufficiently consistent

Figure 8-7: Software tool showing consistency check and calculated weights

8.2 Mapping FR/DP Pairs to Strategy and Requirements

Continuing with the process shown in Figure 8-1, mapping matrices can be developed to show the relationship of each leaf FR/DP pair to each aspect of strategy (matrix M^S) and to each requirement (matrix M^R). The first matrix, M^S, will be of size $s \times \ell$, where s is the number of different aspects of strategy, and ℓ is the number of leaf FR/DP pairs in the MSDD, 46. Each element of this matrix, m^S_{ij}, contains information describing the extent to which FR/DP pair j impacts system performance with respect to the ith strategic objective. A generalized form of this information was represented graphically in Figure 7-2 through Figure 7-8. Although the resulting matrix is rather large (8 x 46) it is important to note that these entries will generally remain unchanged from example to example as the information linking FR/DP pairs to aspects of strategy is primarily application-independent. A weighting system with a continuous scale from zero to one is used to indicate the importance of each FR/DP pair with respect to system performance, with a weight of one indicating a strong relationship and a weight of zero indicating that satisfying or not satisfying that particular FR will have little if any impact on system performance with respect to the relevant requirement or aspect of strategy.

8.2.1 Process for Generating the M^S and M^R Matrices

The suggested method for determining the appropriate scores is to use a technique similar to that used in Quality Function Deployment (QFD) to indicate the strength of relationships between "HOWs" (i.e. product characteristics) and "WHATs" (i.e. customer wants). As described by Prasad (1998), a 0 to 9 scale can be used to evaluate these relationships. The meaning of different scoring values is described in Table 8-4. This scoring system can easily be converted to a 0 to 1 scale simply by dividing each of the scores by nine, as shown in Table 8-5.

Table 8-4: QFD WHAT vs. HOW relationship scale, adapted from (Prasad, 1998)

Score	Meaning
9	Strong relationship
3	Moderate relationship
1	Weak relationship
0	None

Table 8-5: Scale adapted for the proposed trade-off process

Score	Meaning
1	Strong relationship
1/3	Moderate relationship
1/9	Weak relationship
0	No relationship

So, with the scoring system used here, each entry in M^S is assigned a value of one, 1/3, 1/9, or zero. A general version of the complete M^S matrix is shown in Appendix B. A value of one is used in cases where there is a direct and quantifiable relationship between the achievement of the functional requirement and the level of performance that can be achieved. A value of 1/3 is used to indicate that some relationship exists between satisfying the FR and achieving the desired performance, but that this relationship is less direct and/or is more difficult to express in quantifiable terms.

As an example of the structure and elements of M^S, consider FR/DP/PM triplet T32, "Produce in sufficiently small run sizes / Design quick changeover for material handling and equipment / Actual run size – target run size." Each FR/DP/PM triplet is represented by one column in M^S; the column corresponding to FR/DP/PM-T32 is shown in Figure 8-8. The elements of this column show that this FR/DP/PM has a strong impact on system performance in terms of throughput time and delivery performance, product mix flexibility, and innovativeness.

	Produce in sufficiently small run sizes
Cost	0.33
Quality	0.00
Delivery Performance - Dependability	0.00
Delivery Performance - Throughout time	1.00
Product Mix Flexibility	1.00
Volume Flexibility - Upwards	0.00
Volume Flexibility - Downwards	0.00
Innovativeness	1.00

Figure 8-8: One column of matrix M^S

The ability to perform quick changeovers from one product type to the next enables low run sizes, resulting in less total inventory in the system. This inventory reduction improves mean throughput time (quantifiable using Little's law) and helps the system to get new products through the system more quickly, improving the system's ability to deal with innovations in product design. The amount of time it takes to change equipment over from one part type to another also has a strong affect on the overall product mix flexibility of a system in that quick changeover is a prerequisite for having one machine produce a diverse mix of parts in a limited period of time. The achievement of FR-T32 and the implementation of DP-T32 may also have an impact on cost, as reducing setup time might require the purchase of some auxiliary equipment and/or fixtures. The cost of reducing setup time is typically only a small fraction of the cost of the equipment itself, so the overall impact on system cost is less critical and is given a weight of 1/3. As before, the determination of weighting values is still somewhat of a subjective process based on engineering judgment, as the ideas represented by the FR-DP pairs are still very abstract at this early stage of the design process.

As described in section 7.1.6, the MSD software tool can assist designers with the processes of understanding and defining these weights. The software tool contains the generalized M^S matrix shown in Appendix B and allows designers to view this information both numerically and graphically (as was shown in Figure 7-9 and Figure 7-10), and it allows the designers to update the entries in this matrix based on the particular application. The MSD software tool also contains a brief text description explaining the nature of the relationship corresponding to each non-zero entry in the general M^S matrix. One example of this was shown in Figure 7-9; a listing of all of these descriptions is also provided in Appendix B.

Entries in this matrix are, to some extent, based on system designers' knowledge, experience, and engineering judgment. As such, the entries may change over time and opinions may vary from one designer to the next. For example, the relative importance of various cost drivers is likely to change both over time and from one scenario to the next. Designers should review the general-purpose M^S matrix and make revisions based on the specific application as needed. The details of the situation will determine whether or not the relationships described in the general M^S matrix and explained in section 7.1 and Appendix B will hold true. Some examples of such cases will be described in chapter 9.

When determining what the value of a matrix entry should be, designers can ask themselves the following questions:

- Will satisfying this FR lead to improved performance relative to this aspect of strategy?
- If so, can this relationship be expressed in a quantitative way?
- How important is satisfying this FR with respect to other FR's in terms of achieving the desired strategic performance?

A similar matrix, M^R, can be developed relating the FR/DP/PM triplets to the external requirements placed on the system design. This matrix will be of size $r \times \ell$, where r is the number of requirements and ℓ is again the number of leaf FR/DP/PM triplets, 46. No set of generic values of M^R may be determined in advance, as the requirements placed on a system will vary from case to case. The process for determining these entries is the same as for matrix M^S, with a continuous scale from zero to one being used. So, entry $m^R_{i,j}$ expresses how important the satisfaction/implementation of FR/DP j is with regard to the achievement of requirement i. In this case, the MSD software tool can be used to automatically generate an empty matrix M^R with the appropriate row and column headings so that the designers can enter the necessary mapping information.

8.2.2 Prioritizing Among Effectiveness Measures

As described in section 7.2.4, the manufacturing system design decomposition can be used to identify important factors that will need to be monitored during the design and operation of the manufacturing system. The goal here is to take the set of measures derived from the MSDD (shown in Table 7-1 through Table 7-7) and to understand which of these are most important, given the knowledge regarding the relative priority of the various strategic objectives and requirements. Information obtained from the prioritization of strategic objectives and from the mapping of FR/DP/PM's to strategy can be used to provide designers with information on how detailed measures of performance relate to the overall effectiveness of the system in terms of the high-level objectives.

First, a diagonal matrix, S, can be created to reflect the priority or relative importance of each aspect of strategy. This matrix will be of size s x s, where s is equal to the number of different aspects of strategy. For this research, eight aspects of manufacturing strategy are considered (as shown in Figure 8-8). Each diagonal element of the matrix represents the relative importance of the corresponding aspect of strategy or requirement. In the simplest case, these could be binary elements, with a value of 1 meaning that the requirement or aspect of strategy is relevant and a value of 0 meaning that it is not. When a preference structure has been formally defined (as described in section 8.1.1), then the scaled weighting values are placed in the diagonal elements of the matrix. A similar matrix, R, can be created for the external requirements. The size of this matrix will vary with the number of relevant external requirements in a given case. Continuing with the simple example described in section 8.1.1, these matrices would be defined as shown below.

$$S=\begin{bmatrix} 1.00 & - & - & - & - & - & - & - \\ - & 0.00 & - & - & - & - & - & - \\ - & - & 0.00 & - & - & - & - & - \\ - & - & - & 0.17 & - & - & - & - \\ - & - & - & - & 0.00 & - & - & - \\ - & - & - & - & - & 0.00 & - & - \\ - & - & - & - & - & - & 0.00 & - \\ - & - & - & - & - & - & - & 0.50 \end{bmatrix} \qquad R=\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad (8.4)$$

Multiplication of the s x s priority matrix, S, by the s x ℓ mapping matrix, M^S, results in another priority matrix, P (of size s x ℓ), with this matrix showing the relative importance of each FR/DP/PM triplet with respect to the overall objectives of the system design. Because the entries in S and M^S range from zero to one, the resulting entries in P will also range from zero to one. An entry $p_{ij}=0$ means that the jth FR/DP/PM is unimportant with respect to achieving the overall goals of the firm in terms of strategic objective i. $p_{ij}=1$ means that FR/DP/PM j is critical to achieving the desired overall system performance in terms of strategic objective i. Intermediate values of p_{ij} reflect varying degrees of importance of the associated FR/DP/PM towards achieving the high-level goals of the firm. From this matrix, designers can see which FR/DP/PM triplets are the most critical to achieving the desired performance with respect to each aspect of strategy.

This information provides the system designers with a sense of which FR/DP/PM triplets are likely to have the strongest overall impact on the system's performance, and information contained in matrix P can then be used in determining a set of effectiveness measures with which to evaluate different design concepts. To ensure completeness, measures should be chosen to represent all relevant aspects of performance. This can be achieved by selecting the most heavily weighted performance measures in each non-zero row of matrix P. Summing up the entries in each column can give the designer a sense of the overall importance of each FR/DP/PM, with the highest sums indicating the FR/DP/PM triplets with the most importance in terms of achieving the overall objectives.

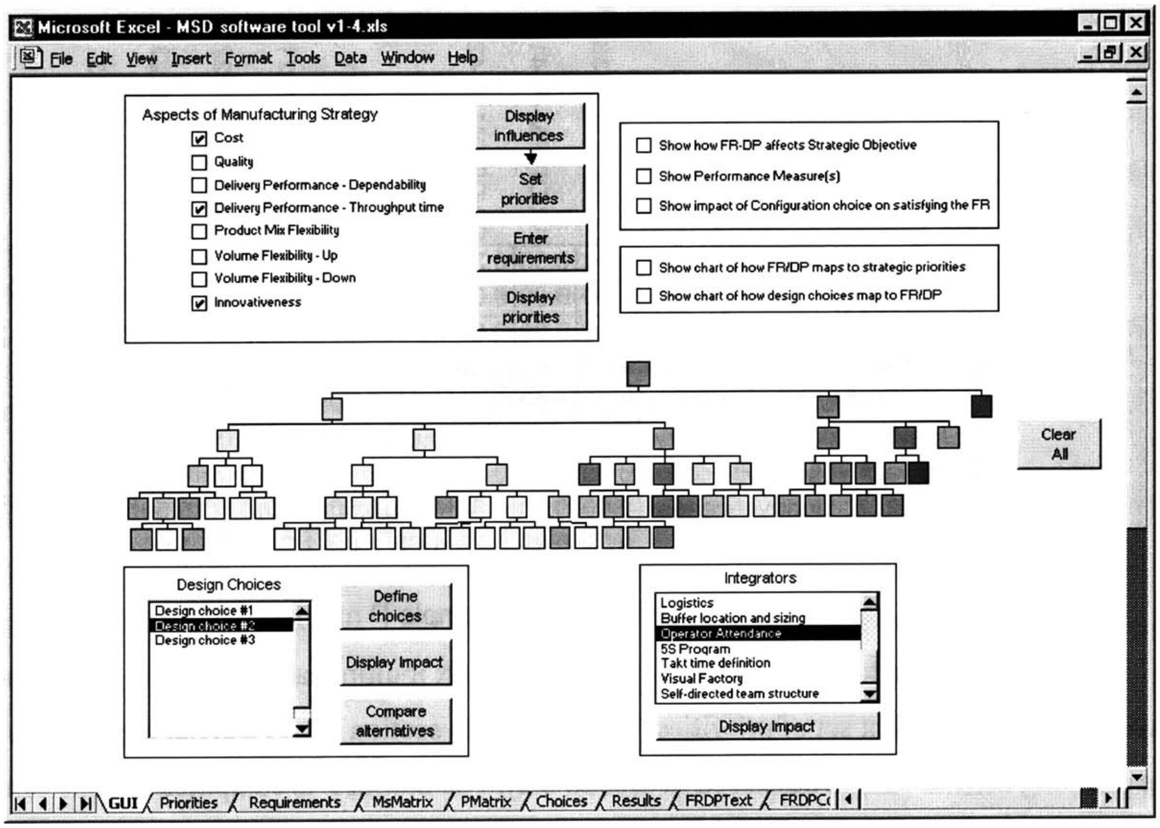
Note that no matrix multiplication is necessary to calculate similar priority information relating each FR/DP/PM to the requirements, as requirements are all equally weighted. Thus, looking across the rows of matrix M^R provides all of the necessary information for determining which FR/DP/PM triplets are most relevant.

Figure 8-9 shows an example of a portion of the priority matrix generated by multiplying the S matrix shown in equation 7.1 by the general version of the mapping matrix, M^S shown in Appendix B. The resulting matrix, P, is of size 8 x 46 ($s \times \ell$); only columns 22-31 are shown in Figure 8-9. The only non-zero rows of this matrix are those corresponding to the aspects of strategy that were determined to be important for this example: cost, throughput time, and innovativeness.

	FR/DP/PM-P133	FR/DP/PM-P141	FR/DP/PM-P142	FR/DP/PM-T1	FR/DP/PM-T21	FR/DP/PM-T221	FR/DP/PM-T222	FR/DP/PM-T223	FR/DP/PM-T23	FR/DP/PM-T31
Cost	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Quality	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Delivery Performance - Dependability	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Delivery Performance - Throughput Time	0.06	0.06	0.06	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Product Mix Flexibility	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Upward Volume Flexibility	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Downward Volume Flexibility	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Innovativeness	0.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.50
	0.39	0.89	0.89	1.00	1.00	1.00	1.00	1.00	0.50	1.00

Figure 8-9: A portion of an example P matrix

The MSD software tool performs the necessary matrix multiplication once the designers have entered a consistent set of priorities (as described in section 8.1.1) and have generated the mapping matrix, M^S (as described in section 8.2). The matrix P is computed and the sum of the entries in each column is calculated. This information can be viewed numerically (i.e., in matrix form), or visually, as shown in Figure 8-10. In this figure, the shading of each box indicates the relative overall importance of the corresponding FR/DP/PM triplet as determined by the sum of all entries in the associated column of the matrix P. The darkness of the shading is proportional to the relative importance of the FR/DP/PM. This display includes shading of not only the leaf FR/DP/PM's, but also of the parents. The importance of each parent is calculated by taking the average of the column totals for each of its child FR/DP/PM's. For example, the relative importance of parent FR/DP/PM-T22 ("Ensure that production cycle time equals takt time") is equal to (1.00+1.00+1.00)/3 = 1.00, as the column total for each of its children (FR/DP/PM's T221, T222, and T223: Ensuring that automatic and manual cycle times are less than or equal to takt time and ensuring a level mix of cycle times) is 1.00 (as shown in Figure 8-9). This process is repeated for higher-level FR/DP/PM's as well. So, for example, FR/DP/PM-T2 ("Reduce process delay") has a relative importance of (1.00+1.00+0.50)/3 = 0.83, based on the importance of its three child FR/DP/PM's, T21, T22, and T23: "Define takt time," "Ensure that production cycle time equals takt time," and "Ensure that part arrival rate is equal to service rate."



Aspects of Manufacturing Strategy
☑ Cost
☐ Quality
☐ Delivery Performance - Dependability
☑ Delivery Performance - Throughput time
☐ Product Mix Flexibility
☐ Volume Flexibility - Up
☐ Volume Flexibility - Down
☑ Innovativeness

☐ Show how FR-DP affects Strategic Objective
☐ Show Performance Measure(s)
☐ Show impact of Configuration choice on satisfying the FR

☐ Show chart of how FR/DP maps to strategic priorities
☐ Show chart of how design choices map to FR/DP

Design Choices
Design choice #1
Design choice #2
Design choice #3

Integrators
Logistics
Buffer location and sizing
Operator Attendance
5S Program
Takt time definition
Visual Factory
Self-directed team structure

Figure 8-10: MSD software tool displaying the relative importance of each FR/DP/PM

8.3 Mapping Design Alternatives to FR/DP/PM Triplets

This step involves mapping the identified design alternatives to the manufacturing system design decomposition in order to understand how the selection of each alternative would affect the ability to satisfy the various functional requirements of the MSDD. Again, matrices can be used to represent the relevant information. A mapping matrix, M^D, can be formed to describe how well each design alternative performs with respect to each FR/DP/PM triplet.

This matrix is formed in a similar manner to the M^S matrix showing the interactions between FR/DP/PM triplets and aspects of strategy. The M^D matrix will be of size ℓ x d, where ℓ is the number of leaf FR/DP/PM triplets (46) and d is the number of design alternatives being considered.

8.3.1 Process for Generating the M^D Matrix

The value of each entry, m^D_{ij}, will range from –1 to +1. When only general information about the design alternatives is known, each entry in the matrix can be assigned a value of -1, 0, or 1. An entry m^D_{ij}= -1 indicates that it will be difficult for design choice j to satisfy functional requirement i. An entry of +1 indicates that the corresponding design choice has inherent characteristics that will ensure the satisfaction of the appropriate FR. A score of 0 means that the design choice does not have a significant effect on performance with respect to the FR. Figure 8-11 shows an example of a portion of such a mapping matrix.

	Choice #1	Choice #2	Choice #3
FR-T53	-1	0	0
FR-D11	0	0	-1
FR-D12	1	0	-1
FR-D21	-1	0	1
FR-D22	0	0	0
FR-D23	0	-1	0
FR-D3	0	0	0

Figure 8-11: Portion of an example M^D matrix

When more detailed information is known, fractional values may be used to quantify the design alternatives' performance with respect to the FR/DP/PM triplet. In this case, scores can be assigned using a technique similar to that used in Quality Function Deployment (QFD) in assessing the correlation between various "HOWs." In QFD, scores can be assigned based on a scale ranging from –9 to +9 according to the strength of the relationship between the different "HOWs" as shown in Table 8-6.

Table 8-6: QFD HOW vs. HOW correlation scale, adapted from (Prasad, 1998)

Weight	Definition
9	Strong positive relationship
3	Medium positive relationship
1	Positive relationship
0	None
-1	Negative relationship
-3	Medium negative relationship
-9	Strong negative relationship

In QFD, these scores are used to indicate whether implementing one "HOW" has a positive or negative correlation with implementing another. In the manufacturing system design process described here, a similar scoring system can be used to describe the correlation between implementing a particular design choice and achieving a particular FR, the primary difference being that in the MSD case, the scoring values are scaled to range between –1 and +1 instead of –9 to +9. So, assigning a score of 0.3 to a matrix entry $m^D{}_{ij}$ means that implementing design choice j will have a positive effect of medium intensity on achieving the ith FR. When assigning scores to each entry in the M^D matrix, designers can ask themselves questions such as:

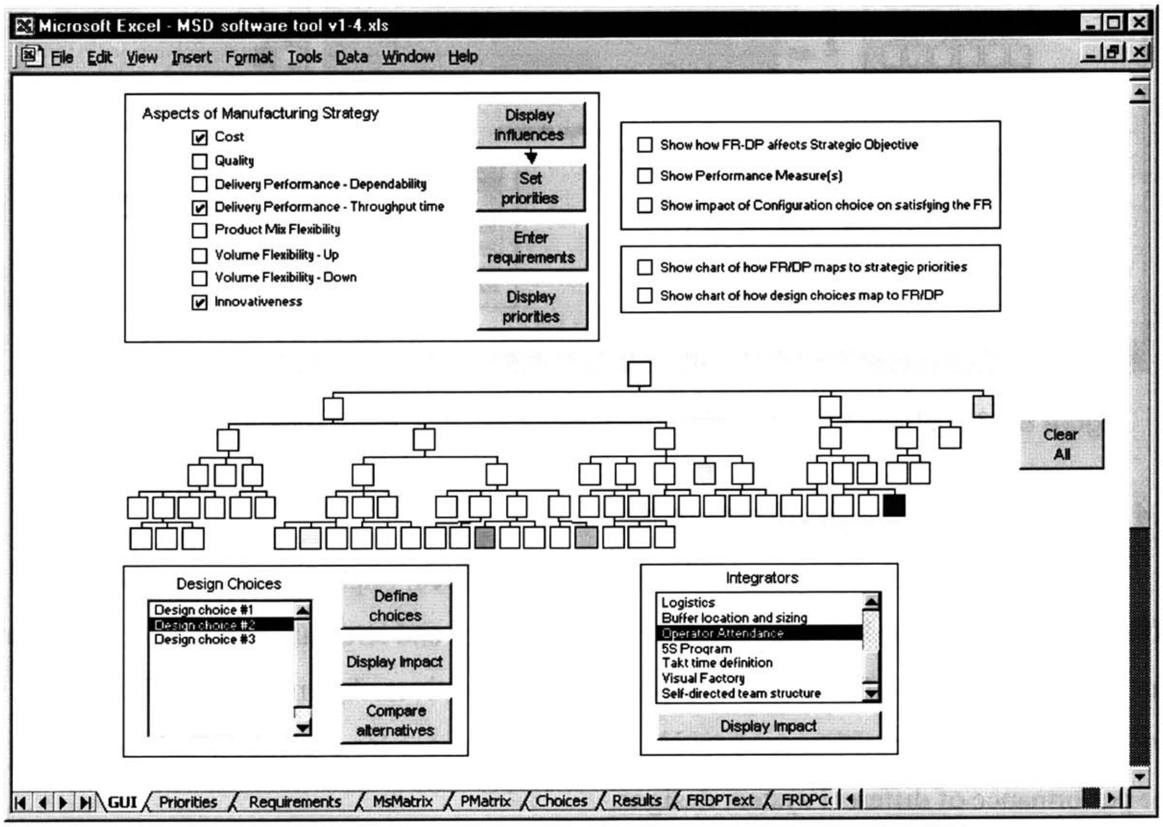
- Will choosing this alternative make it more easy / difficult to satisfy this FR?
- Is this DP a standard element of the alternative?
- Will choosing this alternative make implementing the DP easy / difficult?
- How well can the alternative be expected to perform with respect to the PM?
- How well have similar alternatives satisfied the FR?

An alternative method for filling in the entries of M^D would be to select one design choice to be the baseline and then rate all other choices in terms of how each compares to the baseline choice in terms of the ability to satisfy each functional requirement of the design decomposition. Again, scores ranging from –1 to 1 should be used to assess the relative ease or difficulty of satisfying each FR.

With the M^D matrix, entry scores are likely to change significantly from case to case as well as over time. The score assigned to each entry in this matrix is highly dependent on the details of the associated design alternative, many of which will be unique to the application. Additionally, scores can change over time as more design details are determined and as refinements and improvements are made.

8.3.2 Using the MSD Software Tool

Once the information mapping each design alternative to the manufacturing system design decomposition has been entered in matrix format, it can be viewed graphically using the software tool. Two methods for viewing the data are available. First, the designers can view the mappings from one design alternative to all of the relevant FR/DP pairs, as shown in Figure 8-12. The darkness of the shading is used to indicate the strength of the relationship as before. In the actual software tool, the color of the shading indicates whether a positive or negative relationship exists, with green shading indicating a positive relationship and red shading indicating a negative relationship.



Aspects of Manufacturing Strategy
☑ Cost
☐ Quality
☐ Delivery Performance - Dependability
☑ Delivery Performance - Throughput time
☐ Product Mix Flexibility
☐ Volume Flexibility - Up
☐ Volume Flexibility - Down
☑ Innovativeness

☐ Show how FR-DP affects Strategic Objective
☐ Show Performance Measure(s)
☐ Show impact of Configuration choice on satisfying the FR

☐ Show chart of how FR/DP maps to strategic priorities
☐ Show chart of how design choices map to FR/DP

Design Choices
Design choice #1
Design choice #2
Design choice #3

Integrators
Logistics
Buffer location and sizing
Operator Attendance
5S Program
Takt time definition
Visual Factory
Self-directed team structure

Figure 8-12: Software tool showing mappings from design choice to FR/DP pairs

A second way of viewing this mapping information is to look at how a specific FR/DP pair relates to all of the different design alternatives, as shown in Figure 8-13. In this case, bar graphs are used to show the strength and nature (i.e., positive or negative) of the relationship between the selected FR/DP pair and each design alternative.

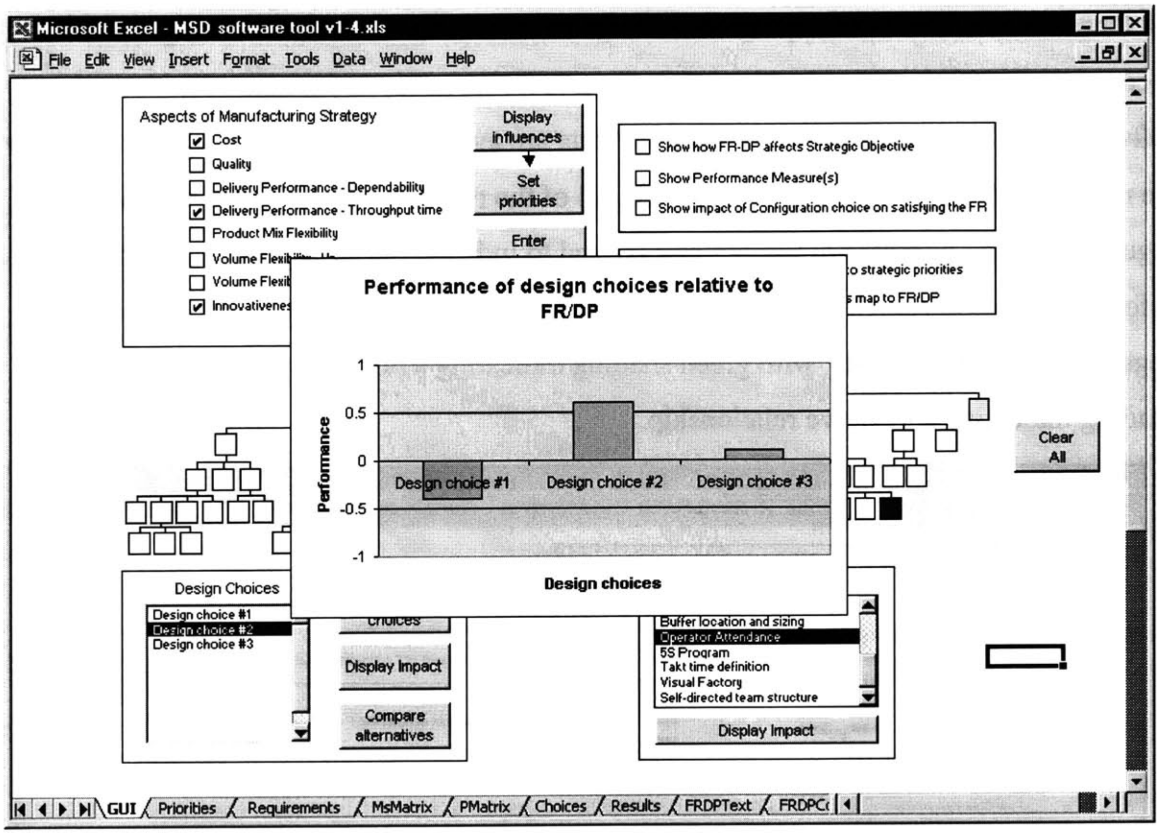


Figure 8-13: Software tool showing mappings from design choices to one FR/DP pair

8.4 Comparing Design Alternatives

With the high-level objectives and requirements defined, important measures of system effectiveness established, and models of system behavior and structure understood, designers can examine the trade-offs among multiple design alternatives. Again, the manufacturing system design decomposition can provide a structured means for evaluating and comparing the performance of different system designs.

Once information on the relative importance of objectives, the relationships between these objectives and the FR/DP/PM triplets of the decomposition, and the relationships between the FR/DP/PM triplets and the design alternatives have been represented in matrix form, these matrices can be combined to show a comparison of the alternative designs with respect to the overall goals of the firm. As described in section 8.1, the priority matrix, S, and the FR/DP/PM-strategy mapping matrix, M^S, can be multiplied to produce a second priority matrix, P, showing the importance of each FR/DP/PM with respect to the overall objectives of the firm.

Because the manufacturing system design decomposition does not have the same number of FR/DP pairs relating to each aspect of strategy, the rows of the matrix P must be normalized before they can be used further. This is done by dividing each entry by the number of non-zero entries in its row. For example, row 1 of matrix P deals with the first aspect of strategy, cost. In the example P matrix shown in Appendix B, there are 46 FR/DP pairs in the MSDD that relate to cost. Each entry in row 1 of matrix p must then be divided by 46. This process is repeated for each row. This normalization is necessary to prevent aspects of strategy from becoming more or less heavily weighted based on the *number* of relevant FR/DP pairs in the MSDD, as the quantity of FR/DP pairs relating to a particular aspect of strategy is more an indicator of how easily decomposable that aspect of strategy is, rather than how important it is.

The normalized matrix, P^n, can then be multiplied with the mapping matrix, M^D, which shows the relationships between FR/DP/PM's and the various design alternatives being considered. The resulting matrix, S^D, will be of size s x d, with one row for each aspect of strategy and one column for each design choice being considered. Each entry, s^D_{ij}, provides information regarding how easily design choice j can meet the firm's objectives in terms of the ith aspect of strategy. Values of s^D_{ij} will range from –1 to 1, with a –1 indicating that design choice j presents serious difficulties in achieving the desired performance with strategic aspect i, and a score of +1 indicating that design choice j has characteristics that will allow it to excel with respect to strategic aspect i.

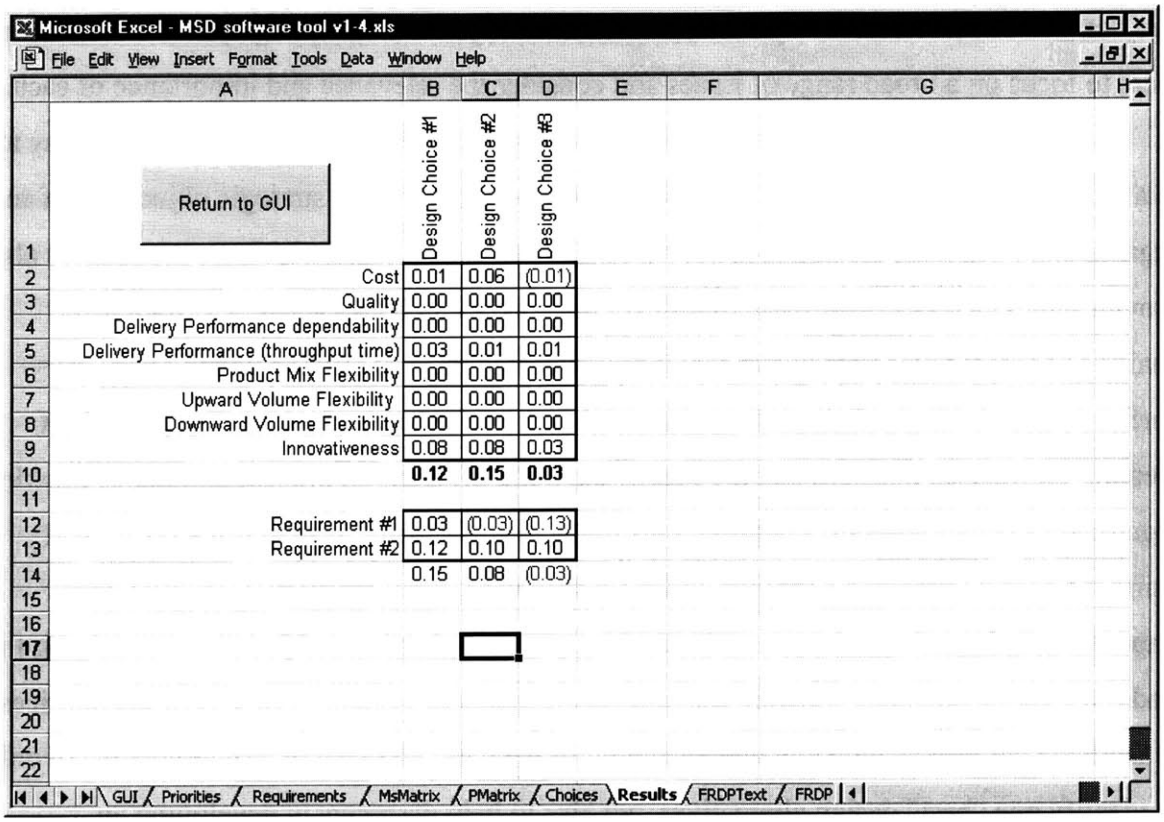
$$P^n * M^D = S^D \tag{8.5}$$

A similar matrix can be generated to evaluate the performance of each design choice with regard to the specified system requirements. In this case, the matrices R, M^R, and M^D are combined. As in the case of the strategy mapping matrix, the entries in M^R must be normalized to account for the differing number of relevant FR/DP pairs for each requirement. To achieve this, each entry in M^R is divided by the total number of non-zero entries in its row. The product of these three matrices, R^D, will have one row for each requirement and one column for each design choice. As with S^D, each entry r^D_{ij} will range from –1 to +1 and will provide information as to how well design choice j can satisfy requirement i.

$$R * M^{R^n} * M^D = R^D \tag{8.6}$$

8.5 Interpreting the Results of the Comparisons

The S^D and R^D matrices show how the design alternatives compare with respect to the strategic objectives and requirements, respectively, as shown in Figure 8-14. This information can be used to compare and evaluate the potential value and performance of the design alternatives, to aid in the selection of one alternative for further study, and/or to guide designers in the process of generating ideas for improvements in one or more design alternatives. Because the process of developing these matrices includes making some judgments that are subjective and/or qualitative (prioritizing objectives, assigning values for the strength of relationships, etc.), the set of data in the S^D and R^D matrices is not meant to be a conclusive evaluation of which design alternative is "the best." Instead, this information is meant to serve as an aid for designers in identifying the strengths (higher scores) and weaknesses (negative scores) of the various alternatives and assessing the ease or difficulty with which each alternative can produce the desired performance.



	Design Choice #1	Design Choice #2	Design Choice #3
Cost	0.01	0.06	(0.01)
Quality	0.00	0.00	0.00
Delivery Performance dependability	0.00	0.00	0.00
Delivery Performance (throughput time)	0.03	0.01	0.01
Product Mix Flexibility	0.00	0.00	0.00
Upward Volume Flexibility	0.00	0.00	0.00
Downward Volume Flexibility	0.00	0.00	0.00
Innovativeness	0.08	0.08	0.03
	0.12	**0.15**	**0.03**
Requirement #1	0.03	(0.03)	(0.13)
Requirement #2	0.12	0.10	0.10
	0.15	0.08	(0.03)

Figure 8-14: Comparing multiple design alternatives

8.6 Summary of the Process for Trade-Off Analysis

This chapter has outlined a general systems engineering-based procedure that uses the manufacturing system design decomposition as a tool for aiding designers in understanding the trade-offs among multiple design alternatives. This process begins with the development of a model of the decision makers' preference structure with regard to the various aspects of manufacturing strategy. With this preference structure in mind, other requirements can be defined, and mappings can be made to show how these aspects of strategy and requirements relate to the various leaf FR/DP pairs of the manufacturing system design decomposition. These FR/DP pairs can also be mapped to the design alternatives being considered. This mapping information can be stored as a series of matrices with values indicating the relative strength or weakness of the appropriate relationships. Combining these matrices effectively uses the MSDD as a common structure for comparing the design alternatives with respect to the strategic objectives and requirements. Using the decomposition in this way helps to ensure that designers consider a variety of key, lower-level objectives and design parameters, forcing them to focus on a broad range of issues and consider the relevance and importance of each.

Several benefits to using this process have been observed. The process provides a way to relate design decisions at various levels of details to the high-level strategic objectives of an organization. Through the use of the design parameter portion of the MSDD, the process also provides guidance as to *how* these high-level objectives can be achieved. The trade-off analysis process is also valuable in that it forces designers to consider a wide variety of performance criteria, including many that might otherwise be overlooked. The process of creating the various matrices that are part of the trade-off analysis process stimulates thinking regarding the many low-level requirements that a manufacturing system must fulfill, and using the MSDD provides a tool for understanding why these low-level objectives are important and how they relate to each other and to the higher-level objectives. Examining the trade-offs using the MSD software tool allows designers to visualize the data in the matrices to facilitate communication and understanding of the data. The goal of the process is not only to identify one "best" design alternatives, but also to help designers in developing an understanding of the alternatives at a system level and generating ideas for new and improved designs that are better able to meet the high-level objectives of the firm.

Chapter 9 Examples of Models and Applications

9.1 Overview

This chapter presents two examples of how the proposed manufacturing system design process can be applied. These examples are drawn from work done at an automotive component supplier's factory located in the US. The examples are intended to give the reader a better sense of what is involved in each step of the process, to show how the process applies to actual manufacturing system design problems, and to illustrate the benefits of such an approach.

9.2 Preliminary Design

This section will focus on describing how the core manufacturing system design process and software tool presented in the previous two chapters can be used during the early stages of design. Section 4.1 presented a review of preliminary engineering design, both in general and as it applies to manufacturing systems. Decisions made at this stage are still general in nature; the designer or design team is investigating different *types* of subsystems rather than selecting among detailed subsystem designs. This section will focus on the selection and design of a manufacturing subsystem configuration using the core system design process. The concept of a subsystem configuration will be defined, and possible configurations will be listed and explained. Next, other approaches to configuration selection will be reviewed, with an emphasis on the work of Miltenburg (1995). With this prior research in mind, a description of the use of the core system design process for configuration selection and design will be presented, with examples of how the MSDD can be used to assist in the design process. An example from industry will be presented to illustrate the proposed design process.

9.2.1 Manufacturing Subsystem Configuration Design and Selection

A manufacturing subsystem configuration can be defined simply as a manufacturing subsystem design at a general, conceptual level. That is, a configuration contains information about the subsystem at a high level, such as the nature of its layout, material flow, control, and equipment. It does not contain detailed information about the specifics of the design, such as detailed operator work definitions, equipment geometry and cycle time, etc. These configurations can be thought of as manufacturing system architectures, where Beam (1990) defines a system architecture as "comprising design elements which are characteristic of a system, and of a class of systems to which it belongs." Other authors have used different terms to describe concepts similar to what is referred to herein as a manufacturing subsystem configuration. Chryssolouris (1992) discusses different system types; Miltenburg (1995) refers to different configurations simply as different production systems. Hayes and Wheelwright (1979) describe them as process structures; Hill (1994) describes them as process choices.

Although each of these authors has defined a slightly unique set of possible configurations, there is a general consensus about the different configurations available. Commonly accepted configurations include: job shop / batch flow, flexible manufacturing system (FMS), equipment-paced line, "lean" cell, project shop, and continuous flow. These different configurations will be reviewed and explained, followed by a discussion of how other researchers have approached the problem of configuration design and selection.

9.2.2 Manufacturing Subsystem Configurations

This section will describe the unique characteristics of the various configurations. The scope of characteristics included has been selected so as to emphasize the design elements over which a designer is likely to have significant influence. For example, factors such as layout and material flow are central to the definitions of the various configurations; defining these is a critical part of the system designer's role. Other factors, such as product variety and volume, are not included here as part of the definition of a configuration. There are two reasons for this. First, the designer is not likely to have control over these decisions. Only in an environment with an exceptional degree of concurrent engineering and decision-making might this be possible. The other reason for leaving product factors out is simply to separate the effects of volume and variety from those of system layout and flow, and to focus on the effects of the physical structure of the configuration. For example, suppose a factory decides to implement a batch flow configuration, with machines grouped by function. It would be possible to run a wide variety of low volume parts through the system, or to produce high volumes of a limited variety of products. The configuration could have very different behavior in those two cases, and it is important to be able to understand the source of these differences, knowing whether differences are due to the mix of products or to the layout. It is also important to note that these configurations are presented as representing points on a continuum, with the possibility of the designer modifying and/or combining various aspects of different configurations. The following sections provide an overview of the different configurations being considered.

One last point that must be emphasized is that the different configurations being described are not necessarily meant to represent complete manufacturing system designs. That is, a manufacturing system might contain several different configurations or subsystems (e.g. an FMS for machining operations and multiple equipment-paced lines for assembly). In terms of the value stream mapping techniques described in section 4.1.4, a configuration might represent only a single "box" in an overall map of the value stream within a factory. The interfaces between this configuration and the other subsystems in the factory are important and can have a significant impact on overall performance, but they are beyond the scope of the decisions being considered in this example.

Job Shop / Batch Flow

A job shop or batch flow configuration is one that has a functional layout, a large number of possible material flow paths, and a decentralized organization. Machines are grouped into departments according to function, i.e. all milling machines will be in one department, all turning machines are in a separate department, etc. Part flow is often complex, as each part can be processed by many if not all of the machines in each department. This flexibility allows for parts to be routed to the first machine available and becomes particularly important when the equipment is unreliable. Material handling between departments is significant, especially when departments are large and contain many machines. Material handling flexibility is required to handle the large number of flow paths and is often performed by forklifts or carts moving around containers of parts. Organizational structure is usually focused on the departments, which can lead to maximization of machine utilization in each department, but high levels of inventory between departments due to infrequent machine changeovers and a lack of communication and coordination of production schedules. Shop floor workers are typically assigned to a particular department, with the result that operators develop specialized skills, becoming experts in running one type of machine while being untrained on the different machines in the other departments.

This type of configuration is most commonly used when routing and mix flexibility are of critical importance. In some cases, parts have very low volumes and are made to order, resulting in the need to frequently determine new process plans and flow paths. Machines and tooling must be very flexible to provide the capability of processing this wide variety of part types. The resulting configuration is often called a job shop environment, as production is based on a series of individual jobs, rather than an ongoing stream of demand. In other cases, product variety is lower and volumes are somewhat higher. In this case, frequently found in automotive components manufacturing, there is a limited and known set of parts to be manufactured. The mix of these parts may vary dramatically over time, though. Routing flexibility becomes important to compensate for shifts in demand and for unreliable equipment. Setups are often avoided to keep utilization high, and so parts are processed in large batches, thus the name "batch flow."

Batch flow and job shop environments are here grouped together as one configuration, as the primary difference between them is the variety of parts that flow through them. Machines and tooling can be more and more specialized as product volumes go up and variety decreases, but the fundamental qualities of layout, material flow and handling, and organization remain unchanged.

Flexible Manufacturing System (FMS)

A flexible manufacturing system, or FMS, is a highly automated configuration consisting of a series of flexible, CNC machine tools connected by an automated, computer-controlled material handling system. A typical FMS will contain 3-10 machines, although smaller or larger configurations have been implemented (Ingersoll Engineers, 1982). The role of direct labor is very limited with such a configuration, with the only routine manual operations typically being the loading of raw materials such as castings or forgings and the unloading of finished products. The role of auxiliary labor, such as maintenance, programming, and other support becomes critical in order to keep the equipment up and running. Because the equipment is flexible and can switch quickly from program to program, an FMS configuration has good flexibility in terms of being able to produce a wide variety of part types. Parts may be fully processed in each machine or may be routed to and from different machines to complete their processing. Because a highly automated and computerized configuration like this will necessarily be expensive, utilization is often a critical factor, with sophisticated algorithms being used to schedule and route parts through the system. Material flow paths are limited compared to a job shop environment, but more complex than those in an equipment-paced line or lean cell. Due to the high degree of automation, computerized tracking can be used to store information regarding part routings.

Equipment-paced line

Equipment-paced lines involve a series of stations, typically arranged in a straight line, to produce a single part or a set of very similar parts with relatively high and stable volumes. Movement of parts from one station to the next takes place automatically, either synchronously or asynchronously. In some cases, much of vehicle assembly for example, the parts may be transported by a continuously moving conveyor. In other cases, such as a typical transfer line, the parts index from one station to the next. Parts might index all at once (synchronously), or they may be able to move independently (i.e. asynchronously), by means of a power-and-free conveyor system, for example. Equipment in this environment can be more part specific and specialized than in the previous configurations. For each station, designers can select whether the work content should be done manually, by some sort of fixed automation, by more flexible robotic stations, or by some combination of these. The result is that any mix of manual work, hard automation, and flexible robotic stations is possible. In some cases, such as machining, an entire line might be fully automated and highly inflexible. In other cases, such as assembly, a line is likely to have at least some operations that are best done manually. Most common is a mix of manual and automated stations.

Material flow and operator work are simplified in an equipment-paced line configuration relative to the previously defined configurations. Often there is only one possible flow path that all parts follow. In some cases, when station cycle times are long, multiple identical stations might be required to run in parallel, complicating material flow somewhat. Operators in an equipment-paced flow line tend to repeatedly perform a series of simple tasks at a single station. The faster the line, the lower the work content per station, and the simpler the tasks must be.

“Lean” cell

The concept of a lean manufacturing cell is based on ideas developed at Toyota over time since the 1950’s. The goal of “lean manufacturing” is the elimination of all waste in production activities (Shingo, 1989). The most common means for attempting to achieve this is through the creation of single-piece-flow cells. Unlike the machines in a job shop or batch flow configuration, equipment is grouped into a cell based on the part to be produced. In the ideal case, exactly one of each type of machine type necessary to fully process a part will be present in a cell. The machines are located close to one another, typically in two parallel rows or in a U-shaped layout. Parts are transported from one station to the next one at a time. When product mix flexibility is desired, the focus is on reducing or eliminating setup time at each machine or station. Such a layout requires operators capable of running a variety of different machine types. Operator responsibilities typically include loading and unloading the machines and performing basic quality checks, as well as performing changeovers and contributing ideas for improving the cell as a whole. Machines are designed to run autonomously (i.e, not requiring operator supervision) and to automatically recognize abnormal conditions. This "autonomation" (also referred to as "jidoka") is critical to enabling the operator to run multiple machines as part of a standard workloop. Several other aspects of "lean manufacturing" deal with higher-level issues such as controlling the flow of materials from one subsystem to the next and reducing the overall throughput time of the manufacturing system so that it is less than the customers' demand interval. More complete descriptions of "lean" practices can be found in (Shingo, 1988, 1989; Monden, 1983, Ohno, 1988, and many others).

Project shop

A project shop (also referred to in the literature as a fixed-position layout) is significantly different from the previous configurations in that the product's position remains relatively fixed during processing. Supplementary materials, resources, and people are brought to the product. Such a configuration is necessary when the product being manufactured or assembled is extremely large and/or heavy; examples can be found in the aircraft, aerospace, ship building, and construction industries.

Continuous flow

A continuous flow configuration differs from the previous configurations in that it processes a *continuous material*, as opposed to a series of discrete parts. Examples include liquid and gas processing and continuous casting. Somewhat similar to an equipment-paced flow line, the process operations are arranged in order and the material flows directly from one to the next. Operations and material handling are typically automated, and the system runs with little direct assistance from operators. Material flow paths are rigidly defined; typically there is only one path for the material to take. Such configurations are generally the least flexible, with the equipment being dedicated to a particular type of product. Changing over from one product type to the next, if possible, involves flushing the old material completely out of the system and then setting up the equipment for the next product.

9.2.3 Selection Approaches

Section 4.1.4 presented an introductory look at preliminary manufacturing system design, reviewing observations from industry as well as a framework for thinking about the appropriate roles of different system configurations (shown in Figure 4-2). In the years since Hayes and Wheelwright (1979) developed this framework many advances have been made in the field of manufacturing system design, including the continuing development and increasing popularity of configurations such as the flexible manufacturing system (FMS) and the lean cell. Chryssolouris (1992) presents a more contemporary review of these configurations, describing the advantages and disadvantages to each in terms of factors such as product mix, volumes, inventory, scheduling, and flexibility. Figure 9-1 was developed by Chryssolouris to provide general guidance in selecting a configuration. Note that the FMS is not included, as Chryssolouris considers it to be a hybrid of the job shop and lean cell configurations. This leads to an important point that Chryssolouris makes: in reality, system structures often occur as combinations or in modified forms. That is, the selection of a configuration is just a starting point for the rest of the manufacturing system design process, and the resulting system design may end up being significantly different from the predefined configurations.

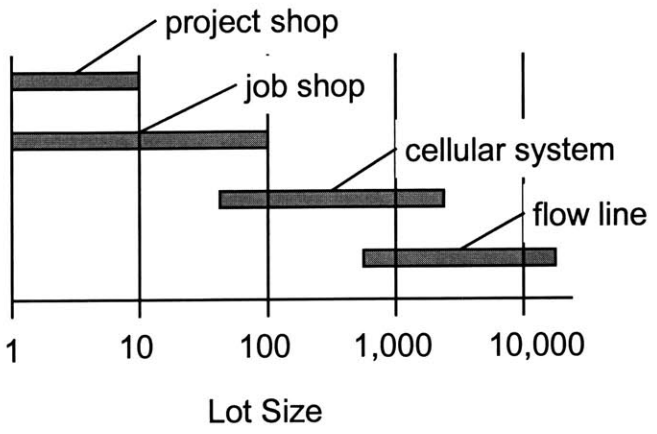


Figure 9-1: Suitable manufacturing configurations as a function of lot size (adapted from Chryssolouris, 1992)

A more structured approach to configuration selection was developed by Miltenburg (1995). This framework (part of which is shown in Figure 9-2) can be considered an expanded and updated version of the product-process matrix developed by Hayes and Wheelwright (shown in Figure 4-2) in that it is based primarily on the relationships between different configurations and different product mix and volume combinations. The framework also rates different configurations in terms of their ability to meet different types of strategic objectives (which Miltenburg refers to as "manufacturing outputs"). Other portions of the framework (not shown in Figure 9-2) provide guidance in using competitive analysis to determine where the firm is and where it would like to be with respect to the manufacturing outputs and in relating "manufacturing levers" such as human resources and sourcing to the outputs. The result is a tool for helping a firm to assess where it stands competitively and to form a rational strategy for improvement.

Because the framework is meant to be a guide for strategy development, it is lacking in some features that could make it more useful as a system design tool. The primary limitation of this approach is that it treats the seven "production system designs" (job shop, batch flow, FMS, etc.) as comprising a discrete and rigidly defined set containing all possible system designs. This simplification of limiting the design space to seven possibilities can be useful for high-level strategic thinking but can be an impediment to an effective system design process. Rather than selecting a predefined solution, designers must have the ability to create a system that combines the positive attributes of multiple configurations, tailoring performance to meet the needs of the system's unique competitive environment.

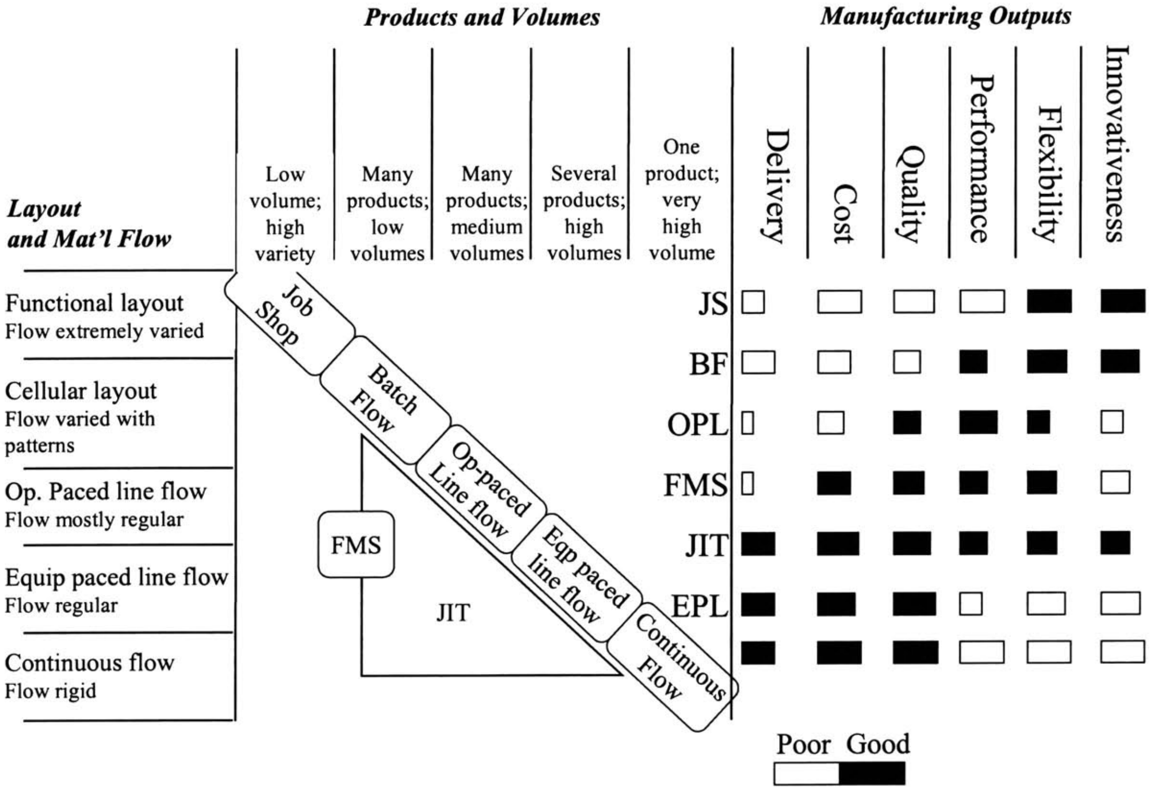


Figure 9-2: Framework for selecting a manufacturing system (Miltenberg, 1995)

For example, suppose that a firm is considering putting in an operator-paced line due to its strong performance with regard to quality and flexibility. However, Figure 9-2 shows that such a configuration will have high costs associated with it. Does this then mean that the designers must abandon the idea of an operator-paced line if the costs are too high? The fundamental shortcomings of the framework are that it does not help the designer to identify trade-offs, or to understand the factors that most strongly affect performance. To continue with the example, perhaps there is a trade-off between cost and system flexibility that, once identified, could help designers to create a modified version of an operator-paced line that would better meet their strategic objectives. The method described in the following section is aimed at providing such guidance to system designers through the use of the core manufacturing system design process described in the previous chapters.

9.3 *An Example of Using the Core Process for Preliminary Design*

The core manufacturing system design process and the manufacturing system design decomposition can be helpful tools for evaluating alternative system configurations. This section will use an actual manufacturing system design case from industry as an example to illustrate the use of these tools. An introduction to the example will be presented, followed by a description of how each step in the core manufacturing system design process applies.

This manufacturing system design case is taken from Visteon Automotive Systems, a US-based automotive component supplier with an existing factory for producing axles for rear-wheel drive and all-wheel drive vehicles. Production at this factory includes the machining of several components of the axle, including the differential gears and the differential case and carrier as well as assembly of these components. Within the factory are several different subsystems of various types to perform the necessary operations. For example, all gear manufacturing is currently performed in a large batch flow subsystem. Gear sets for all varieties of axles and for all customers flow through this one subsystem. Machining of the differential cases and carriers is performed primarily on several transfer lines, each dedicated to a limited set of product varieties. More recently, an FMS was installed to perform the machining of some differential carriers. Most axle assembly is performed on partially automated equipment-paced lines, although there have been recent attempts to introduce "lean" axle assembly cells for some of the low-volume varieties of axles. The overall result is highly complex flow of materials and information throughout the plant, as shown in Figure 9-3. In this figure, each oval represents one manufacturing subsystem (e.g., one assembly line, one transfer line, one batch flow system, one FMS, etc.). A subsystem could contain anywhere from 5 to 500 machines or workstations.

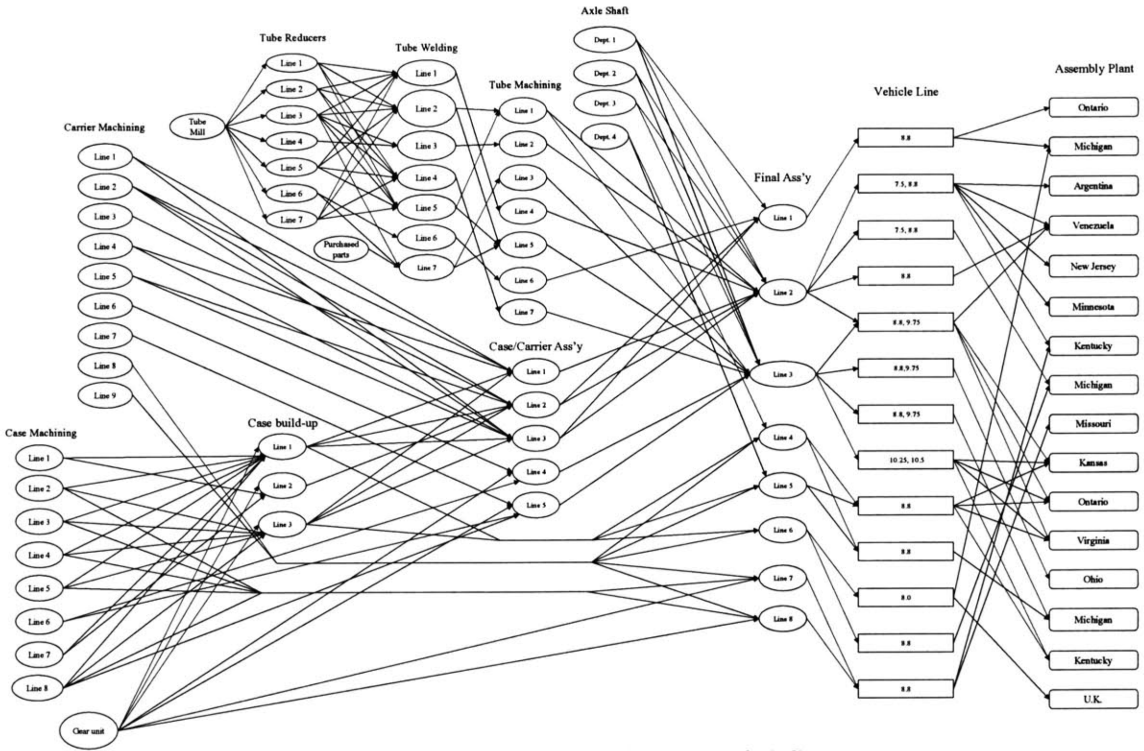


Figure 9-3: Plant-wide material flow

Historically, all production at this factory has been for a single customer, Ford Motor Company. In fact, the plant was wholly owned and operated by Ford until very recently, when a group of Ford component plants was spun off as an independent entity now known as Visteon Automotive Systems. Even though production had traditionally been for just one customer, the axles produced did go to 13 different vehicle programs at 16 different vehicle assembly plants throughout Europe and North and South America. Recent efforts at Visteon have focused on expanding their business to serve additional customers beyond Ford. These efforts have resulted in several successful bids to supply products to other automobile manufacturers, including a bid to start building axles for a new customer. The product to be supplied to this new customer requires a smaller differential unit of a significantly different design than those used in the axles traditionally made at the factory, and, as a result, the components could not be machined or assembled on any of the existing lines in the factory. Retooling various machining and assembly lines to make them flexible enough to process both the old and the new product designs was judged to be prohibitively expensive. Also, it was found that the customer would prefer to see an independent system dedicated to their parts instead of having them mixed in with the axles and differentials for other assembly plants. Thus, it was decided that an independent system would be needed and Visteon was faced with the challenge of designing a complete manufacturing system to machine the components and assemble them into axles for its new customer, as shown in Figure 9-4. The following sections describe how the steps in the core process apply to the preliminary design of new manufacturing systems, both in general and in the specific case of this example, where designers must decide upon an appropriate configuration for each subsystem.

It is important to note that this example focuses only on the design of these subsystems and not on the means for linking them together into an integrated overall system. That is, issues of scheduling across multiple subsystems and coordination with suppliers and customers are beyond the scope of this example.

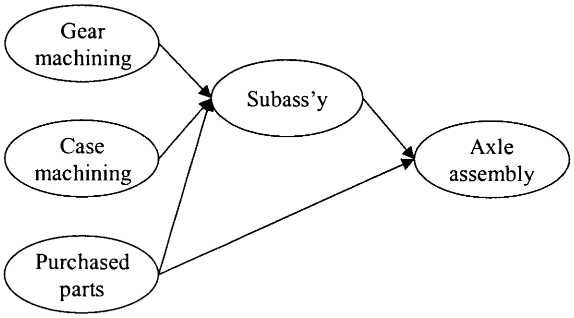


Figure 9-4: Proposed material flow for new manufacturing system

9.3.1 Step 1: Manufacturing Strategy / Requirements Generation

Application of the core system design process begins with the definition of the requirements and objectives of the manufacturing system design. As described in section 6.3, this information can come from the firm's strategic goals or from other sources external to the system (e.g., from the downstream customer). For preliminary manufacturing system design, important requirements will involve the required capacity, product specifications, and product variety information. Other requirements might additionally be placed on the amount of available floor space, the workforce to be used, the amount of funding available for investment in the system, etc. Additional performance objectives will come from the firm's strategy and its desired competitive position with respect to cost, quality, delivery performance, flexibility, and innovativeness.

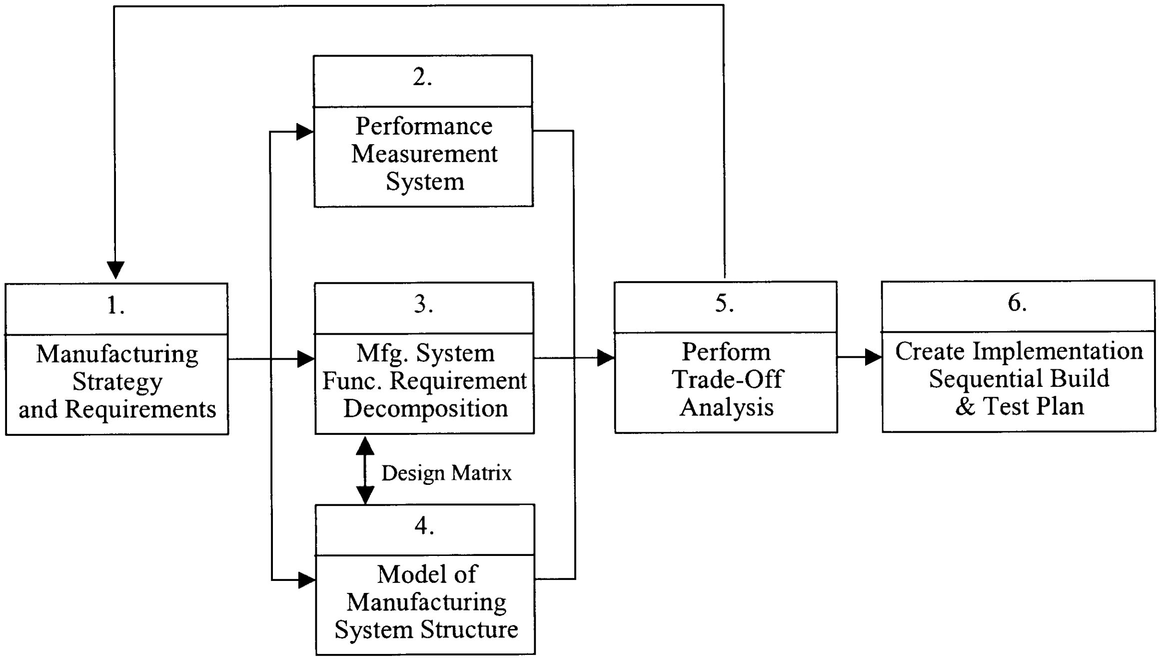


Figure 9-5: Core manufacturing system design process

In the specific case of the axle manufacturing system design example, both external requirements and strategic objectives were judged to be of high importance. Many key requirements came from the customer, including several product design specifications. System capacity requirements were also driven by the customer's needs. In addition to specifying the total number of axles they would require per day, the customer also requested that the axle manufacturing system be designed to operate no more than two shifts per day, thus matching the operating pattern of the vehicle assembly line. In this way, the customer could be sure that if demand for the vehicle increased, the final assembly line could immediately react and increase its weekly output by running overtime and that the axle machining and assembly systems could react in the same way. By requesting that the axle-building system follow the same operating pattern, the customer was requiring that the axle system have the desired level of upward volume flexibility.

Other system requirements came from the existing factory in which the axle machining and assembly systems would be located. A limited amount of floor space was available, so all operations would need to fit within a specified portion of the factory. The labor in the factory was highly unionized, and the operators for the new system would come from this same labor union. This placed several requirements on the system in terms of manual work content and job requirements. For example, the union's job classification system limited the range of activities for which a single operator could be responsible. Union policies also placed restrictions on the possible operating patterns, the cost of running overtime and weekends, etc. Finally, a requirement was placed on the investment cost of the system design, as a limited amount of money was budgeted for the project.

In terms of strategic goals, the performance of a manufacturing system at Visteon Automotive Systems has traditionally been assessed based almost entirely on two factors: quality and cost. Conformance of the finished goods to the design specifications is considered to be a "must-have," i.e., to win an order, a component supplier *must* be able to convince the customer that they are capable of delivering defect-free parts. In the terminology of Hill (1994), quality is considered to be an "order-qualifier." One reason for this is that unplanned downtime on a vehicle assembly line is very costly (Visteon has reported that they are charged $10,000 per minute of unplanned downtime assignable to the components they supply), thus making the avoidance of quality concerns critical to success. Cost has traditionally been the order-winning criteria for Visteon. That is, they convince assembly plants to buy their axles by demonstrating that they can deliver a quality product at the lowest per-piece cost.

Visteon's recent efforts at growing the business by serving additional customers have resulted in a change in their competitive priorities. Cost and quality are still critical, but other factors, such as flexibility and delivery performance are becoming more and more important as order-winning system characteristics. In the case of the axle manufacturing system design project discussed here, the reliability of delivery performance and the system's upward volume flexibility are important factors that must be considered in addition to cost and quality. The need for upward volume flexibility was discussed previously and is based on the customer's desire to have the potential to quickly increase production volume without significantly affecting the per-unit costs and without the delays associated with the purchase and installation of additional equipment. The reliability of delivery performance is also of increased importance due to the high cost of starving an assembly line. In previous system design cases at the factory, delivery performance reliability was ensured by keeping a substantial amount of finished goods inventory between the manufacturing system and the customer. In that way, shipments could be made to the customer regardless of how reliable the system itself was. With the new system design, it was desired that a minimum amount of inventory be kept, thus requiring that the manufacturing system have a predictable, reliable output in order to consistently ensure on-time delivery of axles to the customer.

Other aspects of system performance were less critical for this design case. Only one product type was being demanded, and flexibility for future design changes or additional product types was judged to be of lesser importance than the factors already discussed. So, performance aspects such as innovativeness and product mix flexibility were given low priority during the design process. Although, as stated earlier, it was desired that inventory levels be minimized, this was not an explicit strategic objective as there was no direct benefit to the customer to reduced inventory and improved delivery performance in terms of throughput time. Instead, low levels of inventory were desired primarily to reduce costs and keep required floor space to a minimum, thus making inventory reduction a means to achieving other strategic objectives and requirements, but not a strategic end in and of itself. The key strategic objectives and external requirements placed on the system design are summarized in Table 9-1.

This information can then be used to help create a more formal model of the decision maker's preference structure. In this example, $n = 4$, as only four dimensions of strategy were judged to be of significant importance in selecting a design concept (cost, quality, delivery performance dependability, and upwards volume flexibility).

Table 9-1: Strategic objectives and requirements

	Area of strategy / requirement	**How it applies**
Strategic Objectives	Cost	Cost is critical to winning orders
	Quality	Conformance to design specifications is critical
	Delivery Performance – Dependability	On-time delivery is critical
	Delivery Performance - Throughput Time	Not important to customer
	Product Mix Flexibility	Does not apply (only one product variety)
	Volume Flex – Upwards	Important to customer due to demand uncertainty
	Volume Flex – Downwards	Not important to customer
	Innovativeness	Not important to customer
Requirements	Product Design	Specified by customer
	Production Volumes	Estimated by customer
	Workforce	System will use existing, unionized workforce
	Floor space	System must fit in allocated floor space
	Investment	Specific amount of funding available for the project

Prioritizing among the relevant aspects of strategy

The pairwise comparison matrix for the axle manufacturing system design example is shown in Figure 9-6. Only the shaded entries needed to be entered. These entries were determined based on conversations with engineers and managers involved in making design decisions regarding the project. All other entries and the resulting weights and consistency scores were calculated automatically by the software tool as described in section 8.1. The results of these comparisons show that cost and quality continue to be the dominant factors in making design decisions, but the results also show that other strategic aspects of performance are of significant importance as well. The results of these comparisons can now be used to form the matrix S, to aid in the trade-off analysis process. The matrix R can also be formed at this point. The five requirements listed in Table 9-1 were all assigned equal weights, and so R is simply a 5 x 5 identity matrix.

	Cost	Quality	Delivery Performance - Dependability	Upward Volume Flexibility	Normalized weight, w	**Scaled weight, p**
Cost	1.0000	2.0000	3.0000	7.0000	0.46	**1.00**
Quality	0.5000	1.0000	2.0000	5.0000	0.30	**0.65**
Delivery Performance Dependability	0.3333	0.5000	1.0000	3.0000	0.17	**0.37**
Upward Volume Flexibility	0.1429	0.2000	0.3333	1.0000	0.06	**0.13**

Consistency index: 0.01
Random index: 0.90
Consistency ratio: 0.01

Figure 9-6: Pairwise comparison matrix and resulting weights

$$S=\begin{bmatrix} 1 & - & - & - & - & - & - & - \\ - & 0.65 & - & - & - & - & - & - \\ - & - & 0.37 & - & - & - & - & - \\ - & - & - & 0 & - & - & - & - \\ - & - & - & - & 0 & - & - & - \\ - & - & - & - & - & 0.13 & - & - \\ - & - & - & - & - & - & 0 & - \\ - & - & - & - & - & - & - & 0 \end{bmatrix} \qquad R=\begin{bmatrix} 1 & - & - & - & - \\ - & 1 & - & - & - \\ - & - & 1 & - & - \\ - & - & - & 1 & - \\ - & - & - & - & 1 \end{bmatrix}$$

Creating the M^S mapping matrix

At this point in the process, the FR/DP pairs of the manufacturing system design decomposition can be mapped to the relevant aspects of strategy, creating the M^S matrix as discussed in section 8.2. The general mappings between strategy and the MSDD (shown visually in Figure 7-2 through Figure 7-8 and numerically in Appendix B) were used as a starting point to develop the M^S matrix for this specific example. The relevant rows of M^S (those dealing with cost, quality, delivery performance dependability, and upwards volume flexibility) were reviewed and some modifications were made based on knowledge about the axle-manufacturing project. The revised M^S matrix is shown in Appendix B-2; the specific entries that were changed from the general case are shown in bold in Appendix B-2 and are also shown in Figure 9-7 below.

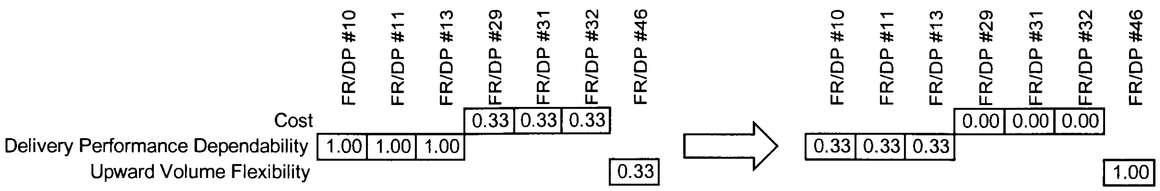


Figure 9-7: Changes to the general M^S matrix

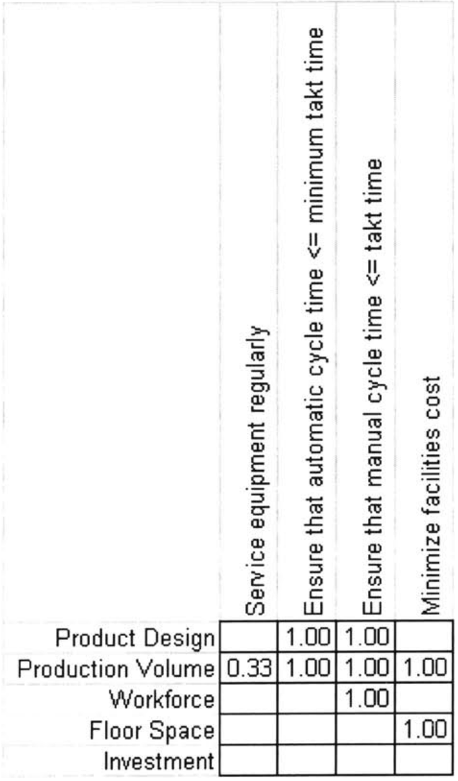
Three matrix entries dealing with cost ($m^S_{1,29}$, $m^S_{1,31}$, and $m^S_{1,32}$) were changed from a value of 0.33 to 0. The general M^S matrix shows that there is a moderate relationship between satisfying the associated FR's ("Ensure level cycle time mix," "Provide knowledge of demanded product mix," and "Produce in sufficiently small run sizes") and achieving a low-cost system. In this specific case, however, only one product type is to be manufactured. Issues involving product run sizes and setup times become unimportant, as no changeovers will be required.

Of the entries dealing with delivery performance dependability, only three ($m^S_{3,10}$, $m^S_{3,11}$, and $m^S_{3,13}$) were modified based on the unique conditions of this example. The FR/DP pairs corresponding with these entries deal with creating the ability to rapidly identify production disruptions when and where they occur, and to rapidly identify the appropriate support resource. Because the system under consideration in this example is being designed for low-volume production and will require a relatively small number of production resources, the problem of identifying a problem is made simpler. When something goes wrong, there are fewer places to look for the source and fewer support resources to consider. In the general case, a strong relationship was said to exist between achievement of these FR/DP pairs and the dependability of delivery performance. Because the time required for these tasks is still important, but simpler, only a moderate relationship was assigned to the appropriate entries in this example.

Only one entry ($m^S_{6,46}$) regarding upwards volume flexibility was changed. FR/DP pair 46 deals with reducing the amount of required investment. In this axle-manufacturing example, many of the necessary operations require expensive machine tools, with capital cost making up a relatively large portion of the total cost. As a result, providing the system with the capability to produce at higher rates would require substantial initial investment and the relationship between achieving upward volume flexibility and controlling investment costs was changed from moderate to strong.

Creating the M^R mapping matrix

In forming the M^R matrix, no general form exists to aid designers, as the requirements for any particular design situation will be unique. As a result, the process of creating this mapping of FR/DP pairs to the requirements must involve the review of each entry M^R. The full M^R matrix for the axle-manufacturing example is shown in Appendix B-3. Discussion of some of the columns of M^R (shown in Figure 9-8) follows to illustrate the thought processes that go into the development of this mapping.



	Service equipment regularly	Ensure that automatic cycle time <= minimum takt time	Ensure that manual cycle time <= takt time	Minimize facilities cost
Product Design		1.00	1.00	
Production Volume	0.33	1.00	1.00	1.00
Workforce			1.00	
Floor Space				1.00
Investment				

Figure 9-8: Sample columns from the M^R matrix

FR: "Service equipment regularly"

DP: "Regular preventative maintenance program"

Only one relationship was identified for this FR/DP pair, that with the requirement on the annual production volume of the manufacturing system being designed. A moderate relationship was said to exist because the production volume will have an impact on the number of hours of production required, which will affect the amount of remaining time available to perform routine maintenance. Because many steps of the manufacturing process are very capital-intensive, if production volumes go up there will likely be a tendency to meet this demand by running additional hours, rather than by purchasing additional equipment. The more hours of production that are required, the less time is left available for routine maintenance activities, and the more difficult it is to service equipment regularly.

FR: "Ensure that automatic cycle time <= minimum takt time"

DP: "Design of appropriate automatic work content at each station"

FR: "Ensure that manual cycle time <= minimum takt time"

DP: "Design of appropriate operator work content and work loops"

In the case of these two columns, relationships were identified with the requirements coming from product design, production volumes, and the workforce. The design of the product has a strong relationship with each of the FR/DP pairs above, as product design details will impact the manufacturing process plan and the cycle time necessary to perform each operation. For example, with the new, smaller differential case, there is some concern that manual work content will increase as it becomes more difficult to manually assemble the internal gears into an increasingly crowded space. There is also a strong relationship between the production volume requirement and these FR/DP pairs, as the required volume will directly impact the rate at which parts must be produced. The higher the required volume is, the lower the takt time will be. Finally, there is also a strong relationship between the workforce requirement and the design of manual work content, as all manual operations must be designed based on union requirements regarding safety and ergonomics.

FR: "Minimize facilities cost"

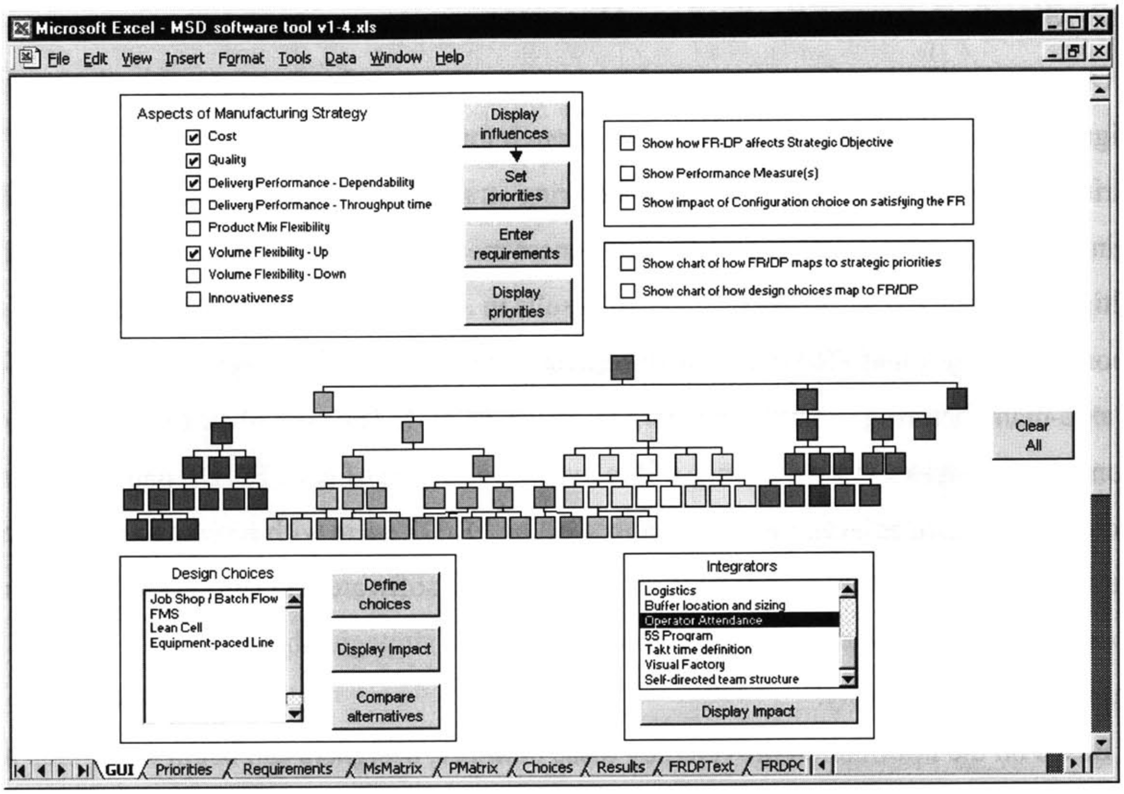
DP: "Reduction of consumed floor space"

Mapping of this FR/DP pair to the design requirements was very straightforward. Two strong relationships were identified. The production volume requirement will impact how much equipment is required and therefore will impact how much floor space the system will consume. The requirement that the system fit into a specified amount of floor space is basically just placing a specific constraint on performance with regard to this FR/DP pair, and so a strong relationship is present for it as well.

9.3.2 Step 2: Defining Effectiveness Measures

Once the system requirements and objectives have been defined and prioritized, system designers can concurrently begin steps two through four of the core process. The S and M^S matrices developed during step 1, "Manufacturing strategy and requirements," can be used to begin the process of defining a set of effectiveness measures. As described in section 8.2.2, multiplying the S and M^S matrices together results in a matrix, P, showing the relative importance of each leaf FR/DP pair with respect to each aspect of strategy. The P matrix for the axle-manufacturing example is shown in Appendix B-4. The sum of all elements in each column is also shown to give a sense of the overall relevance of each FR/DP pair. A similar process can be used to examine the relevance of the FR/DP pairs with respect to each of the requirements. Figure 9-9 and Figure 9-10 show how the software tool can be used to visualize the overall relevance of each FR/DP pair with respect to strategic objectives and requirements, respectively.

Based on the information provided by these matrices, designers can begin to develop a preliminary set of performance measures. At this point in the design process few specific decisions have been made, and so these measures represent a starting point for the ongoing development of a performance measurement system. These measures will need to be modified, added to, and refined as the design process continues and more details of the system design are specified. In designing the preliminary performance measurement system, measures should be chosen from each non-zero row of the matrix P (i.e., those rows corresponding to cost, quality, delivery performance dependability, and upwards volume flexibility performance). Similarly, measures should be chosen to ensure that all requirements are represented.



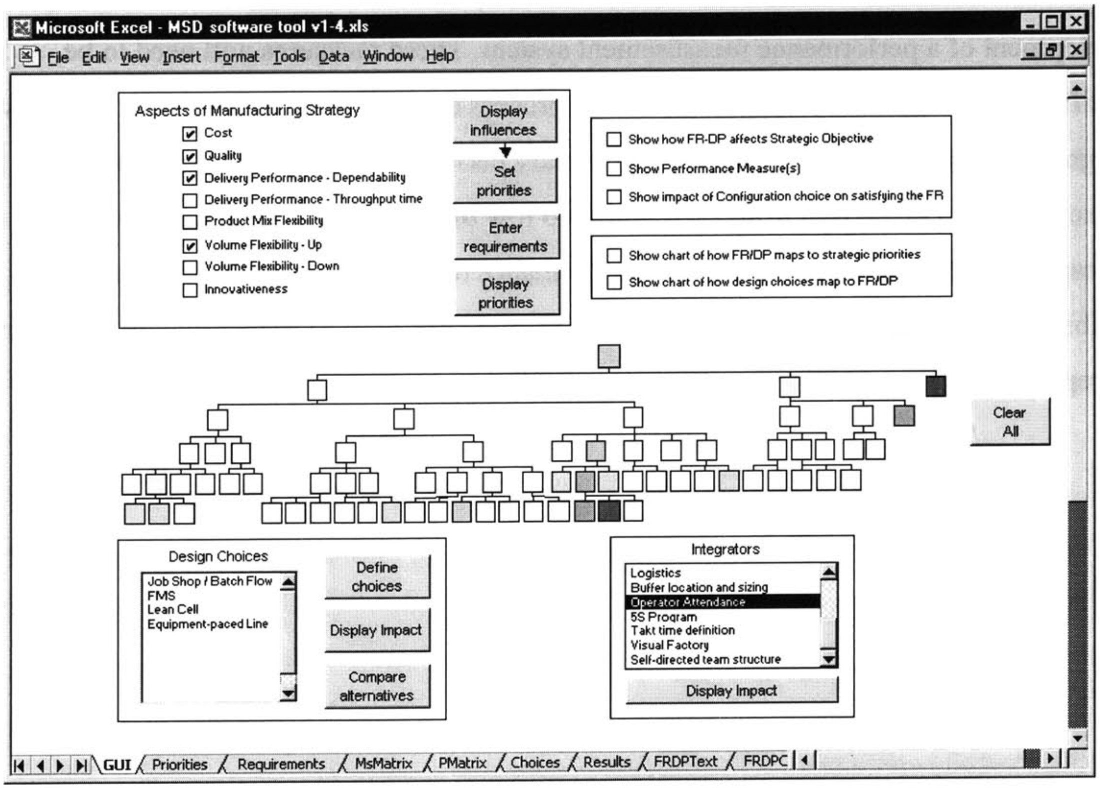
Aspects of Manufacturing Strategy

- ☑ Cost
- ☑ Quality
- ☑ Delivery Performance - Dependability
- ☐ Delivery Performance - Throughput time
- ☐ Product Mix Flexibility
- ☑ Volume Flexibility - Up
- ☐ Volume Flexibility - Down
- ☐ Innovativeness

- ☐ Show how FR-DP affects Strategic Objective
- ☐ Show Performance Measure(s)
- ☐ Show impact of Configuration choice on satisfying the FR

- ☐ Show chart of how FR/DP maps to strategic priorities
- ☐ Show chart of how design choices map to FR/DP

Figure 9-9: Overall relevance of FR/DP pairs with respect to strategic objectives



Aspects of Manufacturing Strategy

- ☑ Cost
- ☑ Quality
- ☑ Delivery Performance - Dependability
- ☐ Delivery Performance - Throughput time
- ☐ Product Mix Flexibility
- ☑ Volume Flexibility - Up
- ☐ Volume Flexibility - Down
- ☐ Innovativeness

- ☐ Show how FR-DP affects Strategic Objective
- ☐ Show Performance Measure(s)
- ☐ Show impact of Configuration choice on satisfying the FR

- ☐ Show chart of how FR/DP maps to strategic priorities
- ☐ Show chart of how design choices map to FR/DP

Figure 9-10: Overall relevance of FR/DP pairs with respect to the requirements

For the axle manufacturing case, all FR/DP/PM's have some relevance, and so the process of developing a set of measures involves selecting a more limited set of measures. A set of measures that monitors performance with respect to the FR/DP pairs impacting the key strategic objectives and requirements for the axle manufacturing case is shown in Table 9-2. This list includes measures based on both leaf and parent FR/DP pairs. For example, high-level PM-111 is included to emphasize the overall importance of achieving good conformance quality. In order to achieve this, several lower-level activities will be important. Two specific lower-level FR/DP pairs dealing with quality are also addressed (FR/DP's Q121 and Q122) as they deal not only with quality, but also with the requirements coming from the workforce that will be responsible for operating the system. Other higher-level performance measures are included to emphasize the importance of delivering products on time (PM's R1 and P1) and of keeping costs under control (PM's 121, 122, 123, and 13). Additional lower-level measures are included to focus on areas that will impact the ability to satisfy requirements based on production volumes (PM-T2) and the need for volume flexibility (PM-D21). The result is a more manageable list of measures that still spans they key needs that must be fulfilled by the manufacturing system. By keeping these measures in mind when examining decisions, designers will be better able to avoid pursuing alternatives that will later prove to be infeasible.

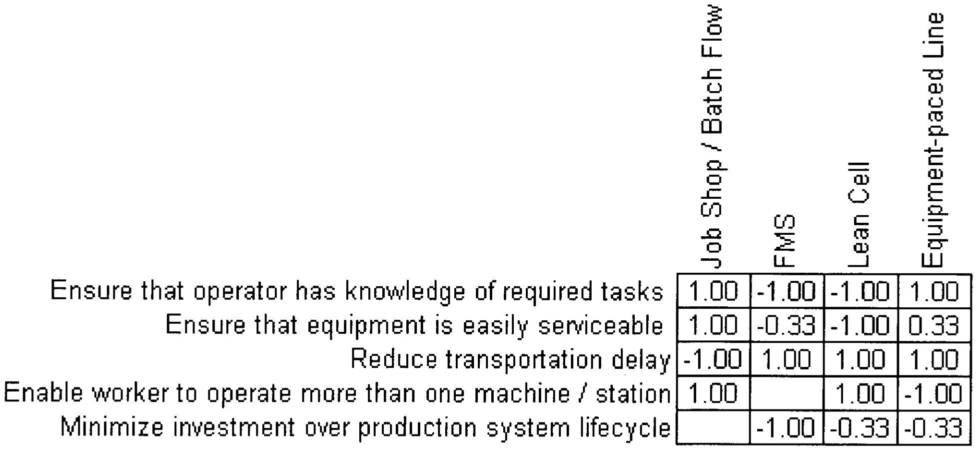
Table 9-2: Key performance measures for axle manufacturing example

PM-111	Process capability
PM-Q121	Number of defects per n parts caused by an operator's lack of understanding about methods
PM-Q122	Number of defects per n parts caused by non-standard methods
PM-R1	Time between occurrence and resolution of disruptions
PM-P1	Number of occurrence of disruptions & amount of time lost to disruptions
PM-T2	Inventory due to process delay
PM-121	Percentage of operators' time spent on wasted motions and waiting
PM-D21	Percentage of operators' time spent walking between stations
PM-122	Amount of indirect labor required to manage / schedule system
PM-123	Facilities cost
PM-13	Total investment over system life cycle

9.3.3 Steps 3 and 4: Defining Behavior and Structure Models

At this preliminary stage in the design process, creating models of behavior and structure involves beginning to define the different design alternatives being considered. In the case of this example, the design alternatives are the different manufacturing subsystem configurations described in section 9.2.2 (job shop, FMS, cell, equipment-paced line, project shop, and continuous flow). Because the product being manufactured is a discrete part (as opposed to a continuous material) and is small and easily transportable relative to the required workstations and equipment, the continuous flow and project shop configurations can be disregarded for further study, and the four remaining configurations can be examined in more detail. At a more detailed stage of the design process, this might involve the development of detailed simulation models to study the behavior of the different alternatives in response to a variety of inputs. At this early stage, however, uncertainty in the important data (e.g. machine cycle times, reliabilities, etc.) makes it difficult to obtain meaningful results. As a result, the focus for this axle manufacturing example will be on the general structural and behavioral properties of the different configurations, as described in section 9.2.2.

Based on this information, designers can evaluate the entries of the mapping matrix, M^D, to show how the anticipated behavior and structure of each choice will impact the ability to satisfy the leaf FR/DP pairs of the manufacturing system design decomposition. Appendix B-5 shows the complete M^D matrix for the axle-manufacturing example. Text descriptions of the rationale behind each entry in M^D were entered using the software tool. These descriptions are listed in Appendix B-6. A portion of this matrix is shown in Figure 9-11 below, followed by more detailed descriptions of the relationships upon which these entries were based.



	Job Shop / Batch Flow	FMS	Lean Cell	Equipment-paced Line
Ensure that operator has knowledge of required tasks	1.00	-1.00	-1.00	1.00
Ensure that equipment is easily serviceable	1.00	-0.33	-1.00	0.33
Reduce transportation delay	-1.00	1.00	1.00	1.00
Enable worker to operate more than one machine / station	1.00		1.00	-1.00
Minimize investment over production system lifecycle		-1.00	-0.33	-0.33

Figure 9-11: Portion of the M^D matrix

FR: "Ensure that operator has knowledge of required tasks

DP: "Training program"

This FR/DP pair has to do with ensuring that defective parts are not produced due to operators' lack of understanding of the work they are responsible for. This is accomplished by providing sufficient training for all operators. This is accomplished the most easily in job shop and equipment-paced line configurations, where each operator is typically responsible for only one operation (i.e. running one type of machine, or performing a set of assembly operations at a single workstation). In an FMS, workers must be highly trained in order to interact with a heavily automated system involving different types of advanced CNC equipment and automated material handling systems. In a cellular configuration, each operator must be trained to run multiple types of machine tools and/or to perform assembly operations at multiple workstations. As a result, more training will be required for operators in FMS and lean cell configurations in order to ensure the same performance relative to this FR/DP pair.

FR: "Ensure that equipment is easily serviceable"

DP: "Machines designed for serviceability"

This FR/DP pair is most easily accomplished in a job shop/batch flow configuration, where space is typically left on all sides of equipment to allow better access for service and maintenance activities. The lack of automation also supports access to the equipment. In an equipment-paced line, access to equipment is limited to two sides, as automated material handling devices typically will load parts on one side and unload them from the opposite side. In an FMS, machine access becomes more difficult due to the increased amount of automation. Automation limits the accessibility of the equipment, and may need to be completely disabled (i.e., "locked out") before any service activities can be performed. In a cellular configuration, designing machines for adequate serviceability becomes particularly challenging, as machines are designed for a narrower profile and are placed very close together, limiting the accessible space for service and repair.

FR: "Reduce transportation delay"

DP: "Material flow oriented layout design"

In the case of this FR/DP pair, the job shop / batch flow configuration performs the most poorly, as machines and equipment are grouped by function rather than by material flow. In cellular and equipment-paced line configurations, machines are arranged according to process flow, reducing the amount of transportation required. In an FMS, many routing paths through the system may be possible, but machines are typically located close together to simplify the automated material handling, resulting in a minimal amount of transportation time and distance.

FR: "Enable worker to operate more than one machine / station"

DP: "Workers trained to operate multiple stations"

In order to make effective use of the operators in a manufacturing system, it is desirable that the configuration support operators running multiple machines and/or stations. In a job shop / batch flow configuration, machines can be arranged so that the operator can run multiple machines of the same type. In a cellular configuration, machines are arranged so that each operator can run multiple machines of different types. In an FMS, this FR/DP becomes much less important, as very little manual work content exists. Enabling the worker to operate multiple stations is particularly difficult in an equipment-paced line, as such lines are generally designed to have one operator specifically assigned to one station. Having an operator run multiple stations would often require the operator to cross the line (i.e., the flow of material) or to walk significant distances from one manual station to the next.

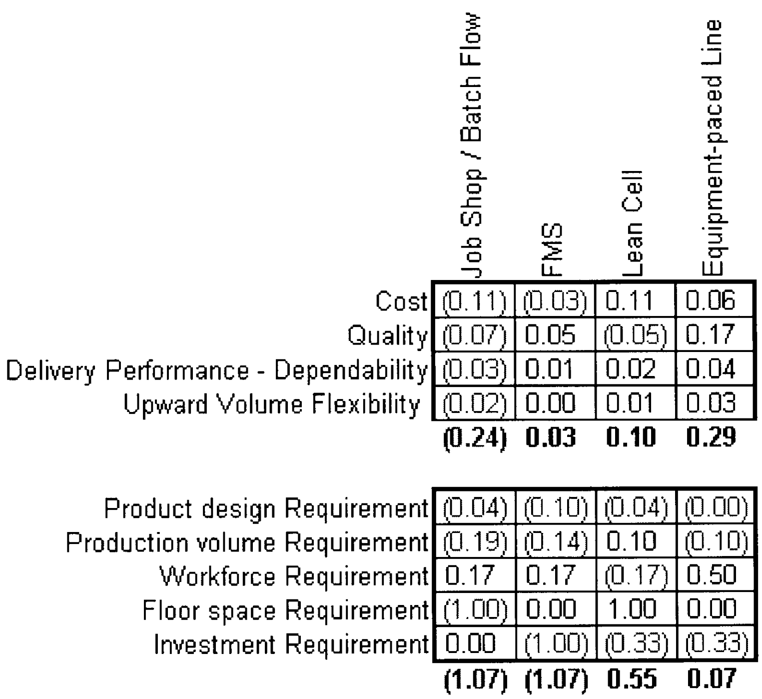
FR: "Minimize investment over production system lifecycle"

DP: "Investment based on a long term strategy"

In this axle-manufacturing example, one goal was to keep investment to a minimum. Product design changes were expected to be minimal and flexibility for future products and volumes was not highly valued. As a result, the focus in terms of investment was on reducing upfront spending with the system considered to be a somewhat "disposable" one. In comparing the alternatives, the job shop / batch flow configuration is treated as a baseline case, representing the basic, minimal investment in standard, "off-the-shelf" equipment. All other configurations require some custom-designed equipment. For the FMS, additional investment will be required for versatile CNC equipment and automated material handling. The equipment-paced line concept can use simpler equipment than the FMS, but still requires some automated material handling. The lean cell design requires additional expense in that "off-the-shelf" machine tools were not suitable and implementing the cell would require working with machine tool builders to custom design some of the necessary equipment.

9.3.4 Step 5: Trade-off Analysis

From filling out the entries of the M^D matrix, it became clear that each alternative configuration had advantages and disadvantages, and that the trade-offs among these alternatives would need to be examined further. This was achieved by multiplying the matrices determined in the previous steps to create two matrices, S^D and R^D to show how the expected performance of the different configurations compare with respect to the important aspects of strategy and to the requirements, respectively. Figure 9-12 shows these matrices and also shows the sum of all entries in each column. As described in section 8.4, the entries in these matrices range in value from –1 to +1 and provide guidance regarding the strengths and weaknesses of each alternative under consideration (negative values are shown in parenthesis).



	Job Shop / Batch Flow	FMS	Lean Cell	Equipment-paced Line
Cost	(0.11)	(0.03)	0.11	0.06
Quality	(0.07)	0.05	(0.05)	0.17
Delivery Performance - Dependability	(0.03)	0.01	0.02	0.04
Upward Volume Flexibility	(0.02)	0.00	0.01	0.03
	(0.24)	**0.03**	**0.10**	**0.29**

	Job Shop / Batch Flow	FMS	Lean Cell	Equipment-paced Line
Product design Requirement	(0.04)	(0.10)	(0.04)	(0.00)
Production volume Requirement	(0.19)	(0.14)	0.10	(0.10)
Workforce Requirement	0.17	0.17	(0.17)	0.50
Floor space Requirement	(1.00)	0.00	1.00	0.00
Investment Requirement	0.00	(1.00)	(0.33)	(0.33)
	(1.07)	**(1.07)**	**0.55**	**0.07**

Figure 9-12: Matrices showing results of the comparison

The information in the matrices shown in Figure 9-12 shows that the equipment-paced line and lean cell configuration are significantly better suited for the objectives of this particular example that the other choices. The job shop / batch flow and FMS are not without advantages, though. The job shop / batch flow configuration is estimated to require the least amount of investment and to be the most accommodating towards the requirements derived from the workforce. However, the job shop configuration presents significant challenges in other areas, including all of the important aspects of strategy. An FMS would be likely to enhance performance significantly relative to the job shop / batch flow configuration, as the FMS has a higher score in nearly every row of the S^D and R^D matrices. The largest drawback of the FMS configuration for this example is the large investment required due to the emphasis on computerization and automation required by this approach.

The lean cell and equipment-paced line concepts each showed the potential for better overall performance than either of the first two alternatives. The cellular configuration had the best performance in terms of expected running costs, while also requiring the least amount of floor space. The equipment-paced line, on the other hand, would make controlling quality and meeting workforce requirements less challenging. After considering the alternatives, a decision was made to go forward with the lean cell configuration, keeping investment and running costs low while satisfying the overall objectives to the greatest extent possible.

9.3.5 Sensitivity Analysis

The MSD software tool can be used to measure the sensitivity of the results shown in Figure 9-12 to changes in the entries of the M^D matrix. The software tool checks each entry in M^D individually, calculating the amount, δ, by which the value of each entry would have to be changed for the results to be altered. Changes of up to ± 1 are considered, although the restriction that $-1 \leq m^D \leq 1$ is maintained. The results are considered to be altered if there is a change in which alternative scores the best in terms of achieving the strategic objectives, fulfilling the requirements, or both. The output of the sensitivity analysis is a score assigned to each entry in M^D indicating the smallest value of δ that would impact the overall results. No score is assigned to entries of M^D that are not capable of affecting the results. So, for example, a sensitivity score of 0.5 for an entry, m^D, means that increasing that entry's value by 0.5 would change the results in terms of which design alternative was ranked the best with regard to strategy, requirements, or overall performance. A sensitivity score of 0.1 would mean that a change of only 0.1 would alter the results. Thus, the lower the sensitivity score, the more sensitive the results are to changes in the associated entry in M^D. If an entry is not assigned a sensitivity score, then an error of ± 1 for that entry would not alter the results.

For this example, eight entries of the M^D matrix were capable of affecting the results (i.e., eight entries were assigned sensitivity scores). None of the others could individually alter the results. Figure 9-13 shows the sensitivity scores for these eight entries. Essentially, these results show that decreasing the assessment of the lean cell with respect to any one of the four FR's listed in Figure 9-13 could result alter the results and make the equipment-paced line be ranked first in terms of overall performance. Similarly, increasing the assessment of the equipment-paced line with respect to one of these four FR's could have the same result. In the case of the FR's "Ensure that automatic cycle time <= minimum takt time" and "Ensure that manual cycle time <= takt time," all design alternatives were rated the same, as no design alternative presented any significant challenges or strengths in terms of meeting the required capacity. It is unlikely, therefore, that errors in judgment could lead to the changes in M^D sufficient to alter the results.

The results were found to be the most sensitive to changes in the evaluations of the lean cell and equipment-paced line in terms of the FR-DP pairs "Minimize facilities cost"-"Reduction of consumed floor space" and "Minimize investment over production system life cycle"-"Investment based on a long term strategy." This is due to the fact that there are specific requirements based solely on these two FR's; a system will be infeasible if its floor space exceeds the amount available or if the required investment is greater than the amount budgeted for the project. Designers must therefore be sure to enter well thought out data for each alternative for these two FR's.

	Job Shop / Batch Flow	FMS	Lean Cell	Equipment-paced Line
Ensure that automatic cycle time <= minimum takt time			-1	1
Ensure that manual cycle time <= takt time			-0.7	0.7
Minimize facilities cost			-0.3	0.3
Minimize investment over production system lifecycle			-0.3	0.3

Figure 9-13: Sensitivity scores

It is important to note that the results of this analysis are intended to provide designers with more information than just which choice is the most promising based on the available information. Another significant contribution is to provide guidance regarding the challenges that are likely to be faced and to provide information regarding how these challenges have been met by other alternatives. In the case of this example, the results of the comparison show that the greatest challenges arising with the cellular approach are likely to involve the workforce, in terms of the amount of training required, achieving satisfactory ergonomics, and defining work tasks that are standardized, repeatable, and result in the desired level of product quality. The earlier that designers are explicitly made aware of these challenges, the better they will be prepared to accommodate them.

9.3.6 Process Validation

In order to validate the results of the process for trade-off analysis, other example problems were tested. Strategy information intentionally biased towards a particular design solution was entered in order to verify that the proposed trade-off analysis process would indeed show that the favored design could be expected to perform the best. For example, a test case was performed using input information biased towards the selection of an equipment-paced line. The factory being considered has several transfer lines in place, and the strategy and requirements that led to the implementation of these transfer lines was modeled and used as a test input into the trade-off analysis process. These transfer lines were typically implemented based on the desire to keep costs low by reducing / minimizing the role of direct labor in the manufacturing process. Many engineers involved in the design of these systems believed that there was a direct relationship between quality problems and the presence of operators in the manufacturing system. As a result, the general design strategy was to reduce costs and improve quality by eliminating manual work content wherever possible. Other aspects of performance such as throughput time, innovativeness, and product mix and volume flexibility were not judged to be of significant importance. Figure 9-14 below shows the S matrix used to model this strategy. Cost was given the highest priority, with quality being the only other aspect of performance considered.

	Cost	Quality
Cost	1.00	2.00
Quality	0.50	1.00

Figure 9-14: S matrix for validation example

Additional requirements were also defined. The first requirement was based on the fact that the workforce for the manufacturing system being designed would need to be selected from the existing operators in the plant. A second requirement was defined based on the fact that there would be a limited budget for investment in the new manufacturing system. The mapping of these requirements to the FR/DP pairs that were judged to be affected is shown in Figure 9-15.

	Ensure that operator has knowledge of required tasks	Ensure that operator consistently performs tasks correctly	Ensure that operator human errors do not translate to defects	Ensure availability of workers	Minimize investment over production system lifecycle
Workforce	1.00	1.00	1.00	1.00	
Investment					1.00

Figure 9-15: Requirements for the validation example

Using this information along with the unchanged M^S and M^D matrices, the process for trade-off analysis was repeated with the results shown in Figure 9-16. These results show that with the input information biased towards a transfer line, the output of the trade-off analysis is biased towards the selection of an equipment-paced line, as would be expected. Although the lean cell configuration has the best score in cost and the job shop configuration is best at meeting the investment requirement, the equipment-paced line clearly is shown to be the most desirable choice given this biased set of input information.

	Job Shop / Batch Flow	FMS	Lean Cell	Equipment-paced Line
Cost	(0.10)	(0.03)	0.10	0.05
Quality	(0.04)	0.02	(0.02)	0.09
	(0.14)	**(0.00)**	**0.08**	**0.14**
Workforce Requirement	0.25	0.25	(0.25)	0.50
Investment Requirement	0.00	(1.00)	(0.33)	(0.33)
	0.25	(0.75)	(0.58)	0.17

Figure 9-16: Comparison results for validation example

9.3.7 Summary of the Preliminary Design Example

This example was intended to illustrate the proposed core manufacturing system design process using an example taken from an actual case from an automotive component manufacturer. By defining and ranking the importance of the relevant aspects of strategy, system designers were able to create a focused set of priorities for design activities. Mapping strategic objectives, requirements, and design alternatives to the manufacturing system design decomposition ensures that a wide variety of lower level requirements and design parameters are considered and not overlooked. Combining these priorities and mappings results in comparison matrices that show the strengths and weaknesses of the design alternatives, giving designers valuable information to aid them in selecting an alternative for further study, as well as providing guidance as to what challenges are likely to arise, how these challenges can be dealt with, and what measures of performance must be carefully monitored throughout the remainder of the design process and after the system is implemented.

Sensitivity analysis showed that significant changes would be needed in an entry of the M^D matrix to impact the overall results of the trade-off analysis. In fact, few of the entries in M^D could individually impact the results with a change in value. In the cases where a change in an individual entry could impact the results, a significant change would be needed (i.e. changing a value from a weak to a strong relationship). These results show that the trade-off results for this example are robust to errors due to the subjective and qualitative judgments that are inherent in the process of determining the values for the matrix entries.

9.4 *Mid-level Design Example*

This section will focus on the application of the proposed trade-off analysis process to a decision at a lower level of detail. In the previous example, different manufacturing subsystem configurations were considered. In this next example, a decision had been made to investigate the design of "lean" manufacturing cells. Designers then had to specify the size (i.e., capacity) of each cell and, therefore, the total number of cells that would be needed to meet the required overall capacity.

9.4.1 Background

This second example comes from a project involving the differential gear manufacturing area at the same Visteon Automotive Systems factory described in the previous example (see section 9.3). At the start of the project, all differential gear manufacturing was done in a batch flow configuration, with machines grouped according to function and large quantities of inventory kept between some subsequent operations (see Figure 9-17). The original motivation for redesigning the existing system was the need to upgrade some of the operations. Several of the machines in use were rather old (up to 40 years old) and management desired to replace the old equipment with machines using more modern technology (CNC) to reduce cost and ensure better part quality. Because some areas of the factory would require significant changes in terms of layout and material handling when the machines are replaced, this was seen as a potential opportunity to redesign the entire system to improve efficiency and eliminate waste. It was believed that conversion to a lean, cellular manufacturing system could help improve quality, eliminate waste, and reduce total costs. Such a system would improve the ability to trace defects back to the machine that caused them and would eliminate nearly all of the transportation and storage of parts between operations.

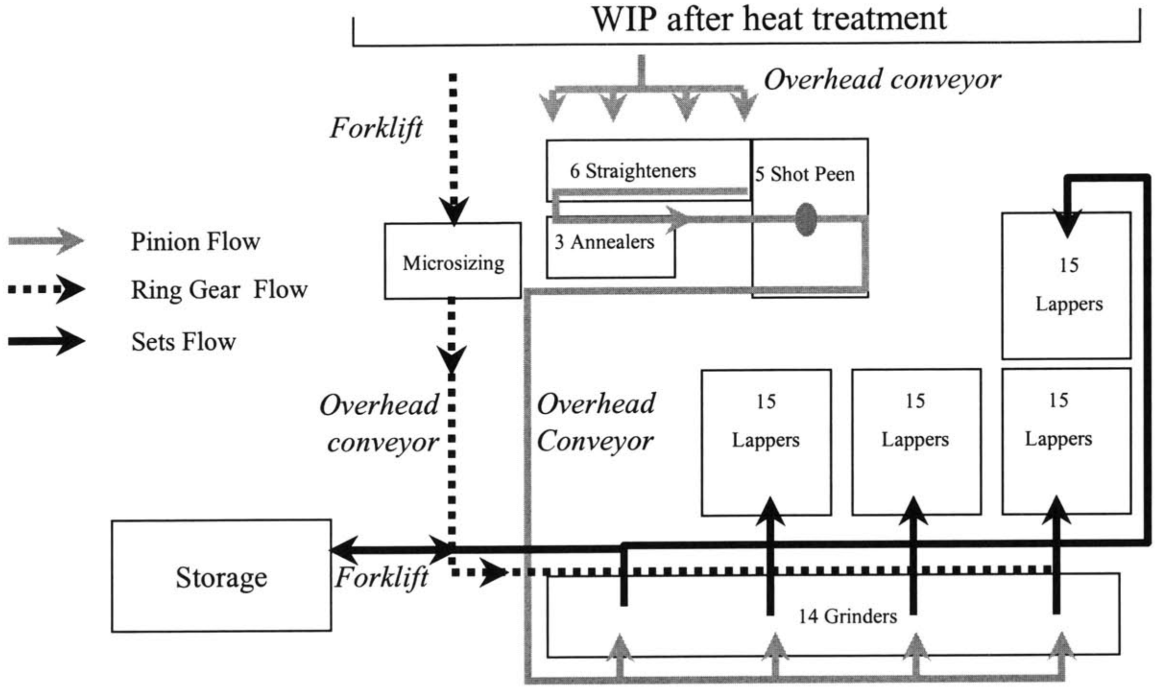


Figure 9-17: Part of the existing system for gear manufacturing

9.4.2 Product Information

The product being manufactured by this system is a matching set consisting of one pinion gear and one ring gear. The existing system produces these parts in five different sizes (or families) with 2-7 ratios per family for a total of about 20 different varieties of sets. Total production volume of the system is approximately 11,000 sets per day, or about one set every 6 seconds. A typical ring gear is about 9 inches in diameter, 2.5 inches thick, and weighs about 15 lbs. A typical pinion gear is about 8 inches long, 4 inches in diameter, and weighs about 8 lbs.

9.4.3 Step 1: Manufacturing Strategy and Requirements

As described in section 9.3.1, cost, quality, and delivery performance dependability have traditionally been the most-emphasized aspects of strategy at Visteon. In this example both cost and delivery performance dependability remain important. Quality is not emphasized, as the design choices being considered are essentially different cellular layouts of the same equipment and there is expected to be no significant difference in product quality from one layout to the next.

Other important aspects of strategy for this example include product mix flexibility and downward volume flexibility. In the existing gear manufacturing area, increasing product variety and constant changes in the demanded product mix have been causing a great deal of difficulties, as the batch flow system in place is not well-equipped to deal with this variety. Designers of the new manufacturing system decided that the new gear manufacturing system needed to be better able to deal with changes in the mix of products demanded. The need for volume flexibility arose from uncertainty in the total amount of demand that could be expected. Because of the long lead times for the purchase and installation of equipment, machines were purchased so that the plant would have sufficient capacity for the peak demand according to forecasts for the next five years of production. While the gear manufacturing system needs to be capable of running at this peak rate, it also will be expected to produce at a significantly lower rate for months at a time. It was desired that the manufacturing cells be designed so that they could run at this lower rate with a minimal per-unit cost penalty. Priorities were assigned to these aspects of strategy, as shown in Figure 9-18. Essentially, all relevant aspects of strategy were weighted equally with the exception of downward volume flexibility. Volume flexibility was given a slightly lower priority as it was viewed as being a less-critical problem area in the existing system relative to factors such as cost, quality, and product mix flexibility.

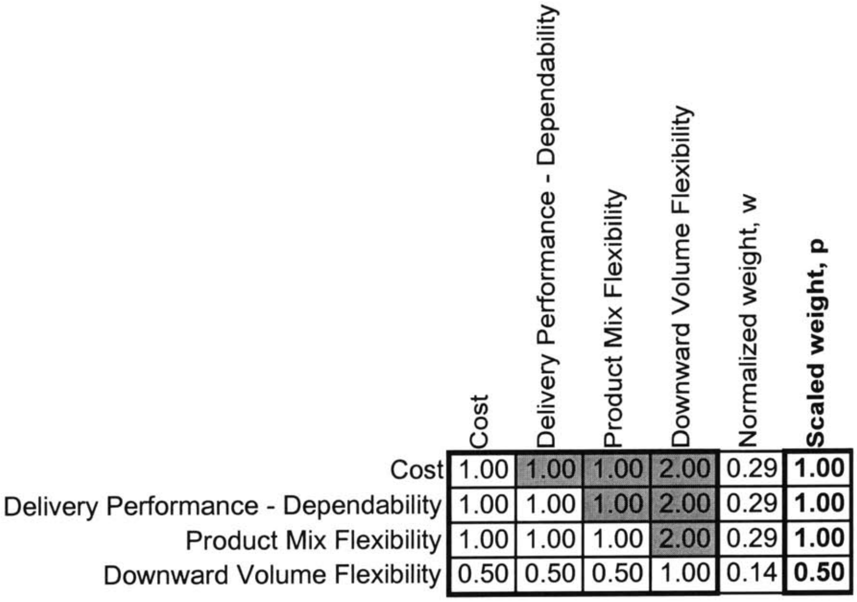
Some additional requirements were placed on the cell designs because the project was considered a "brown-field" design (i.e., it would use existing equipment and resources as opposed to being entirely new). Key requirements on the new system included the following:

- The new system would have to fit into the plant space taken up by the old system
- New system must continue to use recently purchased equipment
- The large furnaces that provide parts to the system cannot be moved

It was also desired that the new system be easier to schedule and control than the existing system. Table 9-3 summarizes the relevant strategic objectives and requirements for this example.

Table 9-3: Strategic objectives and requirements

	Aspect of strategy / requirement	How it applies
Strategic Objectives	Cost	Cost is critical to winning orders
	Quality	Expected to be unaffected by layout decisions
	Delivery Performance – Dependability	On-time delivery is critical
	Delivery Performance - Throughput Time	Not important to customer
	Product Mix Flexibility	Important due to uncertainty
	Volume Flex – Upwards	Not important; system is designed for peak demand
	Volume Flex – Downwards	Important due to uncertainty
	Innovativeness	Not important to customer
Req'ts	Investment	Specific amount of funding available for the project
	Ease of scheduling	Need to reduce the difficulty in scheduling production
	Floor space	Must fit in same floor space as existing system



	Cost	Delivery Performance - Dependability	Product Mix Flexibility	Downward Volume Flexibility	Normalized weight, w	**Scaled weight, p**
Cost	1.00	1.00	1.00	2.00	0.29	**1.00**
Delivery Performance - Dependability	1.00	1.00	1.00	2.00	0.29	**1.00**
Product Mix Flexibility	1.00	1.00	1.00	2.00	0.29	**1.00**
Downward Volume Flexibility	0.50	0.50	0.50	1.00	0.14	**0.50**

Consistency index: 0.00
Random index: 0.90
Consistency ratio: 0.00

Figure 9-18: Comparison matrix and the resulting weights and consistency measures

Creating the M^S mapping matrix

For this example, the general M^S matrix (shown in Appendix B-1) was used without modification, as it was thought to contain an accurate assessment of how the various FR/DP pairs related to the important strategic objectives.

Creating the M^R mapping matrix

As shown in Table 9-3, three additional requirements were defined based on investment, ease of scheduling, and floor space. Mapping was done to relate each of these requirements to the FR/DP pairs of the MSDD. Figure 9-19 shows the non-zero entries of the resulting M^R matrix. Creating this matrix was a straightforward process, as each requirement mapped to only a limited number of FR/DP pairs. In the case of investment and floor space, the MSDD contains a specific FR/DP pair to address the relevant issue. In the case of scheduling ease, two FR's, "Produce in sufficiently small run sizes" and "Eliminate information disruptions" were identified as being critical to achieving the requirement. Producing in large run sizes would mean that increased inventory would have to be stored and tracked, complicating the scheduling process. Failing to eliminate information disruptions would make scheduling more difficult in that the needed information might not be available to the production supervisor when the schedule is to be determined.

	Investment	Scheduling ease	Floorspace
Produce in sufficiently small run sizes		1.00	
Eliminate information disruptions		1.00	
Minimize facilities cost			1.00
Minimize investment over production system lifecycle	1.00		

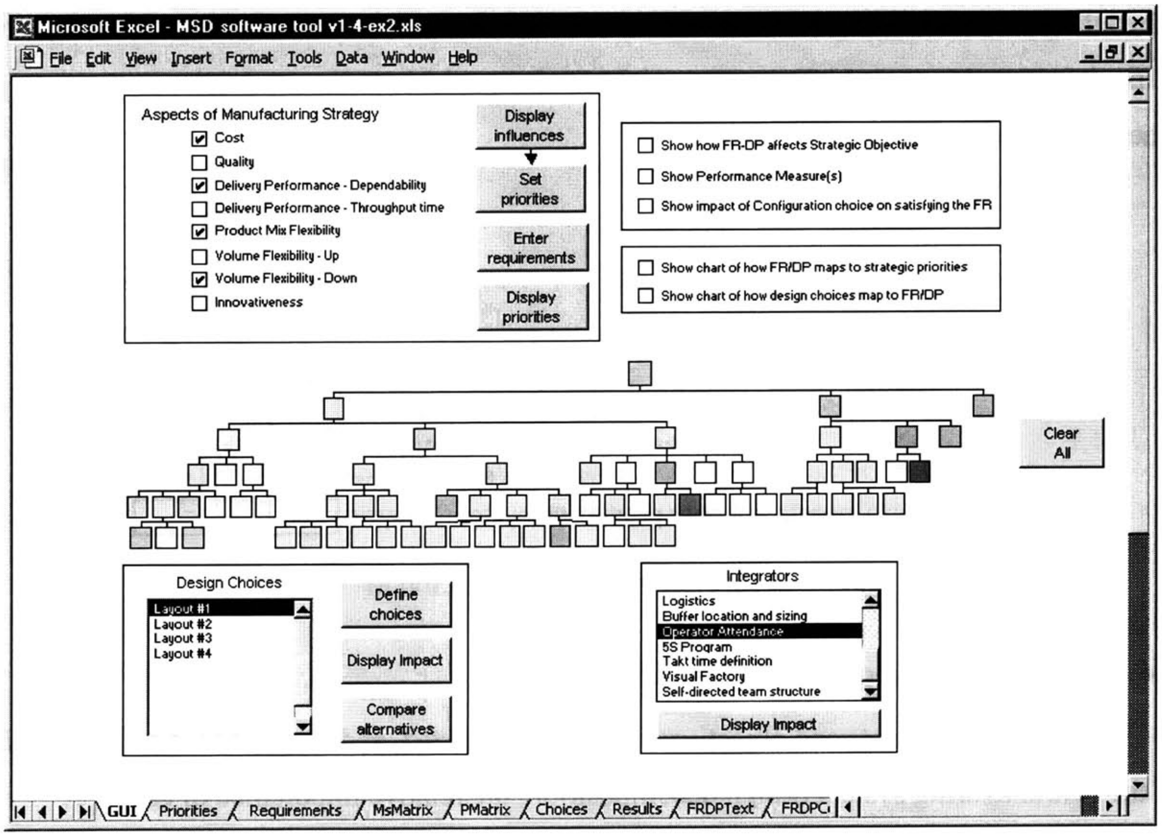
Figure 9-19: Non-zero portions of the M^R matrix

9.4.4 Step 2: Defining Effectiveness Measures

With the requirements and objectives defined, prioritized, and mapped to the FR/DP pairs of the manufacturing system design decomposition, the relative importance of each performance measure in the MSDD could be assessed, as described in section 8.2.2. Figure 9-20 shows the graphical results of this assessment as performed by the software tool. These results can also be viewed in matrix format in Appendix C. As in the previous example, it can be seen that performance measures from all areas of the MSDD have some relevance to the design problem. Table 9-4 shows the set of performance measures that had the highest overall importance and thus were best suited for evaluating and monitoring the performance of the various design alternatives.

Table 9-4: Important performance measures for the cell design example

PM-Q121	Number of defects per n parts caused by an operator's lack of understanding about methods
PM-P11	Number of occurrences of information disruptions
PM-P141	Number of occurrences of marketplace shortages
PM-T32	Actual run size - target run size
PM-I2	Amount of indirect labor required to schedule system
PM-123	Facilities cost
PM-13	Total investment over system life cycle
PM-T3	Inventory due to run size delay
PM-122	Amount of indirect labor required to manage / schedule system



Aspects of Manufacturing Strategy
- ☑ Cost
- ☐ Quality
- ☑ Delivery Performance - Dependability
- ☐ Delivery Performance - Throughput time
- ☑ Product Mix Flexibility
- ☐ Volume Flexibility - Up
- ☑ Volume Flexibility - Down
- ☐ Innovativeness

- ☐ Show how FR-DP affects Strategic Objective
- ☐ Show Performance Measure(s)
- ☐ Show impact of Configuration choice on satisfying the FR

- ☐ Show chart of how FR/DP maps to strategic priorities
- ☐ Show chart of how design choices map to FR/DP

Figure 9-20: Viewing the relative importance of the performance measures

9.4.5 Steps 3 and 4: Defining Behavior and Structure Models

Once the high-level objectives and requirements were identified, different concepts for cellular designs (i.e. different system structures) were generated and examined. The first issue addressed was which machines and operations would be included in the cellular design. Due to some constraints, it would be infeasible to include the entire gear manufacturing process within a cell. For example, all gears must be heat treated, and the existing heat treat furnaces are large, expensive, and have a throughput time of over 16 hours. It would not be feasible to incorporate such furnaces into a cell, nor would it be feasible to replace all of them with small, lower cycle time furnaces. Heat treatment takes place about half way through the manufacturing process; only operations taking place after the heat treat operation were considered in this example.

Once it was decided to examine all operations after heat treatment, cell design efforts focused on generating general cell concepts. This began by first determining the number of machines to be included for each operation, i.e., how to balance the cycle times of the machines in the cell. This proved to be a difficult problem, as the existing machines had a wide range of cycle times, ranging from 6 sec/part for the fastest operation (shot peening) all the way up to over 200 sec/part for the slowest (lapping). The ideal case would be for each cell to contain exactly one of each machine for each operation (so that each part passing through the cell would go through each machine), thus providing a very simple and clear material flow. Since, for example, grinding currently requires 14 machines running in parallel this would mean that there would have to be 14 cells, and 14 of each type of machine. However, the fastest operation, shot peen, currently is done on only 5 machines. This means that an "ideal" cellular layout would require the purchase of 9 new machines for this operation.

A number of alternative cell layouts were examined and from these, three different cell sizes were selected for further investigation (see Table 9-5). A schematic of a medium-sized cell is shown in Figure 9-21, showing the general layout including the number of machines for each operation (8 machines for lapping, for example). Next, various system alternatives were identified. For example, one possibility (Alternative #1) would be to have a system made up of several, small cells. Another alternative layout might use a combination of medium and large cells. Four such system designs were considered, and simulation analysis was used to determine the number of cells that would be required for each alternative to meet the required capacity for all product types. The results are shown in Table 9-6. These four system layouts were each examined in more detail to determine how well they could meet the desired objectives (reduction of work in process and throughput time, simplification of material handling, elimination of in-process sorting, and the ability to trace a defect back to the machine that caused it) while remaining feasible in terms of investment and running costs. Layouts for each concept were designed, and data was collected regarding machine cost, reliability, and cycle time. More information on this analysis can be found in (Cochran et al., 1998 and Taj et al., 1998).

Table 9-5: Different cell sizes

	Cell Size		
Operation	**Small**	**Medium**	**Large**
Microsizing	1	1	1
Shotpeen	1	1	1
Annealing	1	1	1
Straightening	1	1	2
Grinding	1	2	4
Lapping	4	8	16
Operators / Cell	1	1 to 2	1 to 3

Table 9-6: Gear manufacturing system alternative layouts

	Cells Required		
Cell Grouping	**Small**	**Medium**	**Large**
Layout #1	14		
Layout #2	4	5	
Layout #3		7	
Layout #4		3	2

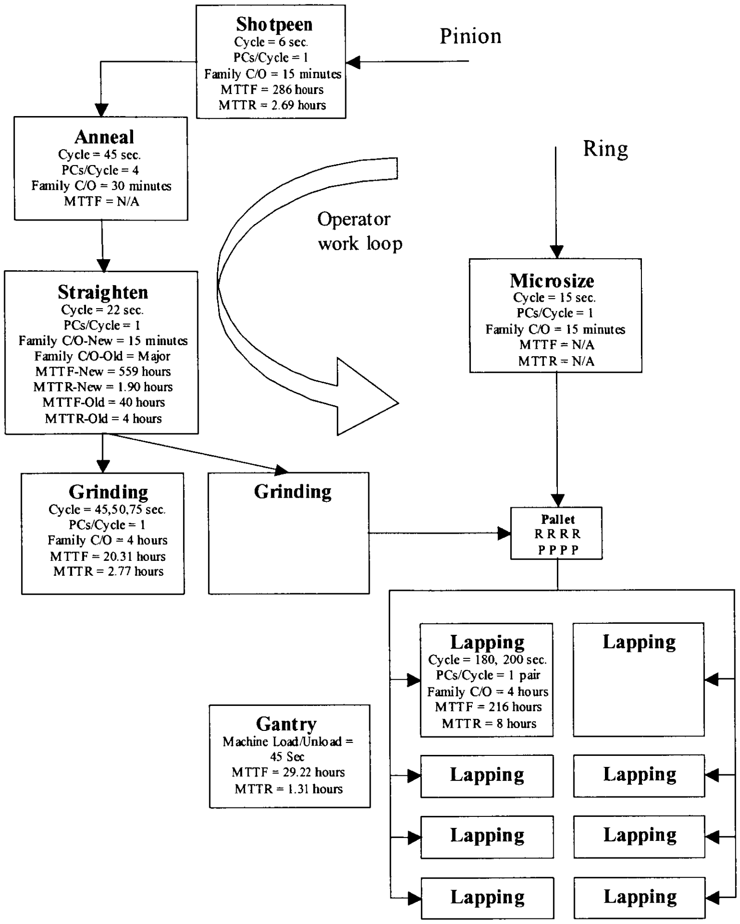


Figure 9-21: Schematic view of a medium-sized cell

These four system design alternatives were then compared in terms of their ability to satisfy the leaf FR's of the MSDD. Figure 9-22 shows the non-zero rows of the M^D matrix, i.e., those in which the system alternatives differed in their ability to satisfy the corresponding FR. For example, the design team identified that the larger cells would make it more difficult to identify the occurrence and source of a disruption (FR's R111 and R112), due to the higher number of machines running in parallel. The largest cells (those in layout #4) would also make it more difficult to produce in small run sizes (FR-T32), as changeovers would take significantly more effort than in the smaller cells. Smaller cells were found to have drawbacks as well, including an increase in required floor space (FR-123) as well as an increase in the required investment (FR-13).

	Layout #1	Layout #2	Layout #3	Layout #4
Identify disruptions when they occur	0.00	0.00	-0.33	-0.33
Identify disruptions where they occur	0.00	0.00	-0.33	-0.33
Service equipment regularly	1.00	0.00	-0.33	-1.00
Do not interrupt production for worker allowances	-1.00	-0.33	0.00	0.00
Define takt time(s)	1.00	0.00	-0.33	-1.00
Produce in sufficiently small run sizes	0.33	0.00	0.00	-1.00
Enable worker to operate more than one machine / station	-1.00	0.00	0.00	0.33
Improve effectiveness of production managers	0.50	0.00	0.00	-0.50
Eliminate information disruptions	0.33	0.00	0.00	-0.33
Minimize facilities cost	-0.50	-0.33	0.00	0.33
Minimize investment over production system lifecycle	-1.00	-0.33	0.33	1.00

Figure 9-22: Non-zero rows of the M^D matrix

9.4.6 Step 5: Trade-off analysis

Figure 9-23 below shows the results of the trade-off analysis (i.e., the multiplication of the matrices formed in steps 1-4). As in the previous example, negative numbers (shown in parenthesis in Figure 9-23) are used to indicate poor expected performance. Some clear trade-offs are shown to exist among the four alternative system layouts. Implementing a system with fewer, larger cells (layout 3 or 4) has the advantages of significantly reduced floor space and investment. These factors are critical in terms of the requirements placed on the system. However, layouts with fewer, larger cells can also be expected to have significant difficulties in terms of achieving strategic objectives such as product mix flexibility and the dependability of delivery performance. Layouts using smaller cells (layouts 1 and 2) are expected to perform better with regards to these two strategic objectives, but will also require increased floor space and investment as more machines will need to be purchased.

9.4.7 Interpreting the Results

Overall, it could be seen that no design alternative was expected to perform well with respect to the complete set of objectives and requirements. It was found that the designs of the existing machine tools and material handling equipment prevented the effective implementation of cellular manufacturing techniques. Large, inflexible machines resulted in poor ergonomics, inefficient operator workloops, and the inability to produce to the desired schedule in an affordable manner. Because the machines were not designed to have balanced cycle times, the required investment would not be used efficiently. The overall result was the determination that the next step should be to go back and re-examine the original design constraints (e.g., the scope of what could be changed and what had to remain as is). In order for a cellular system to be feasible, it was clear that certain improvements in the equipment would have to be made. For example, current changeover times are as long as 4 hours or more for some operations. Although most cells would be dedicated to a particular family of parts, one or two cells would be required to produce multiple part types. Poor reliability (uptimes of approximately 70%) was also a problem for the cells and efforts are currently underway to reduce unplanned downtime in these problem areas. One unexpected finding was that in some cases, changeover time for a machine's material handling was greater than the changeover time for the machine itself. For example, one set of CNC machines could be changed over quite rapidly (in minutes), except for the chutes that feed parts in and out of the machine. These chutes require hours of adjustment to change among even similar part types.

	Layout #1	Layout #2	Layout #3	Layout #4
Cost	0.01	(0.00)	(0.01)	(0.04)
Delivery Performance - Dependability	0.00	(0.01)	(0.04)	(0.07)
Product Mix Flexibility	0.05	0.00	(0.01)	(0.09)
Downward Volume Flexibility	(0.05)	0.00	(0.01)	0.00
	0.01	**(0.02)**	**(0.07)**	**(0.20)**

	Layout #1	Layout #2	Layout #3	Layout #4
Investment Requirement	(1.00)	(0.33)	0.33	1.00
Scheduling ease Requirement	0.33	0.00	0.00	(0.67)
Floorspace Requirement	(0.50)	(0.33)	0.00	0.33
	(1.17)	(0.66)	0.33	0.66

Figure 9-23: Results of the trade-off process

9.5 *Summary / Conclusions*

This chapter has shown two examples of how the proposed core manufacturing system design process can be applied to factory design problems in industry. These examples have illustrated the use of the process at different levels of detail. The first example showed how the design process could be used at a preliminary design stage to examine different manufacturing system configurations; the second example focused on the more detailed design of a particular design configuration, the lean cell.

Chapter 10 Conclusions

10.1 Summary and Conclusions

The ability to understand the impact of lower-level design decisions on the achievement of higher-level strategic objectives is critical for the effective design of manufacturing systems. Furthermore, the development of a set of performance measures in alignment with these strategic objectives is necessary to ensure that ongoing design improvement activities result in better manufacturing system performance with respect to the goals of the firm. This thesis has investigated how manufacturing systems can be designed to achieve the unique high-level strategic objectives of an organization and how performance measures can be derived to ensure that future system improvements support the firm's manufacturing strategy.

Unsatisfactory manufacturing system performance often has evolved as the result of a system design focus that is too localized, too narrow in scope, overly simplistic, or otherwise not aligned to the firm's overall manufacturing strategy. In many cases, the focus is on breaking a complex system into its more simple components and then analyzing each component separately. While this approach can be successful in cases where there is little interaction among the components, too much emphasis on individual components can also lead to solutions that may be locally optimal but that make up an overall system that is unable to meet the desired objectives.

To combat the problems caused by such local optimization, much effort has gone into investigating how to design manufacturing systems in a way that results in the many subsystems and components working together to achieve the overall goals. Unfortunately, the difficulties inherent in designing a manufacturing system are sometimes dealt with through the proposal of seemingly simple solutions. Terms such as "Just-in-time," and "lean" are used to represent generic solutions to contemporary manufacturing problems. These solutions are often presented as being simple, trade-off-free systems that can quickly and profoundly improve all aspects of operations. However, efforts to implement such systems have often met with much resistance and even complete failure and rejection in industry.

The work presented in this thesis has taken the view that designing a manufacturing system in a way that supports a specific set of strategic objectives is not a simple task and is not a task that can be accomplished by following just a few simple rules. The view taken here is that trade-offs will always exist in manufacturing system design, and that the best a firm can do is to clearly define a manufacturing strategy (i.e., a plan for how to create and maintain a competitive advantage) and then carefully and consistently make decisions and trade-offs that are consistent with this vision.

This thesis has presented a design approach based on the principles of systems engineering to help managers and engineers better understand the relationships between a firm's manufacturing strategy, its performance measurement system, and its manufacturing system design. The overall goal of this approach is to facilitate the design of manufacturing systems aligned to high-level objectives. This system design process begins with the identification and prioritization of relevant dimensions of manufacturing performance (cost, quality, delivery performance, etc.). Next, performance measures are developed concurrently with various possible models of system behavior and structure (i.e., design alternatives). Trade-offs among these design alternatives are examined, enabling designers to select the most appropriate feasible alternative and to identify opportunities for improvements. The result of the trade-off analysis is a comparison matrix that gives designers an understanding of the advantages and disadvantages of each alternative being considered with respect to each important aspect of strategy and to each requirement. This information is provided in a way that allows designs not just to rank the design alternatives in terms of their expected performance but also gives designers a way to identify the root causes of performance differences, to recognize areas of difficulty, and to generate ideas for improvements.

The manufacturing system design decomposition, a general set of requirements and design elements for a manufacturing system design, was used as a tool to aid in this trade-off analysis process. This decomposition, developed using axiomatic design, provides a structure for understanding the relationships between high-level system objectives and lower level design decisions, for understanding the interrelations among various elements of a system design, and for communicating this information to a group of designers. Using this decomposition as part of the system design process forces designers to consider a wide variety of both high and low-level requirements and to take these factors into account when making design decisions.

A software tool was also developed to assist designers in managing, visualizing, and communicating the information required for this trade-off analysis. Examples of the application of this process to the design of manufacturing systems at an automotive component supplier were reviewed. These examples show the value of this approach in terms of providing an understanding of how lower-level design decisions can impact a firm's ability to achieve its high-level strategic objectives and in terms of helping designers develop a set of performance measures that is aligned to these objectives.

10.2 Recommendations for Future Work

The manufacturing system design process developed in this thesis was created to provide a means for designers to relate low-level decisions to high-level objectives and to help designers in developing a set of performance measures aligned to these objectives. As these are broad objectives, much room remains for future enhancements and additions to the core process proposed here. This section presents an overview of potential areas of future research that could enhance the approach described in this thesis for linking strategy and performance measurement to manufacturing system design.

10.2.1 The Manufacturing System Design Decomposition

The MSDD was found to be a valuable tool for representing a diverse set of requirements, design parameters, and performance measures. It also provides important information regarding the interrelationships among these requirements, and provided a useful structure to the trade-off analysis defined in this thesis. Ongoing efforts to update and improve this decomposition can make it even more valuable tool for manufacturing system design. Specifically research aimed at validating and quantifying the relationships described in the MSDD can help to make using it a more objective and repeatable process. Case study research of factories from different industries can be used to assess the accuracy and strength of the various precedence relationships expressed in the design matrices of the MSDD. For example, according to the MSDD, factories exhibiting strong performance with respect to delivery performance in terms of throughput time should also perform well in terms of conformance quality and delivery performance reliability, as these FR's are shown to affect a system's ability to achieve reduced throughput time. Surveys of existing factories could be studied to quantify the extent to which these proposed relationships hold true in industry.

Similarly, quantitative analysis techniques could be used to develop more detailed information regarding the fundamental relationships between the FR's and DP's. This thesis contains some preliminary efforts towards this end, in terms of the quantification of the different types of delays in the absence of quality or time variation. Enhancements to these equations to include the effects of variability would help to provide a more numerical background to the MSDD and would help in relating the concepts of the FR/DP pairs to more traditional work in operations research and production management.

10.2.2 Manufacturing Strategy

The manufacturing system design process presented in this thesis begins with the definition and prioritization of the relevant aspects of strategy. Techniques developed for Quality Function Deployment can then be used to develop mapping matrices to identify which of the FR's of the manufacturing system design decomposition lead to the achievement of the strategic objectives and also to begin to quantify these relationships. Further research focused on alternative methods for evaluating these relationships could lead to a more objective and repeatable process.

Continued work could also be done to examine the specific relationships between satisfying the FR's and achieving the strategic objectives. As part of the research described in this thesis, these relationships were discussed with other students in the research group as well as researchers from other universities. It was found that a majority of the relationships were more or less universally accepted. Other relationships, however, were less obvious and subject to more debate. Continuing to further define and describe the nature of each relationship through discussion with other researchers could lead to a more objective mapping from the FR/DP's to each aspect of strategy.

In the literature on manufacturing strategy, several commonly occurring strategies have been identified as described in Chapter 2. Examples include market-intensive firms, technology-driven firms, etc. This information could be used to develop predefined sets of priorities that could be used by designers as a starting point in the manufacturing system design process. That is, designers from a market-intensive firm could use a predefined set of priorities as a convenient starting point for discussion.

10.2.3 Performance Measurement

A set of performance measures can be developed by assessing the relative importance of each FR/DP pair in the MSDD and then selecting the predefined measures corresponding to the most important FR's and DP's. While this set of measures is useful as a starting point for a performance measurement system, it is by no means complete. Further research investigating different techniques for converting this initial set of PM's into a functioning performance measurement system would be a valuable addition to the work presented here. Further research on how these measures can be integrated into an enterprise-wide performance measurement system such as a balanced scorecard approach would also be of value.

One criticism of the performance measures associated with the MSDD is that many of them are difficult to measure in practice. More detailed study of the data required for these measurements and the development of means for capturing this data could help to ease the process of implementing these measures.

10.2.4 Behavior and Structure Modeling

Modeling of manufacturing system structure and behavior was not a primary focus of the research presented here. Many techniques exist for modeling system structure, including object-oriented methods, computer simulation, analytical models, etc. This thesis presented one example of how simulation analysis can be used to support the proposed process for trade-off analysis; other methods could be examined in a similar fashion to determine how such quantitative models can contribute to the systems engineering process proposed here.

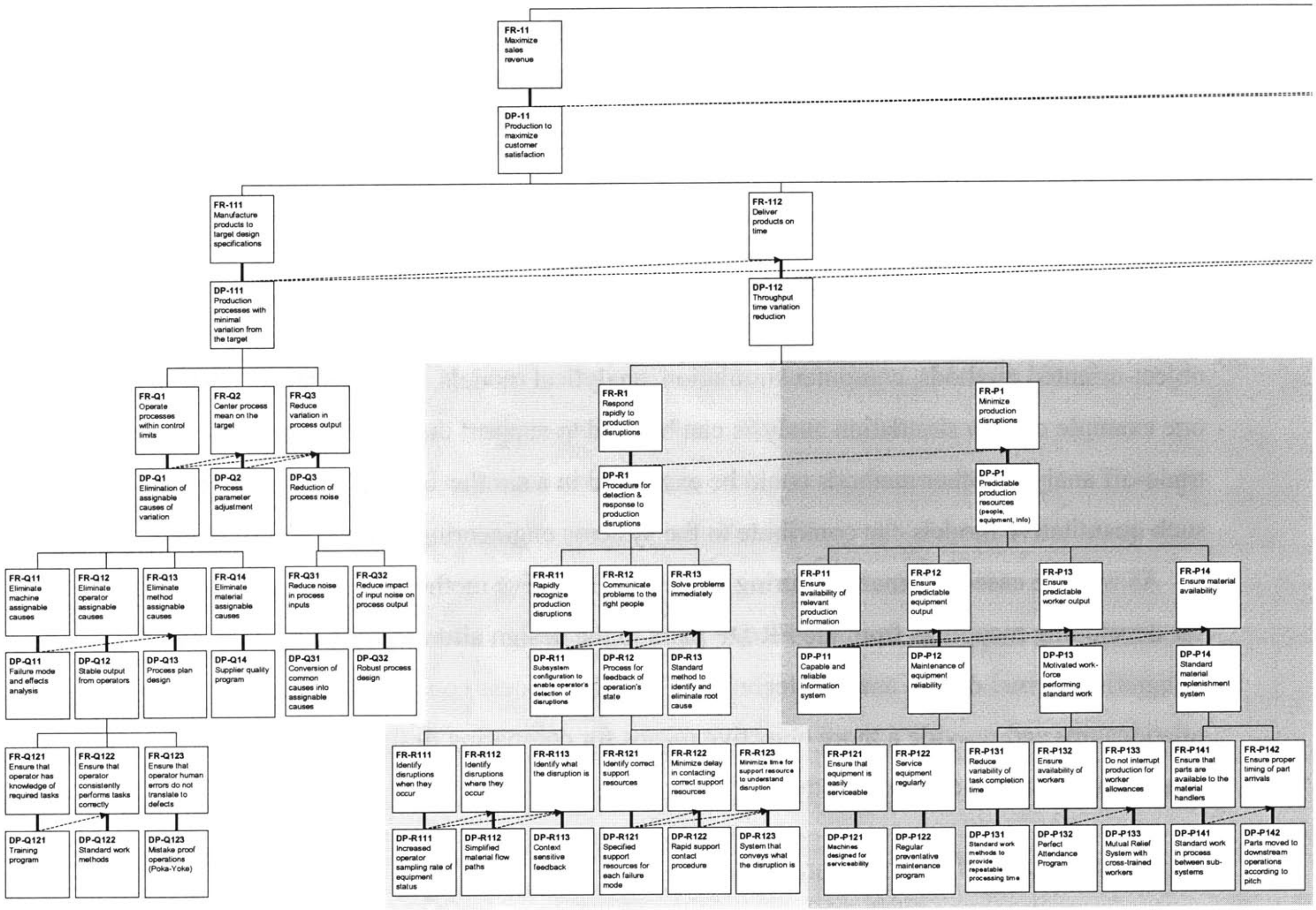
As was the case with manufacturing strategy, qualitative methods are currently necessary for developing mappings from the FR/DP pairs to the design alternatives being considered. Integrating formal design analysis techniques into the process could help to quantify these relationships and provide a more objective means for comparing design alternatives and examining the trade-offs among them.

10.2.5 Summary of Recommendations

Essentially, the primary area suggested for future research is the further quantification of the many relationships that must be examined in order to design a manufacturing system. This research has made initial attempts towards this end, but the potential for further improvements remains. Perhaps the most effective method for better understanding these relationships as well as other opportunities for improvement is through further use of the proposed process, as each implementation presents a unique opportunity to learn more about both the manufacturing system being designed and the tools used to do so.

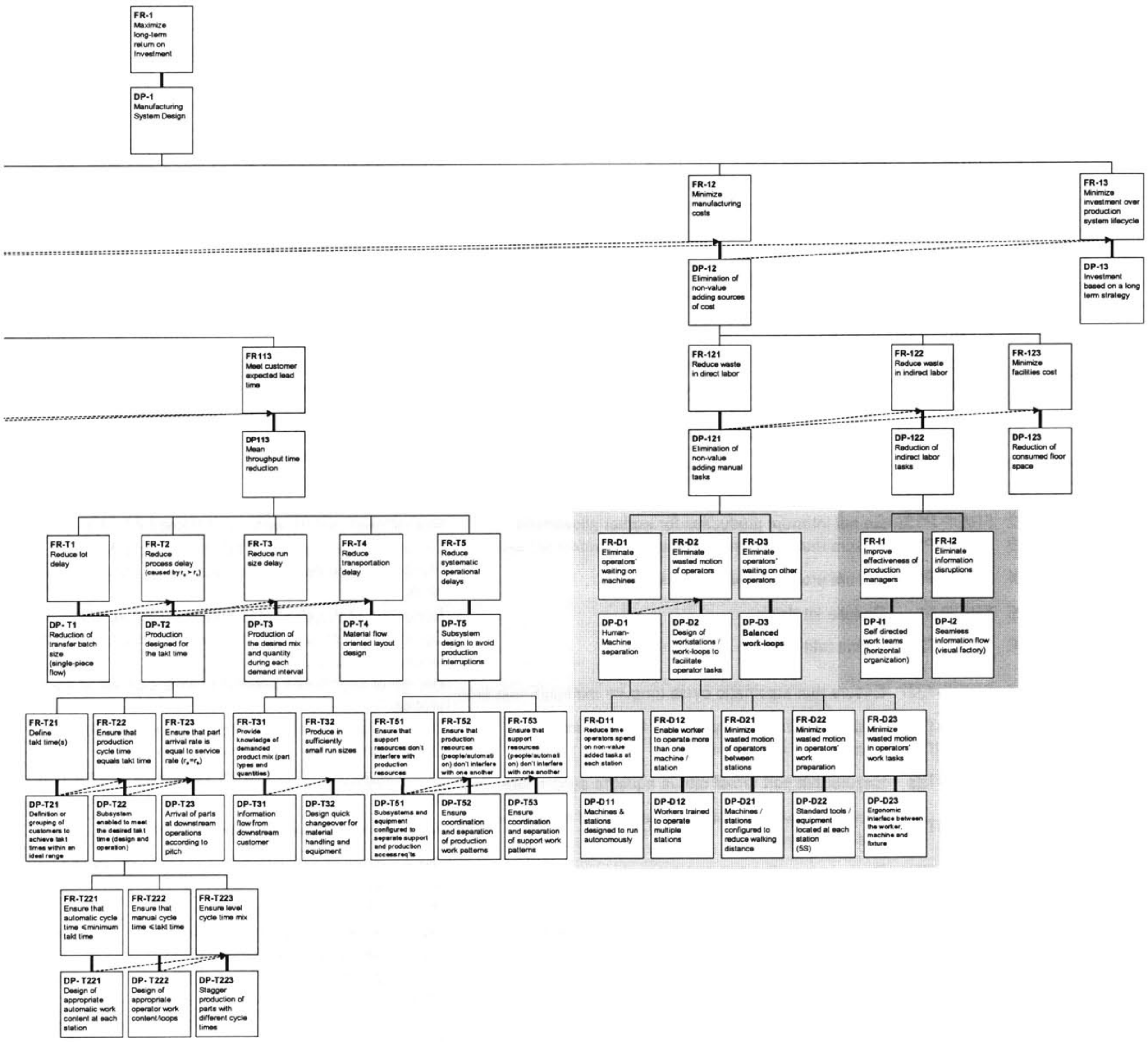
Appendix A

A-1: Manufacturing System Design Decomposition (page 1 of 2)



Manufacturing System Design Decomposition v5.1," Production System Design Lab, Director: Professor David S. Cochran, Massachusetts Institute of Technology, 2000.

Manufacturing System Design Decomposition (page 2 of 2)



A-2: Leaf FR/DP pairs

		FR	DP
1	FR/DP-Q11	Eliminate machine assignable causes	Failure mode and effects analysis
2	FR/DP-Q121	Ensure that operator has knowledge of required tasks	Training program
3	FR/DP-Q122	Ensure that operator consistently performs tasks correctly	Standard work methods
4	FR/DP-Q123	Ensure that operator human errors do not translate to defects	Mistake proof operations (Poka-Yoke)
5	FR/DP-Q13	Eliminate method assignable causes	Process plan design
6	FR/DP-Q14	Eliminate material assignable causes	Supplier quality program
7	FR/DP-Q2	Center process mean on the target	Process parameter adjustment
8	FR/DP-Q31	Reduce noise in process inputs	Conversion of common causes into assignable causes
9	FR/DP-Q32	Reduce impact of input noise on process output	Robust process design
10	FR/DP-R111	Identify disruptions when they occur	Increased operator sampling rate of equipment status
11	FR/DP-R112	Identify disruptions where they occur	Simplified material flow paths
12	FR/DP-R113	Identify what the disruption is	Context sensitive feedback
13	FR/DP-R121	Identify correct support resources	Specified support resources for each failure mode
14	FR/DP-R122	Minimize delay in contacting correct support resources	Rapid support contact procedure
15	FR/DP-R123	Minimize time for support resource to understand disruption	System that conveys what the disruption is
16	FR/DP-R13	Solve problems immediately	Standard method to identify and eliminate root cause
17	FR/DP-P11	Ensure availability of relevant production information	Capable and reliable information system
18	FR/DP-P121	Ensure that equipment is easily serviceable	Machines designed for serviceability
19	FR/DP-P122	Service equipment regularly	Regular preventative maintenance program
20	FR/DP-P131	Reduce variability of task completion time	Standard work methods to provide repeatable processing time
21	FR/DP-P132	Ensure availability of workers	Perfect attendance program
22	FR/DP-P133	Do not interrupt production for worker allowances	Mutual relief system with cross-trained workers
23	FR/DP-P141	Ensure that parts are available to the material handlers	Standard work in process between sub-systems
24	FR/DP-P142	Ensure proper timing of part arrivals	Parts moved to downstream operations according to pitch
25	FR/DP-T1	Reduce lot delay	Reduction of transfer batch size (single-piece flow)
26	FR/DP-T21	Define takt time(s)	Definition or grouping of customers to achieve takt times within an ideal range
27	FR/DP-T221	Ensure that automatic cycle time <= minimum takt time	Design of appropriate automatic work content at each station
28	FR/DP-T222	Ensure that manual cycle time <= takt time	Design of appropriate operator work content/loops
29	FR/DP-T223	Ensure level cycle time mix	Stagger production of parts with different cycle times
30	FR/DP-T23	Ensure that part arrival rate is equal to service rate	Arrival of parts at downstream operations according to pitch
31	FR/DP-T31	Provide knowledge of demanded product mix (part types and quantities)	Information flow from downstream customer
32	FR/DP-T32	Produce in sufficiently small run sizes	Design quick changeover for material handling and equipment
33	FR/DP-T4	Reduce transportation delay	Material flow oriented layout design
34	FR/DP-T51	Ensure that support activities don't interfere with production activities	Subsystems and equipment configured to separate support and production access req'ts
35	FR/DP-T52	Ensure that production activities don't interfere with one another	Ensure coordination and separation of production work patterns
36	FR/DP-T53	Ensure that support activities (people/automation) don't interfere with one another	Ensure coordination and separation of support work patterns
37	FR/DP-D11	Reduce time operators spend on non-value added tasks at each station	Machines & stations designed to run autonomously
38	FR/DP-D12	Enable worker to operate more than one machine / station	Train the workers to operate multiple stations
39	FR/DP-D21	Minimize wasted motion of operators between stations	Configure machines / stations to reduce walking distance
40	FR/DP-D22	Minimize wasted motion in operators' work preparation	Standard tools / equipment located at each station (5S)
41	FR/DP-D23	Minimize wasted motion in operators' work tasks	Ergonomic interface between the worker, machine and fixture
42	FR/DP-D3	Elminate operators' waiting on other operators	Balanced work-loops
43	FR/DP-I1	Improve effectiveness of production managers	Self directed work teams (horizontal organization)
44	FR/DP-I2	Eliminate information disruptions	Seamless information flow (visual factory)
45	FR/DP-123	Minimize facilities cost	Reduction of consumed floor space
46	FR/DP-13	Minimize investment over production system lifecycle	Investment based on a long term system strategy

Appendix B

B-1: A general form of the M^S matrix

An interaction matrix showing the general relationships between FR/DP pairs and the aspects of manufacturing strategy

	Eliminate machine assignable causes	Ensure that operator has knowledge of required tasks	Ensure that operator consistently performs tasks correctly	Ensure that operator human errors do not translate to defects	Eliminate method assignable causes	Eliminate material assignable causes	Center process mean on the target	Reduce noise in process inputs	Reduce impact of input noise on process output	Identify disruptions when they occur	Identify disruptions where they occur	Identify what the disruption is	Identify correct support resources	Minimize delay in contacting correct support resources	Minimize time for support resource to understand disruption	Solve problems immediately	Ensure availability of relevant production information	Ensure that equipment is easily serviceable	Service equipment regularly	Reduce variability of task completion time	Ensure availability of workers	Do not interrupt production for worker allowances	Ensure that parts are available to the material handlers	Ensure proper timing of part arrivals	Reduce lot delay	Define takt time(s)	Ensure that automatic cycle time <= minimum takt time	Ensure that manual cycle time <= takt time	Ensure level cycle time mix	Ensure that part arrival rate is equal to service rate	Provide knowledge of demanded product mix (part types and quantities)	Produce in sufficiently small run sizes	Reduce transportation delay	Ensure that support activities don't interfere with production activities	Ensure that production activities don't interfere with one another	Ensure that support activities (people/automation) don't interfere with one another	Reduce time operators spend on non-value added tasks at each station	Enable worker to operate more than one machine / station	Minimize wasted motion of operators between stations	Minimize wasted motion in operators' work preparation	Minimize wasted motion in operators' work tasks	Elminate operators' waiting on other operators	Improve effectiveness of production managers	Eliminate information disruptions	Minimize facilities cost	Minimize investment over production system lifecycle
Cost	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Quality	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00																																					
Delivery Performance Dependability	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00																						
Delivery Performance Throughput Time	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00										
Product Mix Flexibility	1.00	1.00		1.00	1.00						0.33						1.00						1.00		1.00	0.33	0.33	0.33	1.00	0.00	1.00	1.00		0.33						0.33	0.33	0.33		1.00		1.00
Upward Volume Flexibility																								1.00		0.33	1.00	1.00											1.00			0.33			0.33	0.33
Downward Volume Flexibility		1.00																								0.33		1.00									1.00	1.00	1.00			0.33				
Innovativeness	1.00	1.00	0.33	0.33	1.00		0.33	0.33	0.33														1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00			0.33			1.00	1.00

B-2: M^S matrix for the axle-manufacturing system design example

	Eliminate machine assignable causes	Ensure that operator has knowledge of required tasks	Ensure that operator consistently performs tasks correctly	Ensure that operator human errors do not translate to defects	Eliminate method assignable causes	Eliminate material assignable causes	Center process mean on the target	Reduce noise in process inputs	Reduce impact of input noise on process output	Identify disruptions when they occur	Identify disruptions where they occur	Identify what the disruption is	Identify correct support resources	Minimize delay in contacting correct support resources	Minimize time for support resource to understand disruption	Solve problems immediately	Ensure availability of relevant production information	Ensure that equipment is easily serviceable	Service equipment regularly	Reduce variability of task completion time	Ensure availability of workers	Do not interrupt production for worker allowances	Ensure that parts are available to the material handlers	Ensure proper timing of part arrivals	Reduce lot delay	Define takt time(s)	Ensure that automatic cycle time <= minimum takt time	Ensure that manual cycle time <= takt time	Ensure level cycle time mix	Ensure that part arrival rate is equal to service rate	Provide knowledge of demanded product mix (part types and quantities)	Produce in sufficiently small run sizes	Reduce transportation delay	Ensure that support activities don't interfere with production activities	Ensure that production activities don't interfere with one another	Ensure that support activities (people/automation) don't interfere with one another	Reduce time operators spend on non-value added tasks at each station	Enable worker to operate more than one machine / station	Minimize wasted motion of operators between stations	Minimize wasted motion in operators' work preparation	Minimize wasted motion in operators' work tasks	Elminate operators' waiting on other operators	Improve effectiveness of production managers	Eliminate information disruptions	Minimize facilities cost	Minimize investment over production system lifecycle
Cost	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	**0.00**	0.33	**0.00**	**0.00**	0.33	0.33	0.33	0.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Quality	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00																																					
Delivery Performance Dependability	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	**0.33**	**0.33**	1.00	**0.33**	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00																						
Delivery Performance Throughput Time	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00										
Product Mix Flexibility	1.00	1.00		1.00	1.00						0.33						1.00						1.00	0.00	1.00	0.33	0.33	0.33	1.00		1.00	1.00		0.33						0.33	0.33	0.33		1.00		1.00
Upward Volume Flexibility																								1.00		0.33	1.00	1.00											1.00			0.33			0.33	**1.00**
Downward Volume Flexibility		1.00																								0.33		1.00									1.00	1.00	1.00			0.33				
Innovativeness	1.00	1.00	0.33	0.33	1.00		0.33	0.33	0.33														1.00	1.00	1.00	1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	1.00	1.00		1.00	1.00			0.33			1.00	1.00

B-3: Text descriptions of the general FR/DP – Strategy relationships

FR	**DP**	**affects cost in terms of**	**affects quality as delivered by the**	**affects dependability of delivery performance in that**	**affects throughput time in that**
Eliminate machine assignable causes	Failure mode and effects analysis	the engineering time necessar to do the analysis and implement improvements, and the cost of making defective parts	**machine**	poor quality yields make the system output less predictable and require higher inventory levels	poor quality yields make the system output less predictable and require higher inventory levels
Ensure that operator has knowledge of required tasks	Training program	the costs associated with training operators, and the cost of making defective parts	**operator**	poor quality yields make the system output less predictable and require higher inventory levels	poor quality yields make the system output less predictable and require higher inventory levels
Ensure that operator consistently performs tasks correctly	Standard work methods	industrial engineering time and cost of developing standard work methods, and the cost of making defective parts	**operator and method**	poor quality yields make the system output less predictable and require higher inventory levels	poor quality yields make the system output less predictable and require higher inventory levels
Ensure that operator human errors do not translate to defects	Mistake proof operations (Poka-Yoke)	the cost of designing and implementing poka-yoke devices, and the cost of making defective parts	**operator**	poor quality yields make the system output less predictable and require higher inventory levels	poor quality yields make the system output less predictable and require higher inventory levels
Eliminate method assignable causes	Process plan design	the process plan impacting running costs, and the cost of making defective parts	**machine and method**	poor quality yields make the system output less predictable and require higher inventory levels	poor quality yields make the system output less predictable and require higher inventory levels
Eliminate material assignable causes	Supplier quality program	the costs of establishing such a program, and the cost of making defective parts	**material**	poor quality yields make the system output less predictable and require higher inventory levels	poor quality yields make the system output less predictable and require higher inventory levels
Center process mean on the target	Process parameter adjustment	quality engineering costs, and the cost of making defective parts	**method**	poor quality yields make the system output less predictable and require higher inventory levels	poor quality yields make the system output less predictable and require higher inventory levels
Reduce noise in process inputs	Conversion of common causes into assignable causes	cost of defective parts	**process inputs**	poor quality yields make the system output less predictable and require higher inventory levels	poor quality yields make the system output less predictable and require higher inventory levels
Reduce impact of input noise on process output	Robust process design	cost of defective parts	**process inputs**	poor quality yields make the system output less predictable and require higher inventory levels	poor quality yields make the system output less predictable and require higher inventory levels
Identify disruptions when they occur	Increased operator sampling rate of equipment status	logistics and material handling costs, and costs associated with the waste of resources due to unidentified disruptions		**disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory**	disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory
Identify disruptions where they occur	Simplified material flow paths	the information system required		**disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory**	disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory
Identify what the disruption is	Context sensitive feedback	the cost of the equipment's controls		**disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory**	disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory

FR	DP	affects cost in terms of	affects quality as delivered by the	affects dependability of delivery performance in that	affects throughput time in that
Identify correct support resources	Specified support resources for each failure mode	the information system required		**disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory**	disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory
Minimize delay in contacting correct support resources	Rapid support contact procedure	the information system required		**disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory**	disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory
Minimize time for support resource to understand disruption	System that conveys what the disruption is	the information system required		**disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory**	disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory
Solve problems immediately	Standard method to identify and eliminate root cause	industrial engineering and training costs		**disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory**	disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory
Ensure availability of relevant production information	Capable and reliable information system	the information system required		**disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory**	disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory
Ensure that equipment is easily serviceable	Machines designed for serviceability	logistics and material handling costs		**long machine downtimes create the need for higher levels of inventory**	long machine downtimes create the need for higher levels of inventory
Service equipment regularly	Regular preventative maintenance program	logistics and material handling costs		**unexpected downtime makes the system output less predictable and creates the need for higher inventory levels**	unexpected downtime makes the system output less predictable and creates the need for higher inventory levels
Reduce variability of task completion time	Standard work methods to provide repeatable processing time	industrial engineering and training costs		**disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory**	disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory
Ensure availability of workers	Perfect attendance program	labor costs		**disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory**	disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory
Do not interrupt production for worker allowances	Mutual relief system with cross-trained workers	training costs		**disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory**	disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory
Ensure that parts are available to the material handlers	Standard work in process between sub-systems	transportation, logistics, and inventory costs		**part shortages would lead to unmet demand**	part shortages would lead to unmet demand
Ensure proper timing of part arrivals	Parts moved to downstream operations according to pitch	transportation, logistics, and inventory costs		**part shortages would lead to unmet demand**	part shortages would lead to unmet demand

FR	DP	affects cost in terms of	affects quality as delivered by the	affects dependability of delivery performance in that	affects throughput time in that
Reduce lot delay	Reduction of transfer batch size (single-piece flow)	transportation, logistics, and inventory costs			**large lot sizes increase the amount of WIP and, therefore, the throughput time**
Define takt time(s)	Definition or grouping of customers to achieve takt times within an ideal range	the cost of equipment and the number of machines required			**if production is not aligned to customers, inventory levels and throughput time will increase**
Ensure that automatic cycle time <= minimum takt time	Design of appropriate automatic work content at each station	equipment design and cost			**demand can not be met if this requirement is not satisfied**
Ensure that manual cycle time <= takt time	Design of appropriate operator work content/loops	industrial engineering costs			**demand can not be met if this requirement is not satisfied**
Ensure level cycle time mix	Stagger production of parts with different cycle times	information system			**demand can not be met if this requirement is not satisfied**
Ensure that part arrival rate is equal to service rate	Arrival of parts at downstream operations according to pitch	logistics and material handling costs			**disruptions to the flow of material make the system output less predictable and create the need for higher levels of inventory**
Provide knowledge of demanded product mix (part types and quantities)	Information flow from downstream customer	information system			**production can not be matched to demand if this information is not known**
Produce in sufficiently small run sizes	Design quick changeover for material handling and equipment	equipment cost			**large run sizes increase the amount of WIP and, therefore, the throughput time**
Reduce transportation delay	Material flow oriented layout design	transportation, logistics, and inventory costs			**large transportation times increase the amount of WIP and, therefore, the throughput time**
Ensure that support activities don't interfere with production activities	Subsystems and equipment configured to separate support and production access req'ts	equipment cost			**these delays would interrupt material flow and delay part processing**
Ensure that production activities don't interfere with one another	Ensure coordination and separation of production work patterns	equipment cost			**these delays would interrupt material flow and delay part processing**
Ensure that support activities (people/automation) don't interfere with one another	Ensure coordination and separation of support work patterns	transportation, logistics, and inventory costs			**these delays would interrupt material flow and delay part processing**

FR	DP	affects cost in terms of	affects quality as delivered by the	affects dependability of delivery performance in that	affects throughput time in that
Reduce time operators spend on non-value added tasks at each station	Machines & stations designed to run autonomously	**equipment design and configuration, and labor costs**			
Enable worker to operate more than one machine / station	Train the workers to operate multiple stations	**training and labor costs**			
Minimize wasted motion of operators between stations	Configure machines / stations to reduce walking distance	**equipment design and configuration, and labor costs**			
Minimize wasted motion in operators' work preparation	Standard tools / equipment located at each station (5S)	**tooling costs and labor costs**			
Minimize wasted motion in operators' work tasks	Ergonomic interface between the worker, machine and fixture	**equipment design and configuration, and labor costs**			
Elminate operators' waiting on other operators	Balanced work-loops	**industrial engineering costs and direct labor costs**			
Improve effectiveness of production managers	Self directed work teams (horizontal organization)	**training costs and indirect labor costs**			
Eliminate information disruptions	Seamless information flow (visual factory)	**information system and indirect labor costs**			
Minimize facilities cost	Reduction of consumed floor space	**facilities costs**			
Minimize investment over production system lifecycle	Investment based on a long term system strategy	**investment costs**			

FR	**DP**	**affects product mix flexibility, in that**	**affects upward volume flexibility, in that**	**affects downward volume flexibility, in that**	**affects innovativeness, in terms of the ability to**
Eliminate machine assignable causes	Failure mode and effects analysis	**equipment design affects setup time**			**rapidly adopt new process technologies and adapt to new product designs**
Ensure that operator has knowledge of required tasks	Training program	**training affects how easily workers adapt to changes in work content from one part type to the next**		**operators must be trained for multiple work routines**	**operators must be trained to process the new product or to run the new equipment**
Ensure that operator consistently performs tasks correctly	Standard work methods				update standard work methods for new products / processes
Ensure that operator human errors do not translate to defects	Mistake proof operations (Poka-Yoke)	**mistake proofing devices must be able to handle multiple part types and must prevent the operator from making errors due to model mix**			mistake-proof new products / processes
Eliminate method assignable causes	Process plan design	**process plan could affect changeover time**			**rapidly adopt new process technologies**
Eliminate material assignable causes	Supplier quality program				
Center process mean on the target	Process parameter adjustment				ensure quality of new products / processes
Reduce noise in process inputs	Conversion of common causes into assignable causes				ensure quality of new products / processes
Reduce impact of input noise on process output	Robust process design				ensure quality of new products / processes
Identify disruptions when they occur	Increased operator sampling rate of equipment status				
Identify disruptions where they occur	Simplified material flow paths	having fewer material flow paths limits the flexibility to route parts through different machines			
Identify what the disruption is	Context sensitive feedback				
Identify correct support resources	Specified support resources for each failure mode				
Minimize delay in contacting correct support resources	Rapid support contact procedure				
Minimize time for support resource to understand disruption	System that conveys what the disruption is				
Solve problems immediately	Standard method to identify and eliminate root cause				

FR	**DP**	**affects product mix flexibility, in that**	**affects upward volume flexibility, in that**	**affects downward volume flexibility, in that**	**affects innovativeness, in terms of the ability to**
Ensure availability of relevant production information	Capable and reliable information system	**operators must know what mix to make**			
Ensure that equipment is easily serviceable	Machines designed for serviceability				
Service equipment regularly	Regular preventative maintenance program				
Reduce variability of task completion time	Standard work methods to provide repeatable processing time				
Ensure availability of workers	Perfect attendance program				
Do not interrupt production for worker allowances	Mutual relief system with cross-trained workers				
Ensure that parts are available to the material handlers	Standard work in process between sub-systems	**it is necessary to have multiple part types available**			**rapidly introduce new products**
Ensure proper timing of part arrivals	Parts moved to downstream operations according to pitch		**the material handling system must provide parts at the desired rate**		**rapidly introduce new products**
Reduce lot delay	Reduction of transfer batch size (single-piece flow)	**large transfer batches are associated with large run sizes if different part types are transported separately**			**rapidly introduce new products**
Define takt time(s)	Definition or grouping of customers to achieve takt times within an ideal range	the grouping of customers and equipment affects routing flexibility	the amount of volume flexibility needed will depend on how the customers are grouped	the amount of volume flexibility needed will depend on how the customers are grouped	**rapidly adopt new process technologies and intordure new products**
Ensure that automatic cycle time <= minimum takt time	Design of appropriate automatic work content at each station	if model c/o time >0, mix flexibility becomes related to capacity	**the automatic cycle time could limit capacity**		**rapidly introduce new products**
Ensure that manual cycle time <= takt time	Design of appropriate operator work content/loops	if model c/o time >0, mix flexibility becomes related to capacity	**the manual cycle time could limit capacity**	**the manual cycle time could limit capacity**	**rapidly introduce new products**
Ensure level cycle time mix	Stagger production of parts with different cycle times	**the system must be able to produce the parts in the desired sequence**			**rapidly introduce new products**
Ensure that part arrival rate is equal to service rate	Arrival of parts at downstream operations according to pitch				
Provide knowledge of demanded product mix (part types and quantities)	Information flow from downstream customer	**operators must know what to make**			**rapidly introduce new products**
Produce in sufficiently small run sizes	Design quick changeover for material handling and equipment	**low c/o times are critical for high mix flexibility**			**rapidly introduce new products**

FR	DP	affects product mix flexibility, in that	affects upward volume flexibility, in that	affects downward volume flexibility, in that	affects innovativeness, in terms of the ability to
Reduce transportation delay	Material flow oriented layout design				**rapidly introduce new products**
Ensure that support activities don't interfere with production activities	Subsystems and equipment configured to separate support and production access req'ts	production may or may not be able to continue during changeover			**rapidly introduce new products**
Ensure that production activities don't interfere with one another	Ensure coordination and separation of production work patterns				**rapidly introduce new products**
Ensure that support activities (people/automation) don't interfere with one another	Ensure coordination and separation of support work patterns				**rapidly introduce new products**
Reduce time operators spend on non-value added tasks at each station	Machines & stations designed to run autonomously			**if workers are tied to stations, the labor costs will not go down as volumes decrease**	
Enable worker to operate more than one machine / station	Train the workers to operate multiple stations			**operators must be able to run more machines when volumes drop**	**have operators run any new equipment**
Minimize wasted motion of operators between stations	Configure machines / stations to reduce walking distance		**adding equipment to the system could increase operators' walking distances**	**requiring workers to run more stations could increase walking distances**	**reconfigure the system to accommodate new equipment**
Minimize wasted motion in operators' work preparation	Standard tools / equipment located at each station (5S)	this affects operator c/o time			
Minimize wasted motion in operators' work tasks	Ergonomic interface between the worker, machine and fixture	having many components available can result in less ergonomic work routines			
Elminate operators' waiting on other operators	Balanced work-loops	workloop timing and balancing could be dependent on product type	changing the production rate involves rebalancing operator work loops	changing the production rate involves rebalancing operator work loops	rebalance workloops for new products / processes
Improve effectiveness of production managers	Self directed work teams (horizontal organization)				
Eliminate information disruptions	Seamless information flow (visual factory)	**the operator must know what to make next**			
Minimize facilities cost	Reduction of consumed floor space		adding equipment to the system will increase its required floorspace		**add new equipment to an existing system**
Minimize investment over production system lifecycle	Investment based on a long term system strategy				

B-4: M^R matrix for the axle-manufacturing system design example

	Eliminate machine assignable causes	Ensure that operator has knowledge of required tasks	Ensure that operator consistently performs tasks correctly	Ensure that operator human errors do not translate to defects	Eliminate method assignable causes	Eliminate material assignable causes	Center process mean on the target	Reduce noise in process inputs	Reduce impact of input noise on process output	Identify disruptions when they occur	Identify disruptions where they occur	Identify what the disruption is	Identify correct support resources	Minimize delay in contacting correct support resources	Minimize time for support resource to understand disruption	Solve problems immediately	Ensure availability of relevant production information	Ensure that equipment is easily serviceable	Service equipment regularly	Reduce variability of task completion time	Ensure availability of workers	Do not interrupt production for worker allowances	Ensure that parts are available to the material handlers	Ensure proper timing of part arrivals	Reduce lot delay	Define takt time(s)	Ensure that automatic cycle time <= minimum takt time	Ensure that manual cycle time <= takt time	Ensure level cycle time mix	Ensure that part arrival rate is equal to service rate	Provide knowledge of demanded product mix (part types and quantities)	Produce in sufficiently small run sizes	Reduce transportation delay	Ensure that support activities don't interfere with production activities	Ensure that production activities don't interfere with one another	Ensure that support activities (people/automation) don't interfere with one another	Reduce time operators spend on non-value added tasks at each station	Enable worker to operate more than one machine / station	Minimize wasted motion of operators between stations	Minimize wasted motion in operators' work preparation	Minimize wasted motion in operators' work tasks	Elminate operators' waiting on other operators	Improve effectiveness of production managers	Eliminate information disruptions	Minimize facilities cost	Minimize investment over production system lifecycle
Product Design	0.33				0.33	0.33	0.33													0.33							1.00	1.00																		1.00
Production Volume																			0.33							1.00	1.00	1.00		1.00															1.00	1.00
Workforce		1.00	1.00												1.00					1.00	1.00							1.00								1.00										
Floor Space																																													1.00	
Investment																																														1.00

B-5: P matrix for the axle-manufacturing system design example

	Eliminate machine assignable causes	Ensure that operator has knowledge of required tasks	Ensure that operator consistently performs tasks correctly	Ensure that operator human errors do not translate to defects	Eliminate method assignable causes	Eliminate material assignable causes	Center process mean on the target	Reduce noise in process inputs	Reduce impact of input noise on process output	Identify disruptions when they occur	Identify disruptions where they occur	Identify what the disruption is	Identify correct support resources	Minimize delay in contacting correct support resources	Minimize time for support resource to understand disruption	Solve problems immediately	Ensure availability of relevant production information	Ensure that equipment is easily serviceable	Service equipment regularly	Reduce variability of task completion time	Ensure availability of workers	Do not interrupt production for worker allowances	Ensure that parts are available to the material handlers
Cost	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Quality	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65														
Delivery Performance - Dependability	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.37	0.12	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Delivery Performance - Throughput Time																							
Product Mix Flexibility																							
Upward Volume Flexibility																							
Downward Volume Flexibility																							
Innovativeness																							
	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	0.45	0.45	0.70	0.45	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70

	Ensure proper timing of part arrivals	Reduce lot delay	Define takt time(s)	Ensure that automatic cycle time <= minimum takt time	Ensure that manual cycle time <= takt time	Ensure level cycle time mix	Ensure that part arrival rate is equal to service rate	Provide knowledge of demanded product mix (part types and quantities)	Produce in sufficiently small run sizes	Reduce transportation delay	Ensure that support activities don't interfere with production activities	Ensure that production activities don't interfere with one another	Ensure that support activities (people/automation) don't interfere with one another	Reduce time operators spend on non-value added tasks at each station	Enable worker to operate more than one machine / station	Minimize wasted motion of operators between stations	Minimize wasted motion in operators' work preparation	Minimize wasted motion in operators' work tasks	Eliminate operators' waiting on other operators	Improve effectiveness of production managers	Eliminate information disruptions	Minimize facilities cost	Minimize investment over production system lifecycle
Cost	0.33	0.33	0.33	0.33	0.33	0.00	0.33	0.00	0.00	0.33	0.33	0.33	0.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Quality																							
Delivery Performance - Dependability	0.37																						
Delivery Performance - Throughput Time																							
Product Mix Flexibility																							
Upward Volume Flexibility	0.13		0.04	0.13	0.13											0.13			0.04			0.04	0.13
Downward Volume Flexibility																							
Innovativeness																							
	0.83	0.33	0.37	0.46	0.46	0.00	0.33	0.00	0.00	0.33	0.33	0.33	0.33	1.00	1.00	1.13	1.00	1.00	1.04	1.00	1.00	1.04	1.13

B-6: M^D matrix for the axle-manufacturing example

	Job Shop / Batch Flow	FMS	Lean Cell	Equipment-paced Line
Eliminate machine assignable causes	-1.00	-0.33		
Ensure that operator has knowledge of required tasks	1.00	-1.00	-1.00	1.00
Ensure that operator consistently performs tasks correctly		1.00		1.00
Ensure that operator human errors do not translate to defects		1.00		
Eliminate method assignable causes				
Eliminate material assignable causes				
Center process mean on the target				
Reduce noise in process inputs	-1.00		0.33	0.33
Reduce impact of input noise on process output				
Identify disruptions when they occur	-1.00		1.00	1.00
Identify disruptions where they occur	-1.00		1.00	1.00
Identify what the disruption is				
Identify correct support resources				
Minimize delay in contacting correct support resources				
Minimize time for support resource to understand disruption				
Solve problems immediately				
Ensure availability of relevant production information				
Ensure that equipment is easily serviceable	1.00	-0.33	-1.00	0.33
Service equipment regularly				
Reduce variability of task completion time		1.00		1.00
Ensure availability of workers				
Do not interrupt production for worker allowances	-1.00	-1.00	1.00	-1.00
Ensure that parts are available to the material handlers	-1.00			
Ensure proper timing of part arrivals		1.00	1.00	1.00
Reduce lot delay	-1.00	1.00	1.00	1.00
Define takt time(s)	-0.33			-0.33
Ensure that automatic cycle time <= minimum takt time				
Ensure that manual cycle time <= takt time				
Ensure level cycle time mix				
Ensure that part arrival rate is equal to service rate				
Provide knowledge of demanded product mix (part types and quantities)				
Produce in sufficiently small run sizes				
Reduce transportation delay	-1.00	1.00	1.00	1.00
Ensure that support activities don't interfere with production activities	-1.00	-1.00		
Ensure that production activities don't interfere with one another	1.00			1.00
Ensure that support activities (people/automation) don't interfere with one another				
Reduce time operators spend on non-value added tasks at each station				-1.00
Enable worker to operate more than one machine / station	1.00		1.00	-1.00
Minimize wasted motion of operators between stations	-1.00			1.00
Minimize wasted motion in operators' work preparation				
Minimize wasted motion in operators' work tasks		-1.00		
Elminate operators' waiting on other operators	0.33		-0.33	
Improve effectiveness of production managers	-1.00		1.00	
Eliminate information disruptions	-1.00		1.00	1.00
Minimize facilities cost	-1.00		1.00	
Minimize investment over production system lifecycle		-1.00	-0.33	-0.33

B-7: Text descriptions of M^D matrix entries

Italics indicate a positive relationship; plain text indicates a negative relationship

FR	DP	Job Shop	FMS	Lean Cell	Equipment-paced Line
Eliminate machine assignable causes	Failure mode and effects analysis	Layout of machines based on operation (not product flow) can make it difficult to trace a problem to it's source	There are more sources of machine error in a highly automated environment		
Ensure that operator has knowledge of required tasks	Training program	*Training can be easier, as operators run fewer different types of machines*	More highly trained operators are required to run / maintain the more high-tech equipment	More training required to enable operators to run multiple types of equipment	*Operator is likely to have a very limited set of tasks to perform, making training easier*
Ensure that operator consistently performs tasks correctly	Standard work methods		*Generally, all processing operations are automated*		*Operator is likely to have a very limited set of simple, well-defined tasks to perform*
Ensure that operator human errors do not translate to defects	Mistake proof operations (Poka-Yoke)		*Generally, all processing operations are automated*		
Eliminate method assignable causes	Process plan design				
Eliminate material assignable causes	Supplier quality program				
Center process mean on the target	Process parameter adjustment				
Reduce noise in process inputs	Conversion of common causes into assignable causes	More material flow paths leads to more sources of input noise		*Limited number of material flow paths reduces variability in incoming parts*	*Limited number of material flow paths reduces variability in incoming parts*
Reduce impact of input noise on process output	Robust process design				
Identify disruptions when they occur	Increased operator sampling rate of equipment status	Because production in a functional area (i.e. the milling dept.) can continue when an individual machine is down, there is the risk that response to the problem might be slow.		*Standard workloops mean operator checks each machine once per takt time*	*Problems become visible quickly with limited WIP between operations*
Identify disruptions where they occur	Simplified material flow paths	Layout of machines based on operation (not product flow) can make it difficult to trace a problem to it's source		*Lean cell minimizes the number of flow paths per part*	*Equipment-paced lines typically have very few flow paths*
Identify what the disruption is	Context sensitive feedback				
Identify correct support resources	Specified support resources for each failure mode				
Minimize delay in contacting correct support resources	Rapid support contact procedure				
Minimize time for support resource to understand disruption	System that conveys what the disruption is				
Solve problems immediately	Standard method to identify and eliminate root cause				

FR	**DP**	**Job Shop**	**FMS**	**Lean Cell**	**Equipment-paced Line**
Ensure availability of relevant production information	Capable and reliable information system				
Ensure that equipment is easily serviceable	Machines designed for serviceability	*Machines in a job shop are typically not tightly spaced, allowing easy access for maintenance and repair*	Arranging the machines close together makes this more difficult	Arranging the machines close together makes this more difficult	Arranging the machines close together makes this more difficult
Service equipment regularly	Regular preventative maintenance program				
Reduce variability of task completion time	Standard work methods to provide repeatable processing time		*With a highly automated system, processing times should be highly predictable.*		*Tasks are paced by the equipment*
Ensure availability of workers	Perfect attendance program				
Do not interrupt production for worker allowances	Mutual relief system with cross-trained workers	With a job shop arrangement, it is likely that operators have specialized skills and can not be switched from one dept. to another (i.e. from milling to turning)	With an FMS, it is likely that operators have specialized skills and can not be switched from one line to another	*Increased operator training and job rotation make this easier*	Difficult to achieve if operators are tied to specific stations
Ensure that parts are available to the material handlers	Standard work in process between sub-systems	Without clear material flow paths, flow is unpredictable and it is therefore very difficult to standardize buffer sizes or ensure material availability			
Ensure proper timing of part arrivals	Parts moved to downstream operations according to pitch		*Material flow within an FMS is automated and should be predictable*	*Part transfer is part of standardized work routine*	*Part transfer timing is fixed by the pace of the line*
Reduce lot delay	Reduction of transfer batch size (single-piece flow)	When machines are layed out in departments, transportation distances between dept's will generally be large, making single-piece flow between departments impractical.	*An FMS typically transports parts one at a time on a conveyor*	*With machines close together, single piece flow is possible within the system*	*With machines close together, single piece flow is possible*
Define takt time(s)	Definition or grouping of customers to achieve takt times within an ideal range	The demand for all customers is often aggregated into total demand for one high speed line, so there is no clear flow of information from a customer to a particular operation.			The demand for all customers is often aggregated into total demand for one high speed line, so there is no clear flow of information from a customer to a particular operation.
Ensure that automatic cycle time <= minimum takt time	Design of appropriate automatic work content at each station				
Ensure that manual cycle time <= takt time	Design of appropriate operator work content/loops				
Ensure level cycle time mix	Stagger production of parts with different cycle times				

FR	DP	Job Shop	FMS	Lean Cell	Equipment-paced Line
Reduce transportation delay	Material flow oriented layout design	When machines are layed out in departments, transportation distances between dept's will generally be large.	*Machines are generally close together*	*Machines are generally close together*	*Machines are generally close together*
Ensure that support activities don't interfere with production activities	Subsystems and equipment configured to separate support and production access req'ts	This will be difficult to achieve if material flow and/or operator work is not standardized	This can be difficult; automation might have to be locked out so that an operator can access the equipment		
Ensure that production activities don't interfere with one another	Ensure coordination and separation of production work patterns	*If operators are tied to individual stations, this is achieved*			*If operators are tied to individual stations, this is achieved*
Ensure that support activities (people/automation) don't interfere with one another	Ensure coordination and separation of support work patterns				
Reduce time operators spend on non-value added tasks at each station	Machines & stations designed to run autonomously				Most operators are tied to an individual station in this type of system
Enable worker to operate more than one machine / station	Train the workers to operate multiple stations	*Training can be easier, as operators run fewer different types of machines*		*Having multi-functional workers is a key aspect of the lean cell design*	Most operators are tied to an individual station in this type of system, especially if automated stations are mixed in with manual ones
Minimize wasted motion of operators between stations	Configure machines / stations to reduce walking distance	Machines are often large and not designed with a narrow profile to minimize operator walking distance. Machies are often laid out / configured such that maintenance can / must access the machine from all sides, resulting in significant walking distances from machine to machine.			*Typically, operators do not move between stations*
Minimize wasted motion in operators' work preparation	Standard tools / equipment located at each station (5S)				
Minimize wasted motion in operators' work tasks	Ergonomic interface between the worker, machine and fixture		Ergonomics may be overlooked if the system design is based on automated material handling system		
Elminate operators' waiting on other operators	Balanced work-loops	*Workers are isolated from one another*		Can be difficult to balance workloops due to differing amounts of manual work content at each station	
Improve effectiveness of production managers	Self directed work teams (horizontal organization)	Work teams must be set up by department, not by customer or material flow.		*Product flow-oriented system facilitates a horizontal organization*	

Appendix C

C-1: P Matrix for cell design example

	Eliminate machine assignable causes	Ensure that operator has knowledge of required tasks	Ensure that operator consistently performs tasks correctly	Ensure that operator human errors do not translate to defects	Eliminate method assignable causes	Eliminate material assignable causes	Center process mean on the target	Reduce noise in process inputs	Reduce impact of input noise on process output	Identify disruptions when they occur	Identify disruptions where they occur	Identify what the disruption is	Identify correct support resources	Minimize delay in contacting correct support resources	Minimize time for support resource to understand disruption	Solve problems immediately	Ensure availability of relevant production information	Ensure that equipment is easily serviceable	Service equipment regularly	Reduce variability of task completion time	Ensure availability of workers	Do not interrupt production for worker allowances	Ensure that parts are available to the material handlers	Ensure proper timing of part arrivals	Reduce lot delay	Define takt time(s)	Ensure that automatic cycle time <= minimum takt time	Ensure that manual cycle time <= takt time	Ensure level cycle time mix	Ensure that part arrival rate is equal to service rate	Provide knowledge of demanded product mix (part types and quantities)	Produce in sufficiently small run sizes	Reduce transportation delay	Ensure that support activities don't interfere with production activities	Ensure that production activities don't interfere with one another	Ensure that support activities (people/automation) don't interfere with one another	Reduce time operators spend on non-value added tasks at each station	Enable worker to operate more than one machine / station	Minimize wasted motion of operators between stations	Minimize wasted motion in operators' work preparation	Minimize wasted motion in operators' work tasks	Elminate operators' waiting on other operators	Improve effectiveness of production managers	Eliminate information disruptions	Minimize facilities cost	Minimize investment over production system lifecycle
Cost	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00
Quality	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Delivery Performance - Dependability	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Delivery Performance - Throughput Time	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Product Mix Flexibility	1.00	1.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00	0.33	0.33	0.33	1.00	0.00	1.00	1.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.33	0.33	0.33	0.00	1.00	0.00	0.00
Upward Volume Flexibility	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Downward Volume Flexibility	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50	0.00	0.00	0.17	0.00	0.00	0.00	0.00
Innovativeness	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1.66	2.16	0.66	1.66	1.66	0.66	0.66	0.66	0.66	1.33	1.66	1.33	1.33	1.33	1.33	1.33	2.33	1.33	1.33	1.33	1.33	1.33	2.33	1.33	1.33	0.83	0.66	1.16	1.33	0.33	1.33	1.33	0.33	0.66	0.33	0.33	1.50	1.50	1.50	1.33	1.33	1.50	1.00	2.00	0.00	0.00

C-2: M^D matrix for the cell design example

	Layout #1	Layout #2	Layout #3	Layout #4
Eliminate machine assignable causes				
Ensure that operator has knowledge of required tasks				
Ensure that operator consistently performs tasks correctly				
Ensure that operator human errors do not translate to defects				
Eliminate method assignable causes				
Eliminate material assignable causes				
Center process mean on the target				
Reduce noise in process inputs				
Reduce impact of input noise on process output				
Identify disruptions when they occur	0.00	0.00	-0.33	-0.33
Identify disruptions where they occur	0.00	0.00	-0.33	-0.33
Identify what the disruption is				
Identify correct support resources				
Minimize delay in contacting correct support resources				
Minimize time for support resource to understand disruption				
Solve problems immediately				
Ensure availability of relevant production information				
Ensure that equipment is easily serviceable				
Service equipment regularly	1.00	0.00	-0.33	-1.00
Reduce variability of task completion time				
Ensure availability of workers				
Do not interrupt production for worker allowances	-1.00	-0.33	0.00	0.00
Ensure that parts are available to the material handlers				
Ensure proper timing of part arrivals				
Reduce lot delay				
Define takt time(s)	1.00	0.00	-0.33	-1.00
Ensure that automatic cycle time <= minimum takt time				
Ensure that manual cycle time <= takt time				
Ensure level cycle time mix				
Ensure that part arrival rate is equal to service rate				
Provide knowledge of demanded product mix (part types and quantities)				
Produce in sufficiently small run sizes	0.33	0.00	0.00	-1.00
Reduce transportation delay				
Ensure that support activities don't interfere with production activities				
Ensure that production activities don't interfere with one another				
Ensure that support activities (people/automation) don't interfere with one another				
Reduce time operators spend on non-value added tasks at each station				
Enable worker to operate more than one machine / station	-1.00			0.33
Minimize wasted motion of operators between stations				
Minimize wasted motion in operators' work preparation				
Minimize wasted motion in operators' work tasks				
Elminate operators' waiting on other operators				
Improve effectiveness of production managers	0.50	0.00	0.00	-0.50
Eliminate information disruptions	0.33	0.00	0.00	-0.33
Minimize facilities cost	-0.50	-0.33	0.00	0.33
Minimize investment over production system lifecycle	-1.00	-0.33	0.33	1.00

Glossary of Terms

Balanced: Having the same production rate. Two manufacturing operations are said to be *balanced* if they produce parts at the same pace

Behavior: "Behavior for a system describes *what* the system is to do, independent of *how* the system will do it." (Oliver et al. 1997)

Complex: made up of intricately involved parts, difficult to understand or analyze

Cycle time: The time it takes to perform a manufacturing operation

Flexibility: Flexibility is the ability to change or react with little penalty in time, effort, cost or performance (Upton, 1994)

Framework: a conceptual structure used to organize a group of ideas

Manufacturing strategy: Set of priorities aimed at developing a sustainable competitive advantage and evidenced by a consistent series of decisions made over time

Manufacturing system: A collection of components (machines, equipment, people, etc.) bound by common material and information flow and working together to transform raw materials into marketable goods (adapted from Chryssolouris, 1992 and Wu, 1992)

Manufacturing system design: The process of defining the behavior and structure of a manufacturing system

Operation: A single step in a manufacturing process (e.g. machining one feature in a part

Performance measurement system: "The set of metrics used to quantify both the efficiency and effectiveness of actions," where the term metric is used to represent the measure itself plus information regarding the formula for calculating the measure, how the required data will be collected, who will be responsible for recording this data, etc. (Neely, Gregory, and Platts, 1995).

Process (manufacturing): the sequence of operations necessary to convert a raw material into a marketable product

Structure: The organization of the components that make up a system, including the number of each component, their arrangement, and their interrelations

System: An interacting combination of elements viewed in relation to function (INCOSE, 1998)

Throughput time: The amount of time it takes an individual part to go through an entire manufacturing system, entering as a raw material and leaving as a marketable product

Trade-off: a balancing of objectives all of which cannot be simultaneously optimized

Transfer batch size: Quantity in which parts are transported from one operation to the next

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