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**A Framework for the Performance-Based**

**Design of Flexible Manufacturing Cells.**

by

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(ABSTRACT)

A conceptual framework for the design and performance evaluation of flexible manufacturing cells (FMCs) based on the strategic objectives of firms was developed. Four different types of manufacturing task profiles were identified based on the primary manufacturing task, product characteristics, and manufacturing system characteristics of a strategic business unit (SBU). Performance measures were discussed for each of the manufacturing task profiles, and the task profiles of firms likely to implement FMCs were identified.

A methodology, based on the analytic hierarchy process (AHP), introduced by Saaty, was developed to prioritize the manufacturing objectives of an FMC. The implications of each of the manufacturing objectives for an FMC were hypothesized and related performance measures identified. An interactive computer-based model, based on the theory of closed network-of-queues, was then developed to aid in the preliminary design and evaluation on an FMC.

Field work was carried out to determine the practical applicability of the conceptual framework. Visits to a company in the Southeastern United States were made and an analysis of the FMC being developed in the Department of Industrial Engineering and Operations Research, at Virginia Tech was conducted.

The framework developed in this research was used to determine the manufacturing task profile of the company, identify key performance measures, and exercise the AHP methodology for one cell. Operational measures were then calculated for the FMC, using the computer-based model.

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# Chapter 1

# Introduction

Manufacturing is the process that converts raw material into the desired output; it includes all value-added and support functions. The traditional role of manufacturing in an organization has undergone a dramatic change due to the introduction of new technologies such as robotics, computer integrated manufacturing (CIM), and flexible manufacturing systems (FMSs). As such, manufacturing is now regarded as a major weapon in a company's strategic arsenal (Wheelwright and Hayes, 1985).

Strategic planning is the process of developing a competitive strategy. Porter (1980) has defined competitive strategy as a broad formula for how a business is going to compete, what its goals should be, and what policies will be needed to carry out these goals. It is now recognized that the manufacturing function is critical for a firm to achieve its corporate goals, as formulated in its competitive strategy.

The purpose of this research is to develop a conceptual framework for the design and performance evaluation of a flexible manufacturing cell (FMC), relative to the strategic objectives of the firm. Different manufacturing task profiles are identified based on product characteristics and strategic objectives of firms. A methodology is proposed to provide the decision-maker with a set of prioritized manufacturing objectives. The methodology is based on the analytic hierarchy process developed by Saaty (1980), and will help in prioritizing the manufacturing objectives with a view to change the role of the manufacturing function from being reactive to the demands imposed on it by upper management to being proactive and becoming a function that makes an important contribution to the competitive success of the organization. An interactive computer-based model is developed to serve as a quantitative tool to support manufacturing policy decisions. The model, based on the closed-queuing networks developed by Jackson (1963), will calculate key performance measures, such as throughput, machine utilization, production rate, and work-in-process inventory levels.

A key problem encountered in evaluating flexible manufacturing cells is the fact that the major benefits associated with them are not quantifiable. Further, flexible manufacturing cells are complex combinations of various types of equipment that are interfaced to work in unison. The performance measurement systems prevalent today are based upon the mass production of a mature product, with known characteristics and a stable technology (Kaplan, 1983). But mass production accounts for only 20 per cent of metal-working parts produced in the United States, while 75 per cent are made in a batch environment (Merchant, 1977). Existing performance measurement systems most often emphasize cost reduction, while ignoring other criteria like flexibility and market responsiveness. Based on the manufacturing objectives of a strategic business unit (SBU), the manufacturing system should seek to optimize only the relevant performance measures (those that support the manufacturing objectives). For example, SBUs producing commodity products probably should focus on cost minimization, perhaps through maximizing capacity, labor, or material utilization. Attempting to attain a high degree of product flexibility would be impractical due to the use of specialized equipment. Strategic planning, at the design stage of a manufacturing system will help specify manufacturing performance levels, and enable executives to focus their attention on meeting competitive pressures, rather than concerning themselves with internal operations. There is a need to develop a framework that would accurately reflect manufacturing performance and the strategic benefits that result from implementing flexible manufacturing cells.

The objectives of this research that was undertaken to address the above issues can be summarized as follows:

1. The first phase of the research identified different manufacturing task profiles based on the strategic objectives of firms. The product characteristics and strategic objectives of firms that would implement an FMC were identified, based on an extensive literature review. A procedure was developed for the formulation of the business strategy of firms, which formed the basis for deriving manufacturing objectives.

2. The second phase was the development of a methodology to provide decision-makers with a vector of prioritized manufacturing objectives. The methodology, based on the the analytic hierarchy process (AHP) developed by Saaty (1980), decomposes a complex decision problem into one or more levels of detail, and prioritizes different attributes through pairwise comparisons, with a single attribute on a higher level. Local priorities are then obtained by solving a comparison matrix, for the eigenvector of the largest eigenvalue. Global priorities are obtained by multiplying the vector of local priorities with the priority vector of the attributes at the next higher level.

3. The last phase of the research was the development of a computer-based model for an iterative preliminary design of an FMC to optimize the prioritized manufacturing objectives and to identify key performance measures. Performance statistics were obtained using a closed network-of-queues model. The model helps to specify performance levels of an FMC, with respect to work-in-process inventories, manufacturing lead-times, throughput rate, and machine utilization. The model allows the manufacturing function to predict system performance, given changes in the business strategy, and thus serve as a quantitative tool to enable it to take an active part in formulating the business strategy of the SBU.

To summarize, the research provided a framework for the design and evaluation of an FMC, relative to the strategic goals of the SBU. A methodology to obtain a set of prioritized manufacturing objectives was developed, in which the performance measures to evaluate the FMC are chosen relative to the prioritized manufacturing objectives. An interactive computer-based model was developed to support manufacturing policy decisions.

## Organization of the thesis

This thesis is divided into six chapters. The first chapter outlines the objectives of this research. The second chapter is a literature review of manufacturing strategy; classification of manufacturing systems; flexible manufacturing cells; manufacturing performance measures; AHP, a multiple-criteria decision making methodology; and the theory of queuing networks to determine the operational measures of an FMC. The third chapter develops a framework for the design and evaluation of FMCs. The fourth chapter discusses the field work that was carried out to determine the practical applicability of the framework developed in this research. The fifth chapter presents the analysis and results of the field work and the sixth chapter makes recommendations for future research.

# Chapter 2

# Literature review

## 2.1 Manufacturing strategy

The strategic planning process should be a well-defined effort and should aim for the complete specification of corporate strategy. The first step is to determine the primary task of the organization. Tregoe, Benjamin and Zimmerman (1980) have explained the primary task of an organization, using the concept of "center of gravity." The center of gravity of an organization arises from an organization's initial success in the industry in which it started.

Andrews (1980, p.4) has defined corporate strategy as

> ... the pattern of decisions in a company that determines and reveals its objectives, purposes or goals, produces the principal policies and plans for achieving these goals and defines the range of businesses the company is to pursue, the kind of economic and human organization it is or intends to be, and the nature of the economic and neoeconomic contribution it intends to make to its shareholders, employees, customers and communities.

The strategic objectives of the firm, based on an extensive evaluation of the firm's available resources, will determine how the firm will meet the challenges presented by the external environment and how it will reposition its resources in order to adapt to future changes in the environment. The formulation of corporate strategy will result in a clear understanding of the businesses of the firm.

Determining the primary task should be followed by documenting the goals of the organization and drawing up a corporate mission. The statement of the mission identifies the image the firm attempts to project and reflects the values and priorities of the firm's strategic decision makers (Pearce, 1982). The corporate mission should provide a basis for establishing the strategic direction for the business, based on the various environmental factors that affect the firm.

An example of the corporate mission statement of the Automotive and Industrial Electronics group of Motorola (Hax and Majluf, 1984, p.48) is given below:

> The mission of the Automotive and Industrial Electronics group is the development and production of electronic modules and power conversion equipment for sale to original equipment manufacturers (OEMs) and the associated replacement parts market.
>
> The product scope centers on volume production of electronic modules, in a variety of manufacturing technologies, for monitoring, control, information transmission, information display, and power conversion.
>
> The market scope is the OEM and replacement market segment for instrumentation, electronic power conversion systems, wire line conversion equipment, vehicle power trains, appliances, OE passenger car entertainment, and systems refining visual display capabilities.
>
> The geographic scope is primarily North America and Europe, and secondarily Japan, Latin America, and South Africa.

The corporate mission thus identifies the firm's target markets, products, and current and future business scope. The next step is to translate the corporate mission into a set of guidelines for developing the strategic objectives of the businesses and major functions of the firm. The guidelines will be based on the environmental factors (economic, social, political, and technological) that affect the corporation.

Hax and Majluf (1984) have developed a formal corporate strategic planning process and proposed the segmenting of a firm's activities in terms of strategic business units (SBUs). They have defined an SBU (p.49) as

> ... an operating unit or a planning focus to sell a distinct set of products or services to an identifiable group of customers, in competition with a well-defined set of competitors.

SBUs need not be independent entities. Certain functions, such as R&D or marketing, could be shared in order to attain efficiencies in resource utilization. SBUs are defined with external markets and competitors in mind. Each SBU should select its business strategy so as to best meet the strategic goals of the firm.

A business strategy is a set of well-coordinated action programs aimed at securing a long-term sustainable competitive advantage (Hax and Majluf, 1984). The business strategy for an SBU should be developed so as to best meet the strategic objectives outlined in the corporate mission. The business strategy involves translating the corporate mission into a set of identifiable tasks for the SBU. Development of the business strategy results in a clear understanding as to the markets that the SBU serves and establishes a clear and focused direction for the SBU.

Fine and Hax (1985) stated that a company with a clear competitive objective that focuses on a product mix for a well-defined market will outperform a firm with an inconsistent set of manufacturing policies that attempts to do too many conflicting tasks. This is illustrated in the following case (Whybark, 1986): Company X was an early entrant in the printed circuit board business, achieving a very good reputation for producing high-quality specialty boards. The orders were generally for a small number of technically challenging boards, for prototype applications. At one point the company took a few large orders for standard boards, for production runs. The stress of producing standard boards under cost and delivery pressures, on top of their other businesses, led to decreased quality, poor delivery performance, and decreased profits. The company reached the point where they were promising delivery (to meet competition and keep the business) in less time than they could perform the physical manufacturing steps.

The SBU's business strategy will deal with the primary issues that it has to address over a relatively short period of time, typically four to five years. The formulation of the business strategy would represent the lowest level at which strategic planning would take place and would result in formulating a set of well-defined objectives to meet the long term goals of the firm. Different SBUs would have different business strategies. For example, IBM -- a leading manufacturer of main-frame and micro-computers -- would have a different business strategy for its main-frame division than that for its micro-computer division.

The business strategy will impose certain requirements on the manufacturing system. For example, an SBU producing commodity products will most likely emphasize cost reduction, whereas an SBU serving an industrial goods market may focus on stringent quality specifications.

The manufacturing strategy should be based on the business strategy of the SBU. The literature on manufacturing strategy relevant to this research is discussed below.

Skinner (1974) stated that manufacturing policy must follow from the overall strategic objectives, as outlined in the corporate strategy. He (Skinner, 1978) also suggested the following procedure for the formulation of manufacturing policy:

1. Define the manufacturing task and degree of manufacturing focus.
2. Decide on the number, capacity and location of plants, and the type of equipment and process technology.
3. Decide on the infrastructure which includes people, systems and procedures.

The above procedure gives guidelines for formulating manufacturing policy, but does not suggest how to link manufacturing policy with the business strategy.

Fine and Hax (1985) proposed the following framework as a systematic procedure to develop a manufacturing strategy:

1. Provide a framework for strategic decision-making in manufacturing.
2. Assure that business strategies and manufacturing strategy are linked.
3. Conduct an initial manufacturing strategic audit to detect strengths and weaknesses in the current manufacturing strategy.
4. Address the issue of product grouping by positioning the product lines in the product or process life cycle and by assessing commonalty of performance objectives and product family missions.
5. Examine the degree of focus existing at each plant or manufacturing unit.

6. Develop manufacturing strategies and suggest allocation of product lines to plants or manufacturing units.

The above framework, although rich in ideas, is highly conceptual in nature, and does not lend itself to practical implementation on the shop-floor. In fact, very little work has been done in trying to link manufacturing strategy with the design of the manufacturing system.

Wheelwright and Hayes (1985) have suggested that the role of manufacturing should be "externally supportive" in that it is expected to make an important contribution to the competitive success of the organization. According to them, companies should:

1. Anticipate the potential of new manufacturing technologies and seek to acquire expertise in them long before their implications are fully apparent.
2. Give sufficient credibility and influence to manufacturing for it to extract the full potential from production-based operations.
3. Place equal emphasis on structural (buildings and equipment) and infrastructural (management policies) activities as potential sources of continual improvement and competitive advantage.
4. Develop long-range business plans in which manufacturing capabilities are expected to play a meaningful role in securing the company's strategic objectives.

Thus, Wheelwright and Hayes suggest that the manufacturing function should be an active participant in formulating the business strategy of the firm. The type of manufacturing system that is appropriate for an SBU will depend on the nature of the products and the target market segments of the SBU.

## 2.2 Manufacturing task profiles

Traditionally, discrete-parts manufacturers have been classified as follows (Dervitsiotis, 1981):

Job shop: Job shops produce products that are required in very small quantities using general-purpose machines and tooling.

Batch production: Batch production involves producing components and products in batches. The machines used are general-purpose and must be capable of being set-up in different ways, with a variety of tooling to produce a number of different products. Batch production involves the use of specialized tooling, fixtures, and gages for large batches.

Flow shop: This is a type of manufacturing process in which products are produced continuously, by special-purpose machines. A flow shop (mass production) is often characterized by "hard automation" that cannot be changed easily, since the machines are "dedicated" to their special tasks.

The above classification appears to have been made mainly on the basis of the number of products and the volume of production. A large number of products and low volumes imply a job-shop as the appropriate process, whereas high-volume production of very few products imply the use of flow-shops. A more detailed classification of manufacturing systems, for different SBUs, has been proposed by Richardson, Taylor, and Gordon (1985). A literature search and in-depth interviews with industry executives helped them identify the following factors to specify the manufacturing task profile of a firm: volume of output, cost per unit, quality, delivery on schedule, labor productivity, degree of innovation, product flexibility, and volume flexibility. Four different manufacturing task profiles were identified based on the relative importance of the factors to each of the task profiles.

Table 1 shows the four different manufacturing task profiles related to each of the factors using a numerical rating that shows the anticipated importance of each factor to each of the different task profiles. Each of the task profiles are discussed next.

**Table 1. Manufacturing task profiles [Source: Richardson, Taylor, and Gordon (1985)]**

| factors | A | B | C | D |
|---|---|---|---|---|
| volume of output | 3 | 3 | 3 | 2 |
| cost per unit | 4 | 4 | 1 | 1 |
| quality | 1 | 1 | 1 | 2 |
| delivery on schedule | 3 | 2 | 1 | 2 |
| labor productivity | 3 | 2 | 1 | 2 |
| degree of innovation | 1 | 2 | 4 | 4 |
| product flexibility | 2 | 1 | 1 | 4 |
| volume flexibility | 3 | 1 | 1 | 3 |

*Numerical rating scale: 1 corresponds to "most applicable" and 5 corresponds to "not applicable."*

Manufacturing task profile A -- New-product centered

These manufacturing systems emphasize product quality and a high degree of innovation. Frequent changes in the product make it necessary for manufacturing systems to have a high degree of product flexibility.

Manufacturing task profile B -- Custom innovator

Custom innovators emphasize product flexibility and volume flexibility. They introduce new products and their products compete even when the market becomes price-competitive.

Manufacturing task profile C -- Cost-minimizing job shop

Cost minimization and delivery performance are important factors for cost minimizing job-shops, but since products are made to customer specifications, volume and product flexibility are also important.

Manufacturing task profile D -- Cost minimizer

These firms emphasize cost minimization through economies of scale. New products are rarely introduced and flexibility is relatively unimportant.

Richardson, Taylor, and Gordon (1985) have provided a helpful classification scheme for manufacturing systems, but they have failed, however, to show which manufacturing task profile is appropriate for an SBU based on its strategic objectives and business strategy. The research described in this thesis used a similar framework, but classified the different manufacturing task profiles based on the primary manufacturing task and the strategic criteria on which products compete. This classification is discussed in detail in Chapter 3.

## 2.3 Flexible manufacturing cells

Shorter product life-cycles and intensified competition have forced firms, which manufacture their products in a batch environment (profiles B & C), to produce low-volume high-quality products in order to sustain their market-share. Integrated manufacturing systems attempt to combine modern technologies to manage the manufacturing function better, by synchronizing the different elements in the system with physical and/or information links. Cellular manufacturing is a specific application of a concept called group technology and involves processing similar parts (part families) on dedicated clusters of machines or manufacturing processes (cells) (Black, 1988). A flexible manufacturing system (FMS), based on the concept of cellular manufacturing, is a special type of production system, which attempts to gain for batch production some of the advantages inherent in line production. Warnecke (1983, p.682) has defined an FMS as

> ... several automated machine-tools of the universal or special type and/or flexible manufacturing cells and, if necessary, manual or automated workstations. These are interlinked by an automatic workpiece flow system in a way which enables the simultaneous machining of different workpieces which pass through the system along different routes.

Edquist and Jacobsson (1988, p.62) have defined an FMC as

> ... a flexible manufacturing cell (FMC) (consisting) of two or more numerically controlled machine-tools, for automatically producing a family of different parts or components.

FMCs are complex combinations of various types of equipment that are interfaced to work in unison; they attempt to gain for batch production some of the advantages inherent in high-volume flow-shops. Edquist and Jacobsson (1988) have distinguished between FMSs and FMCs based on the number of types of products and the yearly production of each variant. In a survey, they determined that FMSs produced between 4 and 100 product variants, with 77 per cent producing fewer than 20 variants. FMSs also had higher volumes of production per product variant than FMCs. FMCs produce between 40 and 800 product variants.

Manufacturing task profile D emphasizes cost minimization and produces a relatively small number of product types. Its manufacturing system should therefore resemble a flow-shop. Task profile A produces a large number of product types and the volumes of output of each part-family to be manufactured simultaneously may not justify the creation of cells. Therefore task profiles B and C are most likely to implement cellular manufacturing due to the manufacturing similarities of the products which result in the grouping of products as part families to be manufactured in a cell.

Integral to the concept of flexible manufacturing cells is part family identification. Part families are identified using production flow analysis (PFA) or a classification and coding system (Black, 1988). The essential features that constitute a part family for an FMC are (Office of Technology Assessment, 1986):

1. A common shape: Prismatic and rotational parts cannot be produced by the same set of machines.
2. Size: An FMC will be designed to produce parts of a certain maximum size (parts larger or much smaller than that size cannot be handled).
3. Material: Metal and plastic parts cannot be effectively mixed.
4. Tolerance: The level of precision necessary for the set of parts must be in a common range.

Some of the strategic benefits claimed for flexible manufacturing cells are (Hyer, 1984):

1. Lower work-in-process inventory.
2. Reduced throughput time.
3. Better competitive advantage through better market responsiveness.
4. Improved ability to introduce new products.
5. Ability to adjust to shorter product life-cycles.
6. Improved manufacturing control.
7. Improved product quality.

Despite the advantages claimed for flexible manufacturing systems, they are still relatively rare (about 30 in the United States, as of 1983). Reasons for this scarcity of application include the complexity and newness of the technology. One primary reason is the high cost, estimated to involve a minimum expenditure of $3 million to $4 million (Office of Technology Assessment, 1986).

Rosenthal (1984) stated, based on a survey, that the most cited reasons for not adopting factory automation were the inability to adequately quantify results and the fact that most automation projects fail to meet the investment criteria of the firm. Jaikumar (1986) conducted a detailed study of 95 FMSs (35 in the United states and 60 in Japan) and concluded that management in the United States, captive to old-fashioned Taylorism, treated FMSs as if they were just another set of machines for high-volume standardized production. He found that an average Japanese FMS produced 93 types of parts, with an annual volume of 258 per part, as compared to an average American FMS which produced 10 types of parts, with an annual volume of 1722 per part. Goldhar and Jelinek (1983) pointed out that new advances in manufacturing permit capabilities such as flexibility in product design and product mix, rapid response to changes in market demand, greater process control, and faster throughput. These capabilities permit new strategic options such as customized products, frequent product changes, quality-based differentiation, and other product/market options.

Thus there seems to be a consensus that the evaluation of an FMC should be made on the basis of the strategic options and competitive advantages that they permit, rather than only on the basis of cost.

## 2.4 Manufacturing performance evaluation

Richardson, Taylor, and Gordon (1985) proposed that manufacturing performance should be evaluated in terms of how well it meets the goals and objectives defined for it by the corporate mission. Manufacturing systems should be evaluated based on the strategic criteria on which the SBU decides to compete. Wheelwright (1981) identified four important manufacturing performance criteria: efficiency, dependability, quality, and flexibility, but failed to state how they could be applied practically. The performance measurement systems prevalent today are based on high-volume standardized production (Kaplan, 1983). Traditional performance measures are thus rooted in a desire for cost minimization (through maximizing capacity, labor, and/or material utilization), while ignoring other criteria like flexibility and delivery performance. Further, Kaplan (1984) stated that most accounting and control systems distort product costs; they do not provide the key non-financial measures required for efficient operations, and the data they do provide do not accurately reflect the reality of the new manufacturing environment. Kaplan (1984) proposed that manufacturing measurement systems should consider quality, inventory, productivity, and innovation. Fine and Hax (1985) identified four strategic criteria on which SBUs are most likely to compete: price competitiveness, quality specifications, delivery performance, and market responsiveness. They stressed that manufacturing systems should be evaluated on the basis of the strategic criteria prioritized by the business strategy. Fine and Hax (1985) did not discuss any of the above criteria in detail. The literature pertaining to each of the four criteria is discussed next.

**Price competitiveness**

The marketing function determines the maximum cost per unit that can be incurred by manufacturing, based on the market segment for which the product is aimed. The implication for manufacturing is to minimize unit costs. SBUs competing on cost usually have a stable market for a limited range of standardized mature products. The manufacturing system typically consists of specialized equipment and is geared towards high volume production. A typical example of an SBU competing on price is one which manufactures highly standardized products, such as bearings.

Products competing on price have to maintain a certain minimum level of performance. For example, in the 1970's the United Kingdom television market was predominantly price competitive. Japanese companies captured a large market share by emphasizing product quality and reliability, with a small increase in price (Hill, 1985).

**Product quality**

Garwin (1987) proposed eight dimensions of quality that can serve as a framework for strategic analysis: performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality. He noted that few products rank high on all dimensions, and that an SBU will compete only on selected dimensions. Two of the dimensions -- aesthetics and perceived quality -- are subjective and depend on individual preferences. Ensuring that the product competes on these dimensions depends primarily on how effectively the marketing function evaluates customer needs. This research will consider the implications of only two of these eight dimensions: product reliability and product conformance, on the manufacturing function. These dimensions of product quality are discussed below.

Product reliability

Product reliability reflects the probability that the product won't fail within a specified time period. Increasing the reliability of a product often involves an additional expense due to redundancy, where a parallel component backs up a critical component in case it fails. In some cases reliability may have to be sacrificed in order to improve another dimension of quality. For example, Cray Research, a manufacturer of super-computers, has sacrificed reliability in pursuit of higher speed (Garwin, 1987).

Product conformance

Product conformance refers to the degree to which a product's design and operating characteristics meet established standards (Garwin, 1987). Conformance affects the tolerance requirements on a component. Tight tolerances in products facilitate servicing by increasing the interchangeability of parts. Emphasizing product conformance may require a tighter control over the manufacturing process and/or increased inspection, resulting in an increase in the total cost and total processing time of a product.

### Delivery performance

Randhawa and Bedworth (1985) have defined delivery performance as the ability of the system to meet production schedules, both during normal operating conditions, and during transitions in which the system is adjusting to new conditions, demands, and circumstances. Excepting manufacturing task profile D, which produces high-volume mature products on a continuous basis, all the other manufacturing task profiles have varying demands on their manufacturing systems (for delivery performance), which are reflected as changes in the product-mix and volumes of output. Ensuring the reliability of on-time shipments under varying demands is an important aspect to be considered in the design and evaluation of manufacturing systems of firms subject to such demands. It is assumed that manufacturers of high-volume mature products will have high but constant demands placed on their manufacturing systems.

### Market responsiveness

The major kinds of variations that a firm faces can be broadly classified as external and internal (Karmarkar and Kekre, 1986). External variations in the environment are reflected as changes in the demand for products, by design changes in the products, and/or by the introduction of new products. Internal variations in the SBU are reflected by changes in the process yields due to equipment failures and fluctuations in the raw material supply. External variations and their implications for the manufacturing function were considered in this research, while internal variations like equipment failures, which can be considered only during the detailed design of the manufacturing system are beyond the scope of this thesis.

Goldhar (1985) suggests that flexibility of a manufacturing system will change the objective of a company from economies of scale to economies of scope by increasing the variety of products that may be offered and decreasing the volume of production. Zelenovic (1982) defines flexibility as the probability that the given structure of the manufacturing system will adapt itself to environmental conditions and to process requirements, within the limits of the given design parameters. Falkner (1986) makes the observation that flexibility is a property of the manufacturing system and, once the system is designed, its flexibility is fully specified. Beckman and Jucker (1988) have shown how market responsiveness in an organization can be acquired not only through manufacturing but also through other functions like R&D, marketing, and materials. It is therefore necessary to specify the degree of flexibility that is expected of the manufacturing system, considering the business strategy of the SBU.

Product flexibility

Product flexibility is the ability of the manufacturing system to respond to design changes in the product. Technological developments have resulted in shorter product life-cycles and have highlighted the need to increase the product flexibility of a firm. For example, between 1964 and 1976, IBM introduced two new families of mainframe computers, but from 1976 to 1980, a new mainframe computer was introduced every year (Beckman and Jucker, 1988). Beckman and Jucker (ibid) also noted that many firms process over 2,000 engineering change orders per year.

Volume flexibility

Volume flexibility is the ability of the manufacturing system to respond to variations in the demand for its products. The level of volume flexibility can be increased by increasing the capacity of the plant. Another way to increase the volume flexibility is to design the manufacturing system so that it can manufacture a number of different product types in varying batch sizes.

## 2.5 Prioritizing manufacturing objectives

The manufacturing function cannot be expected to place an equal emphasis on all the above criteria. Skinner (1974) stated that manufacturing objectives must follow from the overall strategic objectives. He emphasized the importance of the tradeoff of objectives and the idea that excellence in one area implies compromise in another. Tradeoffs between manufacturing objectives must be made. The nature of these tradeoffs and the strategic criteria on which the manufacturing function is expected to place an emphasis should be explicitly stated in the business strategy of the SBU. Manufacturing's role in helping the SBU achieve its strategic objectives should be clear and consistent with all the other functions and related support activities. For example, if the manufacturing system, based on the strategic objectives of the SBU, is geared towards cost minimization, then the sales department should not accept orders for customized products.

The design and evaluation of a manufacturing system should be made on the basis of the business strategy of the SBU. Very little work seems to have been done in trying to establish prioritized manufacturing objectives based on corporate and business strategy. Prioritizing manufacturing objectives should be a multiple-criteria decision problem, with tangible and intangible decision factors. Schoemaker and Waid (1982) have compared a number of approaches of dealing with multiple-criteria decision making, and have indicated the advantages of using the analytic hierarchy process (AHP) introduced by Saaty (1980).

The analytic hierarchy process decomposes a complex decision problem into one or more levels of detail; different attributes can be prioritized through pairwise comparisons with a single attribute on a higher level. Priorities are obtained by solving a comparison matrix for the eigenvector of the largest eigenvalue. In addition to providing a structured approach to the problem, AHP results in a single priority vector in the attribute space and provides the decision-maker with a dominant set of objectives.

Using AHP to solve the decision problem of prioritizing manufacturing objectives involves the following steps (Saaty, 1980):

1. Breaking down the decision problem into a hierarchy of interrelated decision problems.
2. Setting up the scale for pairwise comparisons of the decision elements.
3. Estimating the local priorities of the attributes.
4. Estimating the global priorities of the attributes.

AHP has been widely used in a number of diverse applications, such as economics, planning, allocation of resources, material handling, purchasing, marketing, and portfolio selection (Zahedi, 1986). The procedure for implementing AHP in this research will be discussed in detail in Chapter 3.

## 2.6 Performance measures

A set of key performance measures should be identified so that they reflect the effectiveness of the manufacturing system in helping to achieve the strategic goals of the SBU. The manufacturing system should thereafter focus on the prioritized manufacturing objectives and related performance measures.

Performance measures that are traditionally considered to determine the effectiveness of the manufacturing system (operational measures) include machine utilization, work-in-process inventory, throughput rate, set-up times, and manufacturing lead time (Dervitsiotis, 1980).

Implicit in the selection of the manufacturing task profile is a trade-off of certain performance measures. For example a flow-shop maximizes capacity, labor, and material utilization, but has very little flexibility to deal with any variations in the environment in which it operates. A job-shop has a high degree of flexibility, but one trade-off that is usually made is a low machine utilization (Dervitsiotis, 1980). The trade-off of the performance measures should be made explicit at the planning stage, by specifying the performance levels of the manufacturing system, based on the prioritized manufacturing objectives. The performance measures for each of the manufacturing task profiles are discussed in detail in Chapter 3.

For the manufacturing function to be able to take an active part in formulating the business strategy, it is essential to have the capability to predict system performance. Due to the fact that FMCs are combinations of machine-tools interfaced to work in unison, predicting the implications, for the FMC, of changes in the business strategy can be difficult. This research will consider the theory of closed network-of-queues for the preliminary design and evaluation of the FMC in terms of several operational measures. The analysis of the results of the queuing model should then form the basis for a more detailed evaluation of the FMC.

## 2.7 Queuing models

Simple static models which do not take into account system dynamics, interactions, and uncertainties are not appropriate to determine the operational measures of a manufacturing system. Queuing network models incorporate some of the above features and allow for a more refined evaluation of operational measures. Gershwin, et al (1986) indicated the advantages of using queuing models for initial aggregate-planning. A computer model developed for this research, based on the theory of closed network-of-queues, will help to evaluate proposed changes in the business strategy and their effects on the manufacturing system.

A queuing network model consists of a set of workstations, where servers provide service to arriving jobs. The basic theory of queuing networks was developed by Jackson (1963), and was extended by Gordon and Newell (1967). Computational refinements were added by Buzen (1973). The increased use of these models stems primarily from the advances made in the computational algorithms available to solve queuing networks. Recent analysis (Suri, 1983) has given the basis for the robustness of queueing networks for use in evaluating manufacturing systems. The run-time of a typical FMS computer model has been reported to be from 1 to 10 seconds on a microcomputer (Solberg, 1980).

The program for the closed network-of-queues model is discussed in Chapter 3. The proposed computer model will compute measures of machine utilization, manufacturing lead time, work-in-process inventory levels, and throughput rate.

## 2.8 Summary of Literature Review

This literature review showed how the manufacturing system appropriate for an SBU depends on its strategic objectives and business strategy. Four types of manufacturing task profiles were presented and the task profiles that might implement an FMC were identified. The literature review also discussed the strategic criteria that should be considered for the performance evaluation of a manufacturing system. AHP, a multiple-criteria decision making methodology, was presented to show how manufacturing objectives will be prioritized. The literature review then discussed the operational measures that are traditionally used to determine the effectiveness of manufacturing systems and presented the theory of queuing networks to aid the manufacturing function in calculating operational measures, such as machine utilization, lead time, work-in-process inventory, and throughput rate.

# Chapter 3

# Methodology and scope

## 3.1 Conceptual design

The conceptual framework for the design and evaluation of a manufacturing system is shown in Figure 1. The strategic objectives of a firm will be the "drivers" for the formulation of the business strategy. The formulation of the business strategy will help determine the primary manufacturing task of the SBU and the strategic criteria on which its products compete, resulting in the identification of the manufacturing task profile of the SBU. Key performance measures should be identified based on the manufacturing objectives appropriate for the SBU and the manufacturing system should be designed while considering the key performance measures. The performance evaluation system should be designed only after the manufacturing system has been designed and the key performance measures identified. The performance evaluation system provides the feedback to upper-management by which it can determine the effectiveness of the manufacturing system, in terms of the overall strategic goals of the company and the business strategy of the SBU. The performance evaluation system should also be capable of predicting manufacturing system performance, given changes in the business strategy. This will enable the manufacturing function to

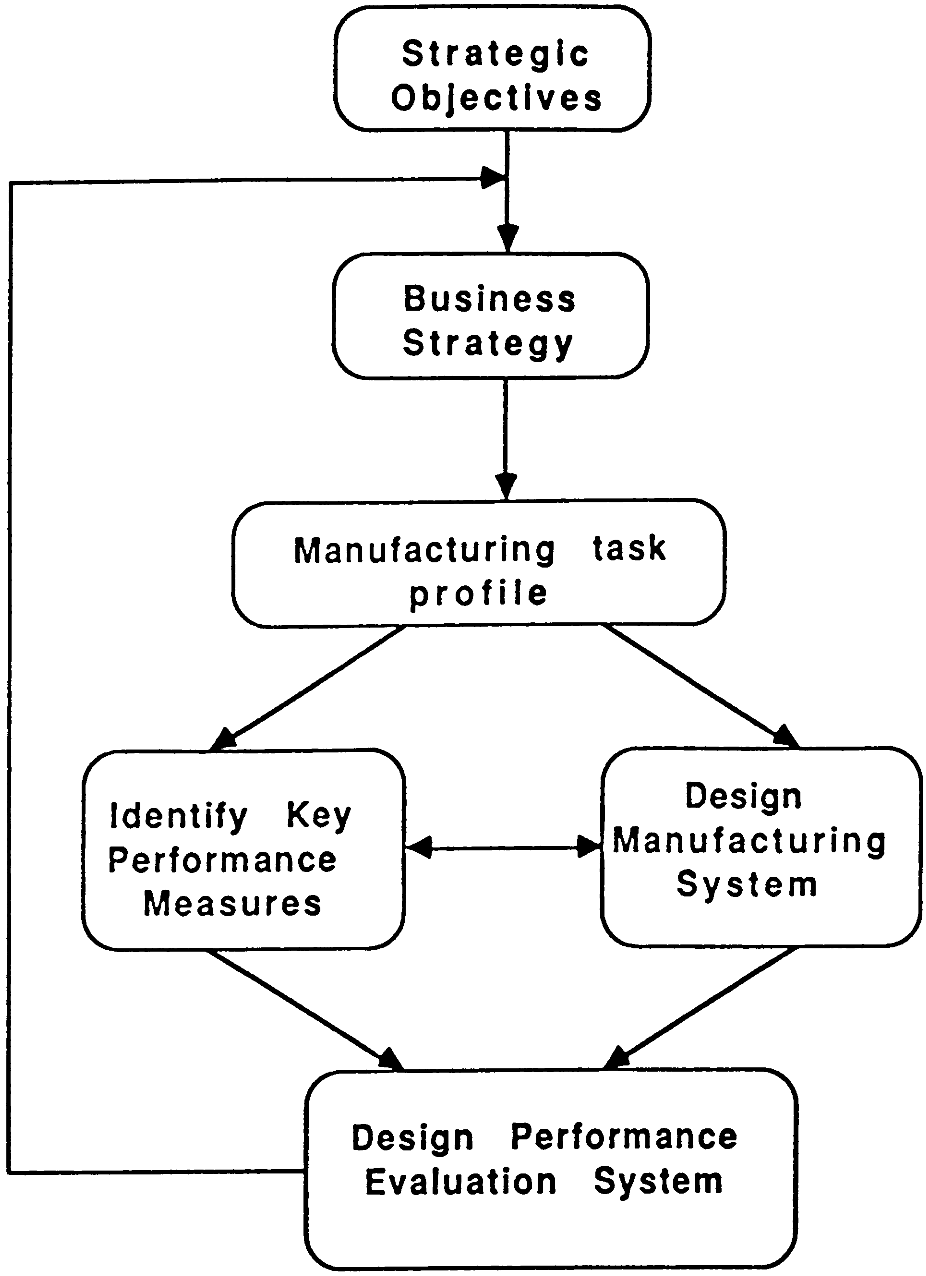


**Figure 1. Conceptual framework for the design and evaluation of a manufacturing system**

take a more active role in formulating the business strategy and changes in the business strategy can be evaluated in terms of their implications for the manufacturing function. Each of the stages shown in Figure 1 are discussed next.

## 3.2 Strategic objectives

The formulation of corporate strategy will result in a clear understanding of the businesses of the firm. The corporate mission will identify the firm's target markets, products, and current and future business scope.

One of the primary objectives of the strategic planning process is to segment the activities of the company into a number of strategic business units (SBUs). Each SBU should select it's business strategy so as to best meet the strategic goals of the firm.

## 3.3 Defining the business strategy for the SBU

A business strategy is a set of well-coordinated action programs aimed at securing a long-term sustainable competitive advantage (Hax and Majluf, 1984). The formulation of the business strategy and its implications for the manufacturing function are discussed further below.

### 3.3.1 Determining the primary manufacturing task of the SBU.

All the products being manufactured in an SBU should be aggregated into product groups, which permits them to be classified as a single group, for strategic planning purposes. For example, a watch manufacturer may broadly classify its products as digital or analog. The implications of the business strategy for the manufacturing function should be specified in terms of the product mix, volumes of output, and the degree of innovation required to fulfill the business strategy. These will help determine the primary manufacturing task of the SBU.

**Product mix**

The product mix of an SBU depends on the strategy for differentiating the product groups offered by the firm for better meeting the needs of the target market. The different product types in each product group should be identified and the resource utilization by each product group should be determined.

**Volumes of output**

For each product group, estimates of current and future volumes of output based on resource utilization should be known for effective capacity planning. The volume of output has important implications on the competitive strategy of the firm and on the type of manufacturing process that is appropriate for the SBU.

**Degree of innovation**

This involves taking into account the number of engineering design changes in existing products and the frequency of introduction of new products. The degree of innovation has important implications on the type of equipment and tooling that can be used. An SBU with a high degree of innovation will use general purpose equipment, while specialized equipment will be used in an SBU with standardized products.

Determining the product mix, volumes of output, and the degree of innovation will help identify the primary manufacturing task of an SBU. Traditionally, a job-shop with a functional layout is considered appropriate for an SBU producing a large number of product groups, with many product types, and a high degree of innovation. As the number of product groups and product types (within each product group) decrease, the manufacturing process will resemble batch production and a flow-shop is considered appropriate for an SBU producing a very small number of product groups with a low degree of innovation,

Identifying the primary manufacturing task alone is not enough to specify the manufacturing system appropriate for the SBU. The business strategy should also reflect how the firm will compete in its markets. For example, Hewlett-Packard has traditionally focused on the relatively low-volume segments of its products' markets and has abandoned products as soon as the market becomes price-competitive. This business strategy emphasizes product quality and product innovation; the manufacturing system at Hewlett-Packard probably resembles a job-shop. Texas Instruments also introduces new products, but follows them through their product life-cycles, even when the market becomes price-competitive. The business strategy for Texas Instruments has emphasized product and volume flexibility to adjust to market changes during the early life of the product, and, as the product matured, has shifted to cost reduction. The manufacturing system at Texas Instruments probably has resembled batch production during the early life of a product, and a flow-shop as the products matured.

The business strategy planning process for a firm will identify the criteria on which the product groups being manufactured in the SBU are most likely to compete. These criteria, shown in Table 2, can be classified as: inherent product characteristics, which include price competitiveness and product quality; and manufacturing system characteristics which include market responsiveness and delivery performance.

Each of these four strategic criteria shown in Table 2 are discussed next.

### 3.3.2 Inherent product characteristics

A natural outcome of the business strategy would be the identification of those product characteristics that distinguish the company's products and enable the firm to capture it's target market share. The product characteristics that need to be considered are: price competitiveness and product quality.

**Table 2. Strategic criteria and related manufacturing objectives**

| Typical strategic criteria | | Related manufacturing objectives |
|---|---|---|
| Inherent product characteristics | Price competitiveness | product cost |
| | Product quality | product reliability |
| | | product conformance |
| Manufacturing system characteristics | Market responsiveness | product flexibility |
| | | volume flexibility |
| | Delivery performance | delivery performance |

**Price competitiveness**

The marketing function determines the price and thus the maximum cost per unit that can be incurred by manufacturing, based on the market segment that the product is aimed for. The implication for manufacturing is to minimize unit costs. In order to compete successfully on the basis of price competitiveness, the product must have high-volume demand and a stable technology. An SBU competing on the basis of cost will normally strive for the maximization of capacity, labor, and material utilization. The manufacturing system of such an SBU typically consists of specialized equipment and is geared towards high volume production.

**Product quality**

Garwin (1987) proposed eight dimensions of quality that can serve as a framework for strategic analysis. He noted that few products rank high on all dimensions, and that an SBU will compete only on selected dimensions. Of Garwin's eight dimensions this research will consider only the implications of product reliability and product conformance. These dimensions of product quality are discussed below.

Product reliability

Reliability reflects the probability that the product won't fail within a specified time period. Reliability of a product becomes important as its downtime and maintainance become more expensive. For example, high reliability of machine-tools used in flexible manufacturing cells is critical since the production of the entire cell is stopped when a machine breaks down. Increasing the reliability of a product often involves an additional expense due to redundancy, where a parallel component backs up a critical component in case it fails. Thus the implication for the manufacturing function (for an SBU emphasizing reliability of the product) is to buy higher-quality machine-tools or to increase the complexity of the product.

Product conformance

Product conformance refers to the degree to which a product's design and operating characteristics meet established standards (Garwin, 1987). Conformance affects the tolerance requirements on a component. Tight tolerances in products facilitate servicing by increasing the interchangeability of parts. Emphasizing conformance may require a tighter control over the manufacturing process and/or increased inspection, resulting in an increase in the total cost and total processing time of a product.

### 3.3.3 Manufacturing system characteristics

The business strategy should also reflect how the manufacturing function is expected to respond to variations to environmental factors. The external variations and how the firm expects to respond to them should be made explicit at the business strategy formulation stage. The manufacturing system characteristics that were considered are: market responsiveness and delivery performance.

**Market responsiveness**

A manufacturing system can be considered as a set of elements organized so as to achieve a predetermined set of objectives based on the business strategy of the firm. Beckman and Jucker (1988) have shown how market responsiveness in an organization can be acquired, not only through manufacturing, but also through other functions like R&D, marketing, and materials. Thus the business strategy should make explicit how the manufacturing function will contribute to increasing the market responsiveness of the firm, by specifying the levels of product and volume flexibility required.

Product flexibility

Product flexibility is the ability of the manufacturing system to respond to design changes in the product. The level of product flexibility required depends on the degree of innovation (number of engineering design changes and the frequency of introduction of new products) of the SBU. A company serving a rapidly changing consumer market will stress product flexibility and the business strategy should specify the range of products that the manufacturing system is expected to produce. A manufacturing system emphasizing product flexibility will probably use general-purpose machines that are capable of performing a variety of operations in order to be able to produce different products and/or implement engineering changes easily.

Volume flexibility

Volume flexibility is the ability of the manufacturing system to respond to variations in the demand for its products. The level of volume flexibility depends on how the SBU decides to respond to variations in demand. Traditionally, production managers have used techniques like production smoothing (based on EOQ calculations) to maintain constant production rates. But this approach often results in large inventories of raw-materials, work-in-process, and finished goods, leading to an increase in the complexity of controlling the manufacturing system. Volume flexibility addresses the need of a system to respond to variations in the demand for its products and is reflected in a varying product-mix. Volume flexibility can also be acquired through increasing the capacity of the plant.

**Delivery performance**

Delivery performance may be defined as the ability of the system to meet production schedules, both during normal operating conditions and during transitions in which the system is adjusting to new conditions, demands, and circumstances (Randhawa and Bedworth, 1985). In some markets, orders may be won through a company's ability to deliver more quickly than its competitors. On the other hand, the delivery performance of a manufacturing system, of an SBU producing commodity goods, is specified by the capacity of the plant and the products will be produced at a constant rate.

The manufacturing process appropriate for an SBU depends on its business strategy. The selection of the manufacturing task profile for an SBU should be made only after a careful analysis of its primary manufacturing task, product characteristics, and manufacturing system characteristics.

## 3.4 Identifying the manufacturing task profile

The manufacturing process selected by an SBU has important implications both on the manufacturing function and the marketing function. The design of the production system imposes constraints on the marketing strategy and, therefore, selecting the appropriate process is vital for a company to meet its strategic objectives.

The formulation of the business strategy involves all the functions of the SBU which include manufacturing, R&D, marketing, and procurement; this research only considers the implications of the business strategy for the manufacturing function. Richardson, Taylor, and Gordon (1985) identified different manufacturing task profiles; this research, using a similar framework, identified four different manufacturing task profiles based on the business strategy of the SBU. Figure 2 shows how the business strategy of an SBU influences the manufacturing task profile appropriate for the SBU through identification of the appropriate the primary manufacturing task. Product characteristics and manufacturing system characteristics also influence the manufacturing task profile (as discussed in Section 3.3). Table 3 shows the four different types of manufacturing task profiles and each task profile in terms of its primary manufacturing task, product characteristics, and manufacturing system characteristics. Each of these task profiles is discussed next.

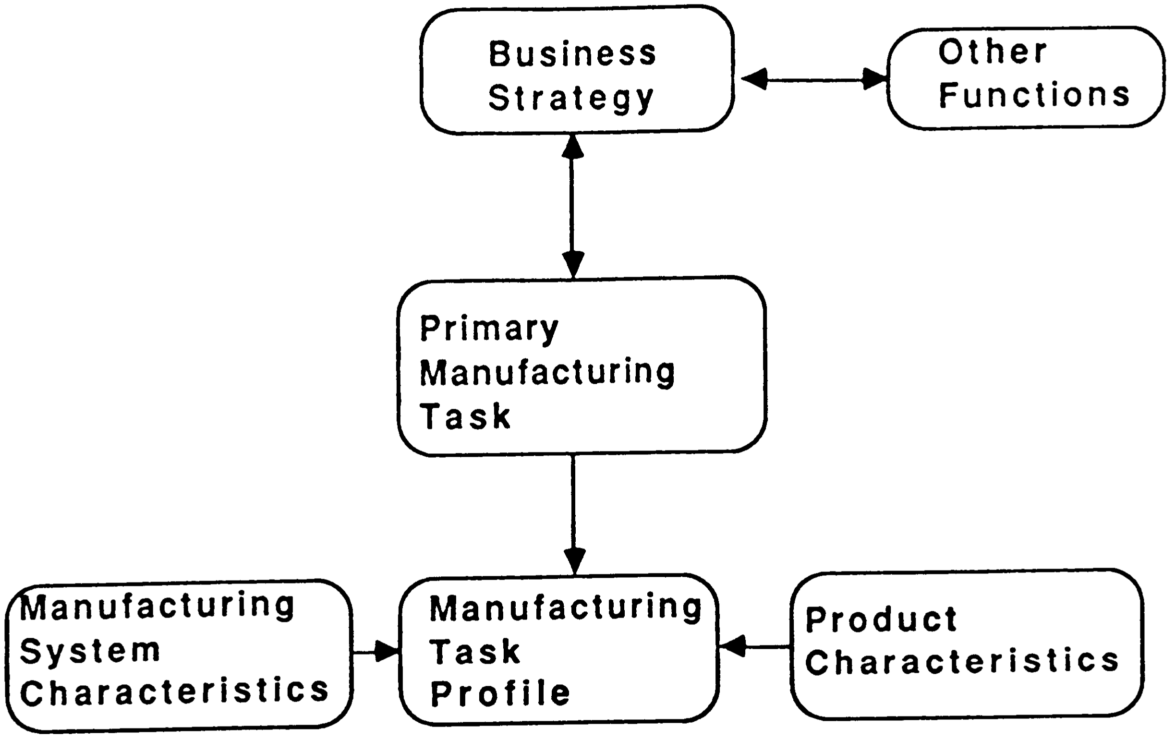


**Figure 2. Identifying the manufacturing task profile of an SBU**

Table 3. Manufacturing Task Profiles

| Manufacturing task profile | | A | B | C | D |
|---|---|---|---|---|---|
| Primary manufacturing task | Number of products | high | medium | medium | low |
| | Volumes of output | low | medium /high | medium | high |
| | Degree of innovation | high | high | medium | low |
| Product characteristics | Product cost | high | low/ medium | medium | low |
| | Product quality | high | high | high | medium |
| Manufacturing system characteristics | Equipment | general purpose | general purpose | general purpose | special |
| | Tooling | general purpose | special | special | special |
| | Layout | job-shop | cellular mfg. | cellular mfg. | flow shop |
| | Complexity | high | medium | medium | low |

**New-product centered (Manufacturing task profile A)**

Companies with this profile focus on bringing new products to market frequently. Typical examples include companies which focus on relatively low-volume segments of their products' markets and abandon products as soon as the market becomes price-competitive.

Primary manufacturing task

These firms are characterized by a high degree of innovation. The introduction of new products, usually accompanied by low-volume production, is a primary objective of such firms. These firms have an outstanding R&D function that plays an important role in the formulation of the business strategy.

Product Characteristics

Cost per unit is not a dominant characteristic and product performance is emphasized. The product attributes that are emphasized are high performance and advanced features. Typical products include micro-computers.

Manufacturing system characteristics

The equipment used is general-purpose and the layout typically is a low-volume job-shop, with a high degree of flexibility. The potential for product flexibility is extremely high and, as long as the equipment is available, any type of product can be manufactured. The emphasis is thus on the ability of the system to adapt to varying product specifications and to maintain product quality. Low volumes prevent the advantages of economies of scale and the labor content is relatively high. The trade-off to the high flexibility of the system is low capacity utilization and large work-in-process inventories.

Manufacturing objectives

These firms emphasize product quality and product flexibility. Product cost and delivery performance are not usually factors on which products compete.

**Custom innovator (Manufacturing task profile B)**

Companies with this profile also focus on introducing new products, along with attempting cost minimization. Typical examples include companies which introduce a stream of new products, but follow them through their product life-cycles, even when the market becomes price competitive.

Primary manufacturing task

These firms compete in medium to high volume markets and simultaneously emphasize product innovation. New products are frequently introduced and product and volume flexibility are emphasized to adjust to market changes during the early life of the product. As the product matures the firms strive to minimize the cost per unit. These firms also have a dominant R&D function.

Product characteristics

Minimizing the cost per unit is a significant factor for such firms. There is also an emphasis on the frequent introduction of new products and on product quality. Typical products include electronic office equipment.

Manufacturing system characteristics

Products are typically manufactured in batches, and the manufacturing system of such firms are good candidates for cellular manufacturing, due to the manufacturing similarities among products. General-purpose equipment and specialized tooling, fixtures, and gages are used for large batches. The complexity of the system is less than that of a job shop and volume flexibility is emphasized. Capacity utilization is high and work-in-process inventory is low, relative to a job shop.

Manufacturing objectives

With the introduction of a new product, the manufacturing system is geared for product flexibility and volume flexibility. As the product matures, the degree of innovation for that product decreases and the volume increases. The manufacturing system would, at that point, emphasize cost minimization.

**Cost minimizing job-shop (Manufacturing task profile C)**

Companies with this profile typically focus on customizing their products. Typical examples are companies which manufacture their products to customer specifications.

Primary manufacturing task

These firms emphasize market responsiveness (the ability to adapt to changes in the product design and production volumes) and strive to minimize the cost per unit. Changes in product design are typically market driven and consequently the marketing function plays an important role in the formulation of business strategy.

Product characteristics

The emphasis here is on the ability to deliver medium-cost customized products on schedule. Customer specifications, resulting in changes in product design and volumes, necessitate outstanding design and process engineering. Typical products include machine-tools.

Manufacturing system characteristics

The manufacturing system is designed for low to medium volumes, with an emphasis on volume flexibility and short production lead times. General-purpose equipment is used and firms with this task profile are also good candidates for implementing cellular manufacturing. Capacity utilization is high and work-in-process inventory is low, relative to a job shop.

Manufacturing objectives

These firms emphasize product quality and delivery performance. A high degree of product flexibility is required as products are made to customer specifications.

**Cost minimizer (Manufacturing task profile D)**

Companies with this profile focus on high-volume production of standardized products. Typical examples are companies which strive for cost minimization through economies of scale.

Primary manufacturing task

These firms are high-volume low-cost producers of mature products. Very few standard products are produced and the introduction of new products is rare. The primary objective of such firms is cost minimization.

Product characteristics

Product standardization results in very few product design changes and the volume of output is determined by the capacity of the production system. Typical products include bearings.

Manufacturing system characteristics

The manufacturing system consists of specialized equipment dedicated to a special task and the layout is typically a flow shop. High capacity utilization and low work-in-process inventories result in minimizing the cost per unit and the system is not generally flexible to changes in product design nor production volumes. Optimization of such systems often results in transfer-lines, with a high degree of capacity utilization.

Manufacturing objectives

The dominant objective is cost minimization. Due to the standardization of products, market responsiveness and delivery performance are not usually emphasized.

Implicit in the decision as to the type of manufacturing task profile that is appropriate for an SBU is a tradeoff of certain operational measures like machine utilization, work-in-process inventory, throughput rate, manufacturing lead time, and set-up time. These operational measures for each of the manufacturing task profiles are discussed next.

### 3.4.1 Operational measures for different manufacturing task profiles

Manufacturing task profile A, which has a functional layout, and manufacturing task profile D, which resembles a flow-shop, are two extreme cases of the types of manufacturing systems. Manufacturing task profiles B and C, which use batch production, have intermediate values for the above performance measures. The operational measures for the different manufacturing task profiles are shown in Table 4 and are discussed next.

#### Machine utilization

Machine utilization will probably be greatest for flow-shops (manufacturing task profile D) since specialized machines perform similar operations on successive products. Similarly, machine utilization will be the lowest for manufacturing task profile A, due to high set-up times.

#### Work-in-process inventory

Manufacturing task profile A will probably have the highest work-in-process inventory due to a large amount of time spent waiting for machines and transportation. Manufacturing task profile D, on the other hand, has only a prespecified level of work-in-process inventory as jobs move serially from machine-to-machine.

#### Throughput rate

The throughput rate is maximum for manufacturing task profile D. The throughput rate is a function of the machining times, set-up times, waiting times, and travel times of jobs. In a flow-shop the throughput rate is high, as set-up times, waiting times, and travel times are minimized. Manufacturing task profile A has high set-up and travel times, and consequently a low throughput rate.

Table 4. Operational measures for different manufacturing task profiles

| Oper. measures \ Mfg. task profile | A | B | C | D |
|---|---|---|---|---|
| Machine utilization | low | medium | medium | high |
| Work-in-process | high | medium | medium | low |
| Throughput rate | low | medium | medium | high |
| Manufacturing lead time | high, uncertain | medium, uncertain | medium, uncertain | low, certain |
| Set-up time | high | medium | medium | low |

**Manufacturing lead time**

The manufacturing lead time is the average time that the job spends in the system. It is the sum of the waiting times, set-up times, travel times, and machining times. In a flow-shop, the manufacturing lead time is minimized as the set-up times, travel times, and waiting times are minimized. The lead time in a flow-shop thus depends mainly on the machining time and is specified while designing the system. In a functional layout, the set-up times are high, and the waiting and travel times are uncertain, thus resulting in a high and uncertain manufacturing lead time.

**Set-up time**

Manufacturing task profile D typically has the lowest set-up time due to the use of specialized equipment producing stable products. Changes in the product typically result in a complete change in the layout of the manufacturing system. Manufacturing task profile A, on the other hand, has high set-up time due to the wide variety of products being produced.

To summarize, this section presented a classification of manufacturing systems based on the primary manufacturing task, product characteristics, and manufacturing system characteristics of firms. Four manufacturing task profiles were identified and operational measures were discussed for each of the task profiles.

As discussed in Chapter 2, a manufacturing system should be evaluated in terms of how well it meets the goals and objectives defined for it by the corporate mission. The performance measurement systems prevalent today are based on high-volume standardized production and emphasize cost minimization through maximizing labor, capacity, and material utilization, which is typical of firms resembling task profile D. But task profiles A, B, and C probably should not emphasize cost minimization but should focus instead on other objectives, such as quality and flexibility. A new development in manufacturing, that is of personal interest to this researcher, is the concept of flexible manufacturing cells (FMCs), which are combinations of various types of equipment that are interfaced to work in unison and produce automatically a family of products. FMCs are specific applications of group technology and are designed to produce different part families that are grouped based on manufacturing similarities. Since FMCs may produce only a small number of the total product types manufactured in a plant, it is possible to view an FMC as a separate manufacturing system within the plant, and to evaluate the FMC based on the strategic criteria on which its products compete. This research will now focus on developing a framework to evaluate FMCs that accurately reflects the strategic benefits and competitive advantages that they permit.

## 3.5 Flexible manufacturing cells

Companies with manufacturing task profile A produce a large number of products types, and the volumes of output of each part-family to be manufactured simultaneously may not justify the creation of cells. On the other hand, a company with task profile D produces a small number of product types and is likely to use specialized equipment, using a flow-shop layout, due to the emphasis on cost minimization. Companies with manufacturing task profiles B & C, which manufacture their products in a batch environment are good candidates for implementing FMCs, due to the manufacturing similarities of the products they manufacture. The manufacturing objectives that firms implementing FMCs are likely to emphasize can be any of the objectives emphasized by firms with task profiles B or C. These manufacturing objectives are:

1. product reliability.
2. product conformance.
3. product flexibility.
4. volume flexibility.
5. delivery performance.

Hyer (1984), on the basis of a survey, found that firms using cellular manufacturing usually produce a wide variety of items manufactured in relatively small lots. She determined that 75 per cent of users of cellular manufacturing cited reduced manufacturing lead times, resulting in improved delivery performance, as the major factor for implementing cells. Other reasons cited were improved quality and reduced work-in-process inventories.

## 3.6 Identification of key performance measures for FMCs

The manufacturing function cannot be expected to place an equal emphasis on all the criteria shown in Table 2 (p. 29). Key performance measures should be selected so that they accurately reflect the effectiveness of the FMC in helping the SBU achieve the strategic goals of the firm. Figure 3 shows the procedure for identifying the key performance measures for FMCs. As discussed in Section 3.5, task profiles B and C are likely candidates for implementing FMCs. The next step is to prioritize the manufacturing objectives of the cell, based on the strategic criteria on which the products to be manufactured in the cell compete. Prioritizing the manufacturing objectives of an FMC is discussed in detail in Section 3.6.1. Performance measures related to the prioritized objectives should then be identified as the key performance measures and the FMC should be designed considering the key performance measures. The procedure shown in Figure 3 is discussed in the next few sections.

### 3.6.1 Prioritizing the manufacturing objectives of an FMC

Integral to the concept of cellular manufacturing is part family identification. As the part families to be manufactured in a cell are grouped based on manufacturing similarity, the strategic criteria on which they compete need not be the same. The analytical framework to be used for prioritizing the manufacturing objectives of an FMC is the analytic hierarchy process (AHP) introduced by Saaty (1980).

Using AHP to solve the decision problem of prioritizing manufacturing objectives involves the following steps (Saaty, 1980):

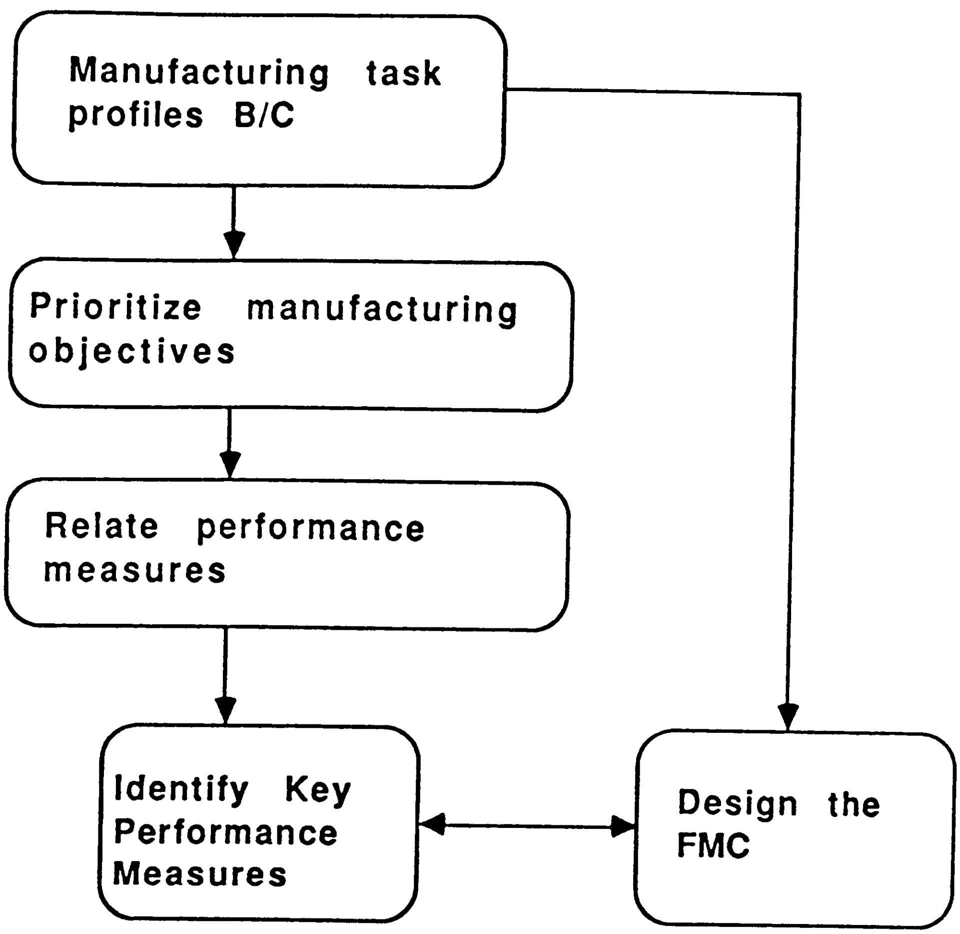


Figure 3. Identification of key performance measures for FMCs

1. Breaking down the decision problem into a hierarchy of interrelated decision problems.
2. Setting up the scale for pairwise comparisons of the decision elements.
3. Estimating the local priorities of the attributes.
4. Estimating the global priorities of the attributes.

1. Breaking down the decision problem into a hierarchy of interrelated decision problems.

The hierarchy is an abstraction of the structure of a system and allows study of the various components of the system in terms of their interactions and impacts on the entire system (Saaty, 1980). The advantages of using a hierarchy are:

1. Hierarchical representations of systems can be used to describe how changes in priority at upper levels affect the priority of elements at lower levels.
2. Hierarchies give details on the structure and function of a system at the lower levels.
3. Hierarchies are stable and flexible; stable in that small changes have little effect and flexible in that additions to a hierarchy generally do not disrupt the performance of the hierarchy.

At the top of the hierarchy lies the most macro decision objective; lower levels contain attributes which contribute to the quality of the decision. Saaty (1980) suggests that each level of a hierarchy should not contain more than nine elements. The reason cited was that psychological experiments suggest limiting the number of items to $7 \pm 2$, in simultaneous comparison studies.

The hierarchy suggested for prioritizing the manufacturing objectives of an FMC is shown in Figure 4. The first level of the hierarchy (at the top of Figure 4) is the goal, which is to design the FMC based on the strategic criteria on which products compete. The second level of the hierarchy consists of the different products that have been selected to be produced in the FMC. The third level of the hierarchy contains the manufacturing objectives: product cost, product reliability, conformance, product flexibility, volume flexibility, and delivery performance.

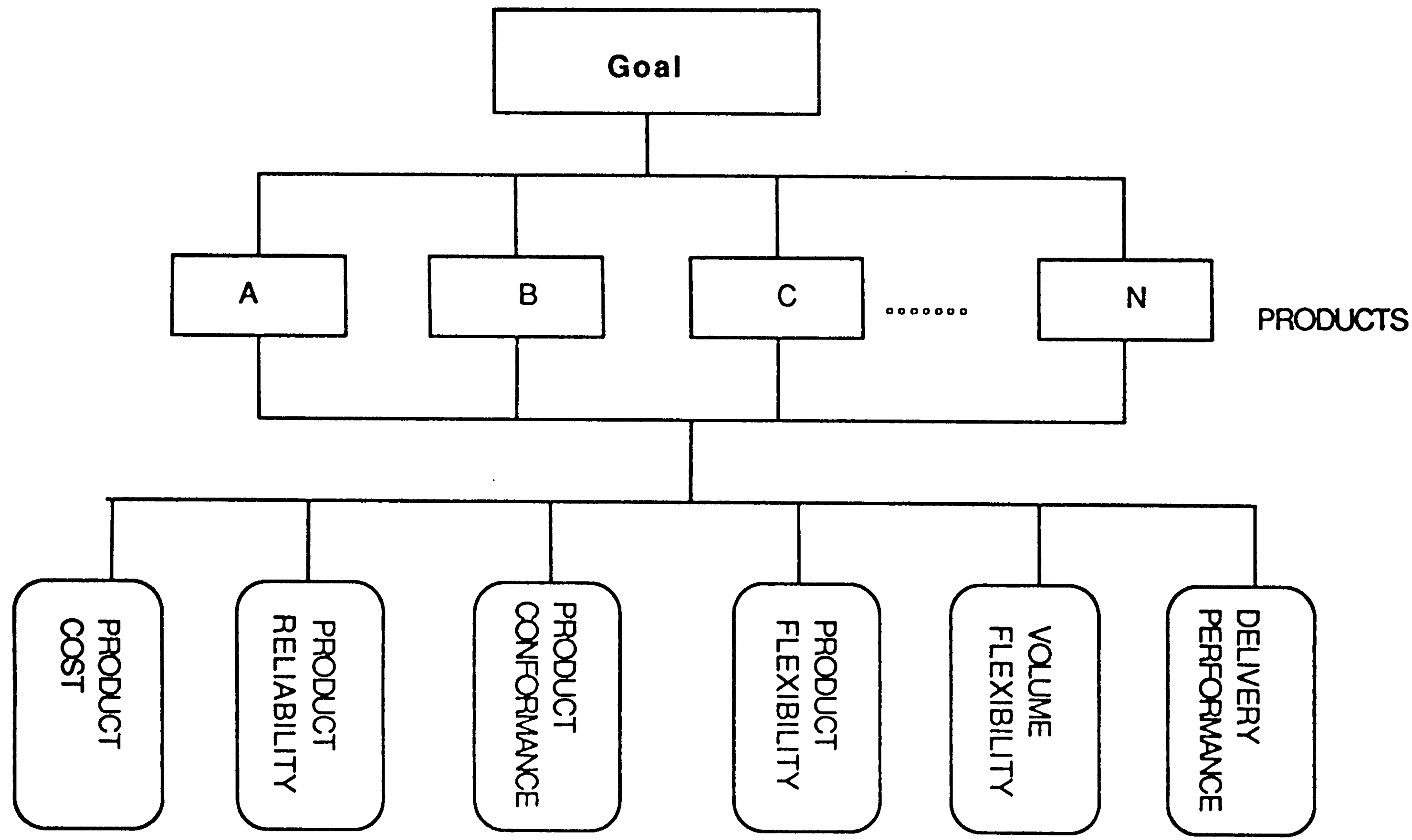


**Figure 4. AHP To Prioritize Manufacturing Objectives**

2. Setting up the scale for pairwise comparisons of the decision elements.

The elements in the second level (products) are prioritized with respect to the first level (goal) based on the fraction of resource utilization of the cell, of each product type. Each product at the second level is assigned a priority fraction, $f_i$ , $i = 1,2,...,n$, where $n$ is the number of products to be produced in the FMC.

$$\sum_{i=1}^{i=n} f_i = 1$$

Pairwise comparisons of the manufacturing objectives at the third level of the hierarchy are carried out (for importance of one objective to another) using the scale suggested by Saaty (1980), as shown in Table 5, to determine their local priorities. The input data for any AHP problem consists of matrices of pairwise comparisons of the elements of one level that contribute to achieving the objectives of the next higher level.

Consider an example where two objectives -- cost and reliability -- are compared with respect to product N, at the second level, as shown in Figure 2. Let $A$ denote the comparison matrix.

$$A = \begin{bmatrix} 1.0 & 2.0 \\ 1/2 & 1.0 \end{bmatrix}$$

The properties of any comparison matrix are:

<u>Property 1:</u> The comparison matrix is a square matrix, with the number of rows $n$ equal to the number of columns.

<u>Property 2:</u> The diagonal elements of the comparison matrix $A$ ($a_{11}$, $a_{22}$) will always be 1, as any objective will have equal importance when compared to itself (Refer Table 5). Therefore

$$a_{ij} = 1$$

Table 5. Scale for pairwise comparisons [Source: Saaty (1980)]

| Intensity Of Importance | Definition |
|---|---|
| 1 | Equal importance |
| 3 | Weak importance of one over the other |
| 5 | Strong importance of one over the other |
| 7 | Very strong importance of one over the other |
| 9 | Absolute importance of one over the other |
| 2,4,6,8 | Intermediate values between adjacent scale values |

if $i = j$, where $a_{ij}$ is the $j^{th}$ element of row $i$, of matrix $A$.

Property 3 The lower triangle elements of the comparison matrix are reciprocals of the upper triangle elements.

$$a_{ij} = \frac{1}{a_{ji}}$$

where $i \neq j$.

Therefore in matrix $A$, $a_{12}$ (the second element of row 1) has a value of 2, which indicates that cost has a weak importance over reliability (Refer to Table 5) and $a_{21}$ has a value of 1/2.

Pairwise comparison data are thus required for fewer than half of the matrix elements.

3. Estimating the local priorities of the attributes

The solution technique of AHP calculates the local priorities of each objective at the third level, with respect to each product at the second level. For the above example, the local priorities of cost and reliability are calculated with respect to product N. The methodology proposed by Saaty (1980) is as follows:

Let $w_C$ and $w_R$ denote the actual priorities of objectives -- cost and reliability -- respectively, with respect to product N. Then

$$a_{ij} = \frac{w_i}{w_j} \qquad (1)$$

For the given example, $a_{CC} = \frac{w_C}{w_C}$, $a_{CR} = \frac{w_C}{w_R}$, $a_{RC} = \frac{w_R}{w_C}$ and $a_{RR} = \frac{w_R}{w_R}$. From equation (1) we have,

$$a_{ij} . \frac{w_j}{w_i} = 1$$

or

$$\sum_{j=1}^{j=n} a_{ij}.w_j = n.w_i$$

which is equivalent to

$$A.W = n.W \tag{2}$$

where $W = (W_1, W_2, \ldots, W_n)$ is the vector of actual priorities, which has to be estimated (the symbol "." represents a multiplication sign for the rest of this thesis).

The estimation of $W$ (denoted as $\hat{W}$) can be obtained from the following equation

$$A.\hat{W} = \lambda_{\max}.\hat{W} \tag{3}$$

where $A$ is the matrix of pairwise comparisons, $\lambda_{\max}$ is the largest eigenvalue of $A$, and $\hat{W}$ is the eigenvector for $\lambda_{\max}$.

A square matrix with $n$ rows will have $n$ eigenvalues. Due to the fact that the comparison matrix is a reciprocal matrix, all the eigenvalues except $\lambda_{\max}$ will be zero. The eigenvalues can be computed from the equation

$$A - \lambda.I = 0$$

where $I$ is the identity matrix. The eigenvalues computed for the given matrix A are:

$$\lambda = 0, 2$$

Therefore $\lambda_{\max} = 2$. For $n = 2$, as only one comparison is carried out between two attributes, the eigenvector has to be equal to 2, since the comparison is always consistent.

Equation (3) can be written as

$$A.\hat{W} = \lambda_{\max}.\hat{W}.I$$

Solving the above equation, we get

$w_C + 2w_R = 2w_C$

$\frac{w_C}{2} + w_R = 2w_R$

Therefore

$$w_C = 2.w_R \tag{4}$$

In order to have a normalized solution where the priorities sum up to 1, we have

$$w_C + w_R = 1 \tag{5}$$

Solving equations (4) and (5), we get $w_C = 0.667$ and $w_R = 0.333$ . Hence for the given example, cost has a priority of 0.667 and reliability has a priority of 0.333.

Saaty (1980) has shown that $\lambda_{max}$ in (3) is always greater than or equal to $n$, and has defined a consistency index (CI) as

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{6}$$

The consistency index (CI) gives an indication of the consistency of the pairwise comparisons. To assess the consistency derived in (6), Saaty (1980) obtained a random index (RI) by filling the elements of pairwise comparison matrices at random for $n = 1,2,...,10$, where $n$ is the order of the matrix. As can be seen from Table 6, the random index for $n = 1$ and $n = 2$ is 0. Thus for a comparison matrix with $n = 1,2$; $\lambda_{max}$ should be equal to $n$.

Saaty (1980) defined the consistency ratio (CR) as

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

**Table 6. Random index for different n [Source: Saaty (1980)]**

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0.0 | 0.0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

which is required to be less than 0.1 for acceptable results.

4. Estimating the global priorities of the attributes.

After deriving the local priorities of the objectives with respect to each of the products on the second level, global priorities are obtained by multiplying the local priority vector of the objectives by the priority vector of the products at the next higher level.

For the given example, let $w_{CM}$ and $w_{CN}$ be the priorities of cost for products $M$ and $N$ respectively, and let $w_{RM}$ and $w_{RN}$ be the priorities of reliability for products $M$ and $N$ respectively. Also let $M$ and $N$ be the only two products to be produced in the FMC, and let $f_M$ and $f_N$ be the priorities of $M$ and $N$ respectively. Then the global priorities are obtained by multiplying the vectors of the local priorities cost and reliability with the priority vector of $M$ and $N$

$$\begin{bmatrix} w_{CM} & w_{CN} \\ w_{RM} & w_{RN} \end{bmatrix} \begin{bmatrix} f_M \\ f_N \end{bmatrix} = \begin{bmatrix} W_C \\ W_R \end{bmatrix}$$

Therefore the global priority of cost $=$ $W_C$ is

$$W_C = w_{CM} \cdot f_M + w_{CN} \cdot f_N$$

and the global priority of reliability $=$ $W_R$ is

$$W_R = w_{RM} \cdot f_M + w_{RN} \cdot f_N$$

### 3.6.2 Key performance measures

Depending on the prioritized manufacturing objectives, an FMC should focus on a set of key performance measures (those that support the prioritized manufacturing objectives). For example an FMC that has been designed for a high degree of product flexibility would tend to have small batches, due to the range and variety of products being produced in the cell. This will result in an increase in the set-up time. Using the set-up time alone as a performance measure might lead to managers scheduling larger batch sizes thus reducing the market responsiveness of the firm. On the other hand, focusing on product flexibility would result in an effort to reduce the set-up time, through better design of jigs and fixtures, or to eliminate set-up times by performing more than one operation per set-up. Manufacturing performance measures should therefore be selected so that they accurately reflect the advantages of the FMC, in support of the manufacturing objectives of the firm.

For each of the manufacturing objectives (at the third level of Figure 4), related performance measures are shown in Table 7. The implications of each of the manufacturing objectives on the manufacturing system are discussed below:

**Product cost**

Typical measures include maximizing labor, capacity, and material utilization. The implications for an FMC producing products which compete primarily on cost are:

1. High volumes to take advantage of economies of scale.
2. Specialized equipment and tooling.
3. Low degree of innovation allowing little or no product customization.
4. High machine utilization.
5. Prespecified level of work-in-process inventory.
6. Low manufacturing lead time.
7. Little flexibility to deal with variations in the environment.

It should be noted that an FMC is not likely to be used for producing products that compete on cost, since it will be more appropriate to use specialized equipment ("hard automation") for that purpose.

Table 7. Manufacturing objectives and related performance measures.

| Typical strategic criteria | Related manufacturing objectives | Performance measures |
|---|---|---|
| Price competitiveness | product cost | labor utilization |
| | | capacity utilization |
| | | material utilization |
| Quality specifications | product reliability | mean time between failures |
| | product conformance | per cent rejected |
| Market responsiveness | product flexibility | response time to engineering changes |
| | | product options or variants |
| | volume flexibility | response time to volume changes |
| Delivery performance | delivery performance | per cent on time shipments |
| | | predictability of delivery dates |

**Product reliability**

A typical measure is the maximizing the mean time between failures of the product. The implications of emphasizing product reliability are:

1. Increased complexity of the product.
2. Increased total processing time of the product.
3. Increased manufacturing lead time.
4. Increased product cost.

Thus emphasizing product reliability will result in an increase in the total processing time of the job, in the FMC.

**Product conformance**

A typical measure for an FMC emphasizing product conformance is minimizing the per cent of products rejected. An FMC emphasizing this manufacturing objective will have the following characteristics:

1. Use of high-precision equipment.
2. Increased inspection.
3. Increased manufacturing lead time.
4. Increased product cost

Emphasizing product reliability will therefore result in increased inspection and/or the need for tighter control of the manufacturing process.

**Product flexibility**

Typical measures include maximizing the number of product options or variants produced in the cell and minimizing the response time to engineering changes. An FMC emphasizing product flexibility will have the following characteristics:

1. Use of general-purpose equipment and tooling.
2. Increased set-up times.
3. Increased manufacturing lead time.
4. Increased product cost.

An FMC emphasizing product flexibility will have to contend with frequent set-ups and increased manufacturing lead time.

**Volume flexibility**

A typical measure for an FMC emphasizing volume flexibility is minimizing the response time to volume changes. The implications for the FMC are:

1. Additional capacity.
2. Varying product mix.
3. Varying machine utilizations.

Emphasizing volume flexibility will therefore result in low/varying machine utilization.

**Delivery performance**

Typical measures include maximizing the per cent on time shipments and predictability of delivery dates. An FMC emphasizing delivery performance will consider:

1. Low machine utilization.
2. Low work-in-process inventory.
3. Small lot-sizes to reduce manufacturing lead times.

Emphasizing delivery performance will therefore require the FMC to have low work-in-process inventories, to minimize the waiting times of jobs.

To summarize, this section discussed a procedure for the identification of the key performance measures of an FMC. A methodology to prioritize the manufacturing objectives of an FMC was presented, and, based on the prioritized objectives, related performance measures were identified. The implications of emphasizing each of the manufacturing objectives, for an FMC, were also hypothesized. It should be noted that the manufacturing objectives are not independent of each other, and the implications of emphasizing two or more of the objectives simultaneously may be different than those hypothesized above.

## 3.7 Design of the FMC

The manufacturing system should be designed considering the key performance measures that have been identified for the FMC. This research will only consider the preliminary design and evaluation of the FMC, in terms of operational measures like throughput rate, work-in-process inventory, machine utilization, and manufacturing lead time. Since the operational measures of an FMC are very system specific (depending on the type of machines and products to be manufactured in the FMC), a queuing model is used to aid in the preliminary design and evaluation of the FMC. A computer-based model developed for this research, based on the theory of closed network of queues (Jackson, 1963), will help determine operational measures and also evaluate how changes in the products and the product-mix will affect the performance of the FMC.

A queuing network model consists of a set of workstations, where servers provide service to arriving jobs. The flowchart for the computer-based model developed for this research is shown in Figure 5 and is discussed next.

The program for the above model was written using the C language on a UNIX-based PC (AT&T 7300). The program consists of two basic modules:

(i) User-interface module.

(ii) Computation module.

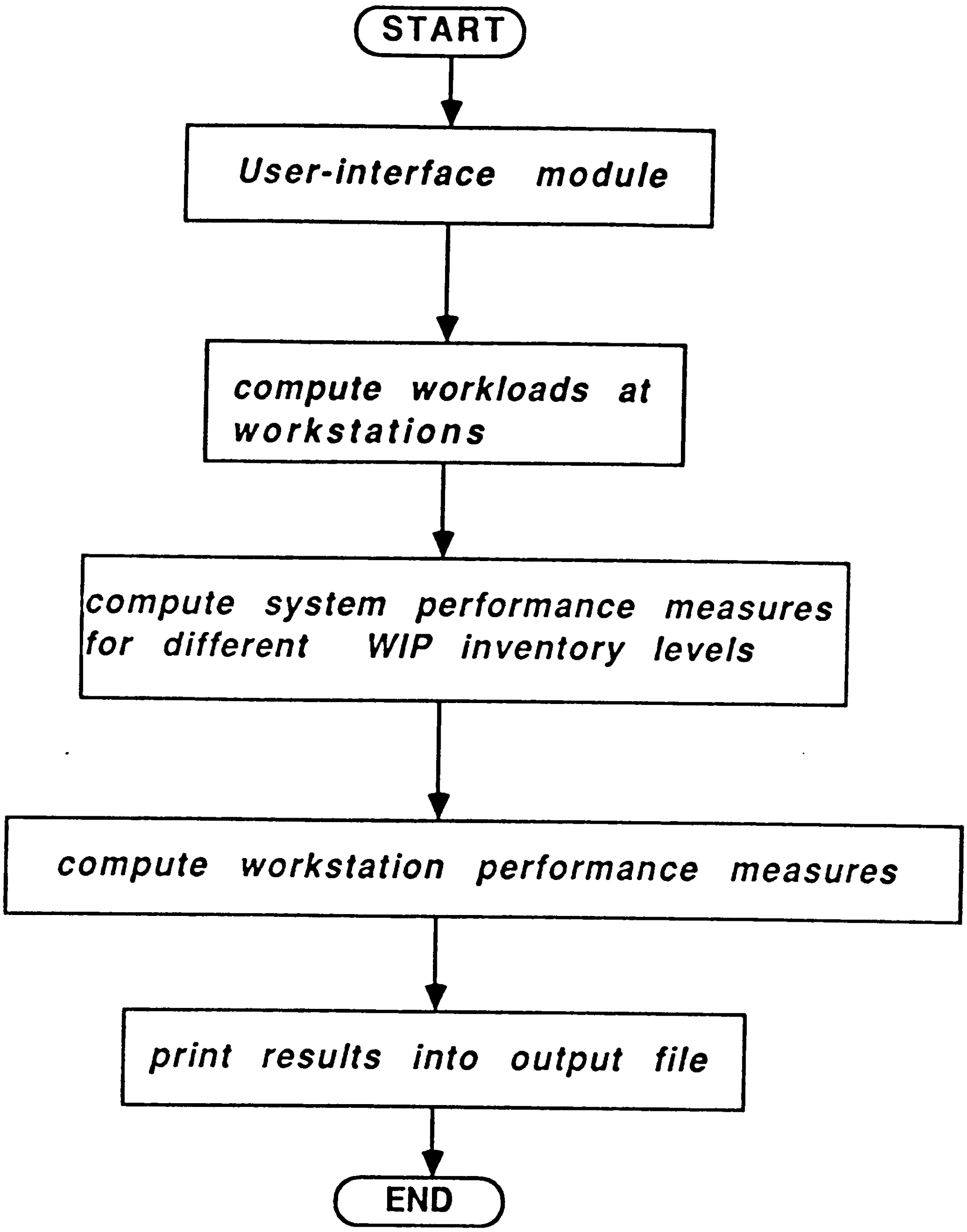


Figure 5. Flowchart for computer-based model

**User-interface module**

The first module is a user-interface that enables the user to input data describing the system. This module uses the "UNIX CURSES" screen management package. The first function in this module sets-up the initial "window" on the screen. The second function of this module sets-up the screen to enable the user to input the system description as to the number of workstations $M$, and the number of servers $S_{i,}$ at each station $i$.

Consider a manufacturing system with $M - 1$ workstations. Let the transport mechanism be the $M^{th}$ workstation. The number of servers at a workstation is equal to the number of jobs that can be processed simultaneously at that station. The program has a data-structure associated with each workstation. The input parameters to this function are:

$M$ - the number of workstations.

$S_i$ - the number of servers at workstation $i$.

For the $M^{th}$ workstation (transport mechanism), the user is also required to input the transport time ($w_m$), which is the total travel time divided by the number of operations.

The third function sets-up the screen to enable the user to input data regarding the number of jobs to be processed in the cell and the process-plan of each of the jobs. Each job has a data-structure associated with it which contains all the information about that job. The process plan of the job is defined as the description of the sequence of stations visited by the job, and the duration of each visit. All jobs which follow the same process plan make up one product type. Let the number of product types to be manufactured in the system be $n$. The fraction of production of each product type will describe the product mix. The input parameters to this function are:

$n$ - the number of product types.

$N$ - the work-in-process inventory.

$p_j$ - the fraction of production of job $j$, $(\sum_{j=1}^{j=n} p_j = 1)$.

$t_{ijk}$ - the processing time for operation $k$, of job $j$, at station $i$.

$f_{ijk}$ - the frequency of operation $k$, of job $j$, at station $i$.

**Computation module**

The second module implements Buzen's algorithm (1973) to compute system performance measures.

Assumptions

1. All the processing times are assumed to be exponentially distributed.
2. The service discipline at each workstation is assumed to be first come first served (FCFS).
3. There is a fixed work-in-process inventory level ($N$) (specified by the user).

The first function in this module calculates the mean number of visits to each workstation, and the mean processing time at each workstation $i$.

The mean number of visits to station $i$: $v_i = \sum_j \sum_k f_{ijk} \cdot p_j$

The mean processing time at station $i$: $t_i = \sum_j \sum_k t_{ijk} \cdot f_{ijk} \cdot p_j$

The workload at each station $i$: $w_i = t_i . v_i . v_m$

where $v_m$ is the frequency of visits to the transporter and is given by:

$$v_m = \frac{1}{\sum_i \sum_j \sum_k f_{ijk} \cdot p_j}$$

Let $n_i$ denote the number of jobs at station $i$. Let $\bar{n}$ denote the vector $(n_1, n_2, \ldots\ldots, n_m)$ , or the global state of the network at a particular instant. Let $p(\bar{n})$ denote the steady-state probability of finding the network in state $\bar{n}$. For the negative exponential distribution, the stochastic process is a continuous time Markov process. At steady-state, the probability that a unit leaving station $i$ goes to the transporter is 1, and the probability that the unit goes to station $i$ from the transporter is $e_i = \frac{v_i}{v_m}$ .

Gordon and Newall (1967) have shown that

$$p(\overline{n}) = \frac{1}{G(M,N)} \prod_{i=1}^{i=M} f_i(n_i)$$

This is known as the product-form solution which helps in deriving the equilibrium probabilities of finding the system in a particular state. $G(M,N)^{-1}$ is a normalizing constant defined to ensure that the probabilities sum to 1 . The $f_i(n_i)$ are functions defined for each station $i$:

For workstations with a single server:

$$f_i(n_i) = w_i^{n_i}$$

For workstations with multiple servers:

$$f_i(0) = 1.0$$

$$f_i(n_i) = \frac{w_i^{n_i}}{n_i!}$$

when $n_i \leq s_i$.

$$f_i(n_i) = \frac{w_i^{n_i}}{s_i^{n_i - s_i} . s_i!}$$

when $n_i > s_i$.

The normalizing constant G(M,N) has to be calculated for all states $k \geq 0$ . Buzen (1973) developed an efficient recursive technique to compute G(M,N).

$$G(m,n) = \sum_{k=0}^{k=n} f_m(k).G(m-1,n-k) \quad (7)$$

for $m = 1$ to $m = M$, and $n = 1$ to $n = N$. For a workstation with a single server,

$$f_m(k) = w_m^k = w_m.f_m(k-1)$$

Substituting this value of $f_m(k)$ in equation (7), we get

$$G(m,n) = G(m-1,n) + w_m.G(m,n-1) \quad (8)$$

The computation of the normalization constant is performed by an iterative procedure which fills in values in a vector $G$. One iteration is performed for each of the $M$ workstations in the system. The initial conditions are $G(1,n) = f_1(n)$ and $G(m,0) = 1$. Each succeeding iteration computes a new set of values for the vector $G$, from those values stored in $G$ by the preceding iteration. For each iteration $G(m,n)$ is calculated from either equation 7 or 8, depending on whether the workstation has multiple-servers or a single server, respectively.

After the computation of the normalization constant $G(M,N)$, the next function in the computation module computes system performance measures using the relationships derived by Solberg (1976, 1980).

Throughput rate: $R = \frac{G(M,N-1).v_M}{G(M,N)}$

where $v_M$ is the frequency of visits to the transporter.

Average time in system: $T = \frac{N}{R}$

Average processing time: $T_p = \frac{G(M,1) - w_M}{v_m}$

where $w_m$ is the transportation time.

Average travelling time: $T_t = \frac{w_M}{v_M}$

Average waiting time: $T_w = T - T_p - T_t$

For different values of $N$, the throughput rate and the average time in the system are given by:

$$R = \frac{v_M}{G(M,1)}$$

$$T = 1/R$$

when $N = 1$.

For $N > 1$,

$$R_n = \frac{v_M . G(M,n-1)}{G(M,n)}$$

$$T_n = n/R_n$$

where $n$ is the work-in-process inventory ($N - 5 \leq n \leq N + 5$).

The next function computes the performance measures for the individual workstations.

Mean number of busy servers at station $i$: $B_i = \frac{w_i . G(M,N-1)}{G(M,N)}$

$B_i$ is also equal to the average number of jobs being processed at station $i$.

Utilization per server of station $i$: $U_i = \frac{B_i}{S_i}$

For a workstation with $N$ jobs and $M$ workstations, the probability that there are $k$ jobs at that station, is given by

$$p_i(k) = \frac{f_i(k).g^i(M,N-k)}{G(M,N)} \tag{9}$$

where $g^i(M,k)$ is an auxillary function defined as:

$$g^i(M,k) = G(M,k) - \sum_{k=1}^{k=N} f_i(k).g^i(M,N-k)$$

This auxillary function is calculated in a similar manner as the normalization constant $G(M,N)$.

For a workstation with a single server

$$p_i(k) = \frac{f_i(k).[G(M,N-k) - w_i.G(M,N-k-1)]}{G(M,N)} \tag{10}$$

The expected number of jobs at station $i$ is given by

$$E(x_i) = \sum_{k=1}^{k=N} k.p_i(k) \tag{11}$$

The number of items in queue at workstation $i$: $q_i = E(x_i) - B_i$

The total time spent at workstation $i$ per job: $t_t = \frac{t_i.E(x_i).v_i}{B_i}$

The average processing time per job at workstation $i$: $t_p = t_i.v_i$

The average waiting time per job at workstation $i$: $t_w = t_t - t_p$

The last function of the computation module writes the input data into file "input" and the results into file "output." The user can then view these files on the screen or print them on a line-printer.

The computer-based model thus allows the user to input data via a user-interface; operational measures are typically obtained in less than 10 seconds. The results of the computer-based model can be used as the basis for performing a more detailed analysis of the FMC. The computer code for the closed network-of-queues model is presented in Appendix A.

## 3.8 Performance evaluation system

The performance evaluation system provides feedback to upper-management to determine the effectiveness of the FMC. The performance of the FMC should be evaluated based on the manufacturing objectives prioritized by the business strategy of the SBU. Depending on the prioritized manufacturing objectives, there will be a trade-off between some manufacturing objectives. For example, an FMC designed for volume flexibility (that is, the ability to accommodate fluctuations in the demand of products) would have a certain amount of redundant capacity, and machine utilization should not be a critical performance measure. In fact, using machine utilization as a measure of manufacturing efficiency might lead managers to believe that the FMC is underutilized and they may try to increase the volume of products being manufactured in the cell, to the detriment of other objectives.

Typically the manufacturing function in many firms does not participate in the formulation of the business strategy (Wheelwright and Hayes, 1985). A possible reason is that predicting the performance of the manufacturing system, given changes in the business strategy, can be difficult. Allowing the performance evaluation system to have the capability to evaluate changes in business strategy in terms of their implications for the manufacturing system, will enable the manufacturing function to take a more active role in the formulation of business strategy.

## 3.9 Summary of methodology

The methodology presented in this chapter discussed the development of a conceptual framework for the design and evaluation of flexible manufacturing cells. Four types of manufacturing task profiles were identified based on the primary manufacturing task of an SBU, and the strategic criteria on which its products compete. Operational measures were discussed for each of the task profiles. The task profiles of firms likely to implement FMCs (task profiles B & C) were identified and a methodology was developed to help prioritize manufacturing objectives. The implications of each of the manufacturing objectives for an FMC were hypothesized and a program for an interactive computer-based model to calculate operational measures was discussed.

## 3.10 Scope of field work

The practical applicability of the conceptual framework proposed in this research was determined by field-visits to a company in the Southeastern United States. The purposes of the field-visits were:

(i) To identify the manufacturing task profile of the plant.

(ii) To identify the key performance measures for the plant.

(iii) To implement the AHP methodology for deriving prioritized manufacturing objectives.

Due to the non-availability of data required for the computer-based model from the above company, the FMC being developed at the department of IEOR at Virginia Tech was used to demonstrate how the computer-based model can be used to calculate the operational measures of a manufacturing system.

# Chapter 4

# Field work

## 4.1 Field-visits

As part of the field work three visits were made to one division of a large machine-tool company, located in the Southeastern United States. The purposes of the field-visits were:

1. Determination of the manufacturing task profile of the plant.
2. Identification of the key performance measures for this plant.
3. Implementation of the AHP methodology to derive prioritized manufacturing objectives.

The plant was first visited in April, 1988. The researcher met with the Vice-President (Personnel), and had an extensive plant-tour of the manufacturing system.

The plant manufactures products in quantities ranging from 1 to 1000 pieces per shop order. Due to the wide variety of products being manufactured at this division, cellular manufacturing was implemented ten years back, with a view to reducing lead times, and improving product quality. Currently eleven cells are in operation, and the average number of machines per cell is six. Fifteen per cent of all production is currently done in cells, and this is expected to rise to fifty per cent in the future.

The date of the second visit to this plant was February 16, 1989. The researcher met with the Director of Manufacturing and interviewed him for approximately one hour and thirty minutes regarding the company's business strategy, products, and manufacturing process.

## 4.2 Strategic objectives

The master-plan (mission statement) at this company is based on a five year planning horizon. The manufacturing function is treated as a strategic part of the business. At the corporate headquarters, the manufacturing advisory committee is involved in all aspects of strategy formulation for the company. The company releases a firm plan as to what is expected from manufacturing for the following year and a two-year plan subject to changes at the beginning of the current year. According to the Director of Manufacturing, the master-plan determines the direction of manufacturing ("Where we have to go and how to get there.").

At this division, the manufacturing function is the "driver" for cost, quality, customer service, and customer response-time and all other functions support manufacturing in achieving the strategic goals of the company.

## 4.3 Business strategy

**Primary manufacturing task:** This division manufactures five primary product groups A, B, C, D, and E. The division has 60 per cent of the world market for product group A and 33 per cent of the world market for product group B. Overall the division has about 40 per cent of the world market for its various products. The different product groups being manufactured at this plant are shown in Table 8. Each of the product groups are discussed next.

Product group A

Six types of this product group are currently produced and eight product types are planned for the future. This product group consumes 25 per cent of the overall resources (labor and equipment) of the plant, and the number of engineering design changes is high since the products are made to customer specifications.

Product group B

Forty types of this product group are currently produced and an increase to fifty types is envisioned in the future. This product group has a high degree of innovation and consumes another 25 per cent of resources used.

Product group C

Currently 200 different types of this product group are produced in this division, and they consume 15 per cent of the resources used. The degree of innovation for this product group is low.

Product group D

These are required for field-support of products and consume 25 per cent of resource used. Currently 15,000 product types are produced. In the future the number of product types is likely to increase to 20,000. The degree of innovation for each product type is low.

Product group E

Currently 60 types of this product group are produced. These consume 10 per cent of resources used. This product group has a high degree of innovation, and the number of product types is expected to increase to 80.

**Table 8. Characteristics of the product groups produced at the plant**

| Product groups | Types | | Volumes of output | | per cent resource utilization | Degree of innovation |
|---|---|---|---|---|---|---|
| | current | future | current | future | | |
| A | 6 | 8 | high | high | 25% | high |
| B | 40 | 50 | high | high | 25% | high |
| C | 200 | 300 | medium | medium | 15% | low |
| D | 15000 | 18-20 K | high | high | 25% | low |
| E | 60 | 80 | low | medium | 10% | high |
| | | | | | | |
| | | | | | | |

**Product characteristics:** According to the Director of Manufacturing, the criteria on which products compete vary from product to product. The criteria on which the product groups compete are discussed below.

A: This product group competes primarily on product reliability and conformance.

B: This product group is made to customer specifications and competes primarily on quality.

C: This product group competes primarily on product differentiation, to meet customer requirements.

D: This product group competes primarily on delivery performance.

E: This product group competes primarily on quality and meeting customer specifications.

**Manufacturing system characteristics:** The manufacturing system characteristics of the plant are discussed below.

Product flexibility

Most of the products have to be made to customer specifications. All engineering changes are discussed with manufacturing engineering prior to implementation. The decision whether to implement the change in-house or to subcontract is a manufacturing decision. The manufacturing function also decides on the "loading of the change" (onto the master schedule), and the timing of when to make it.

Volume flexibility

Significant increases in the demand for products create problems as the division is not geared towards short-term volume flexibility. The reason could be that, due to the nature of the products, forecasting accuracy is high and volume changes tend to be long-term. Manufacturing reviews all forecasting and sales with marketing on a monthly basis and then decides (on the basis of capacity) to make or buy.

Delivery performance

Predictability of manufacturing lead times is considered very important, in order to set production schedules and meet due-date requirements. According to the Director of Manufacturing, reducing lead times was one of the primary reasons for implementing cellular manufacturing. Product group D, which consumes 25 per cent of resource utilization at this division, competes primarily on delivery performance.

## 4.4 Cellular manufacturing

Cellular manufacturing was implemented at this division with a view to reducing manufacturing lead times and improving product quality. Replying to a question as to how the manufacturing function decides on which of its products are to be manufactured in cells, the Director of Manufacturing said that part-families are identified based on design and manufacturing similarity. The essential features that constitute a part-family (according to the Director of Manufacturing) are:

1. The commonalty of the product types within a part-family.
2. The ability to process part families completely within one cell.
3. Sufficient volumes of the part families to be manufactured simultaneously, to justify the creation of the cell.
4. The number of machines in a cell not exceeding 10, for efficient control.
5. Simple material-flow within cells, to facilitate material-handling.

The benefits associated with the implementation of cellular manufacturing for this plant are: reduced work-in-process inventories, improved quality control, reduced set-ups for parts, standardization of product designs, and improved tooling.

## 4.5 Performance measurement system

The division has a common plant-wide performance measurement system for both the job-shop and cellular manufacturing. But managers informally evaluate the performance of cells based only on the output at the end of each shift. The performance levels of each cell are specified in terms of the volumes of output of each part-family depending on the part-mix. The simplification of manufacturing control and performance evaluation are benefits (in addition to those already mentioned) that the Director of Manufacturing associates with the implementation of cellular manufacturing. The cells have been designed so that supervisors and managers have visual monitoring capability. For example, one of the cells has a rack that carries raw material for one shift's work. At the end of each shift the rack containing finished bits is moved for heat-treatment. Thus the cells have been designed for specific levels of performance and, if the master schedule (which is planned at the beginning of every month) is followed, the performance of the cell is considered satisfactory.

Due to the simplification of control resulting from the implementation of cellular manufacturing, managers do not have to involve themselves in the day-to-day operations of the plant, but are responsible for planning process improvements. Since the division has a common plant-wide performance evaluation system, key performance measures for the plant were identified by the researcher based on the planned process improvements. They are:

1. Manufacturing lead times.
2. Product quality.
3. Product flexibility

The planned process improvements with respect to each of these performance measures are discussed in detail in Chapter 5.

The plant was visited for a third time on April 3, 1989 to exercise the methodology for deriving prioritized manufacturing objectives. The Director of Manufacturing was interviewed for approximately one hour. One particular cell and the products it produces were the focus of the interview.

## 4.6 Prioritizing the manufacturing objectives for one cell

The AHP methodology proposed in Chapter 3 to prioritize manufacturing objectives was explained to the Director of Manufacturing, who selected one of the cells as the candidate cell.

This cell consists of the following machines:

1. 4-axis lathe.
2. Combination gun/deep hole drill.
3. 18-inch chucker.
4. CNC hob.
5. Standard milling machine.
6. Machining center.
7. Miscellaneous equipment, including inspection gages and stamping tools.

**Part-families:** This cell manufactures three part families:

Part-family I: 5 types of this part-family are manufactured in this cell, which consume 65 per cent of the resources used in the cell.

Part-family II: 5 types of this part-family are manufactured in this cell, which consume 20 per cent of the resources used.

Part-family III: 8 types of this part-family are manufactured in this cell, which consume 15 per cent of the resources used in the cell.

The Director of Manufacturing, acting as the decision-maker, carried out pairwise comparisons of each of the manufacturing objectives, for each of the part families produced in the cell. Three pairwise comparison matrices were obtained for each of the part-families with respect to each of the manufacturing objectives. The pairwise comparison matrices, the calculation of the local priorities of the objectives with respect to each of the part-families, and the calculation of the global priorities of the manufacturing objectives for the cell are discussed in Chapter 5.

**Performance measures:** Replying to a question as to the performance measures that he felt were appropriate for this cell, the Director of Manufacturing mentioned volumes of output based on the required changeover time, and the per cent of parts rejected. These two performance measures will be discussed in Chapter 5 with respect to the prioritized manufacturing objectives.

To summarize, the purpose of the field-visits was to determine the practical applicability of the conceptual framework developed in this research. Based on extensive interviews with the Director of Manufacturing, the required information to determine the manufacturing task profile of the plant was obtained. The planned process improvements, with respect to the key performance measures for the plant, were discussed with the Director of Manufacturing. The methodology to prioritize manufacturing objectives was exercised for one cell. The key performance measures for this cell were identified by the Director of Manufacturing.

The next step in the framework was the preliminary design of the cell considering the key performance measures, and involved determining the operational measures of the cell. Due to the non-availability of the data required to determine the operational measures of the cell, in the target company, a computer-based model (described in Chapter 3) was used to calculate the operational measures of the FMC being developed in the department of IEOR at Virginia Tech.

## 4.7 Implementing the computer-based model

The second phase of the case-study involved demonstrating how the computer-based model can be used to calculate the operational measures for a manufacturing system. The manufacturing system considered for this research is the FMC being developed in the department of IEOR at Virginia Tech. The required information was obtained by interviewing Dr. M. P. Deisenroth and students involved in developing the FMC. A schematic representation of the FMC is given in Figure 6. This system is designed to produce two miniature products: wax robots and wax CNC machines. The FMC consists of:

1. Automatic storage and retrieval system (AS/RS):

   This is the automatic storage and retrieval system and stores pallets containing finished products and raw materials.

2. Feeders:

   These are pneumatically-actuated devices which feed the assembly workstation with raw material. These contain the raw material for the different products to be manufactured in the cell. The different parts include: base for a wax robot, base for a wax CNC machine, and wax links.

3. Assembly workstation:

   This consists of an IBM 7547 robot. This workstation performs two operations:
   Kitting operation: Parts requiring machining are placed onto the pallet.
   Assembly operation: Machined parts are assembled to form the finished products.

4. Machining workstation:

   This consists of an IBM 7545 robot and two milling machines. Assembled pallets requiring machining are sent to this workstation where the robot loads the milling machines according to the process-plan of the product. Machined parts are then sent to the assembly workstation for assembly.

5. Conveyor:

   The two workstations (assembly and machining) are integrated by means of a Shuttleworth roller conveyor.

Empty pallets are brought from the AS/RS to the assembly workstation, where raw-material from the feeders are placed on the pallet. The pallet is then sent to the machining workstation

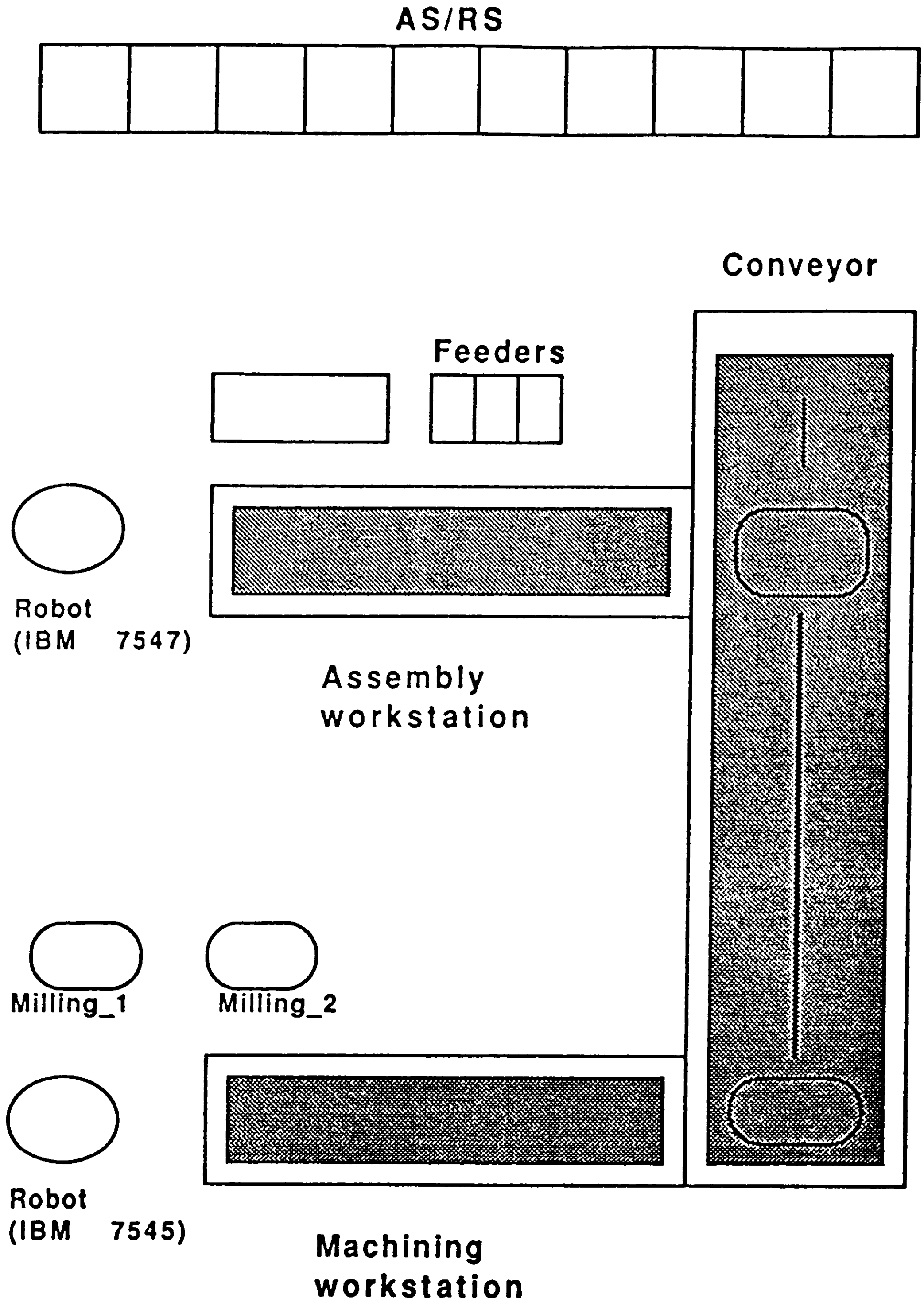


**Figure 6. Schematic representation of the FMC**

where the robot "loads" the milling machine according to the process-plan of the product. Machined parts are then sent to the assembly workstation for assembly. After assembly the pallet proceeds to the AS/RS. One hypothetical process plan for the two products is shown in Table 9 and includes the processing times (in minutes) of the products at each workstation. The robot consists of a base and two links whereas the CNC machine consists of a base and one link. Therefore the kitting operation and the assembly operation are longer for the robot than for the CNC machine. More machining is required for the CNC machine base than the robot base.

The operational measures of the FMC, calculated using the computer-based model, are discussed in Chapter 5. Using information gathered from these two phases of the case study, the framework developed in this research was exercised. Analysis of the results is discussed next in Chapter 5.

Table 9. Process plan for the two products

| Workstation | Operation | Robot | CNC machine |
|---|---|---|---|
| Assembly | kitting | 5 | 3 |
| Machining | milling | 10 | 13 |
| Assembly | assembly | 9 | 7 |

Processing time in minutes.

# Chapter 5

# Analysis and results

The first step of the conceptual framework developed in this research for the design and evaluation of FMCs involved identifying the manufacturing task profile of a plant. As discussed in Chapter 3, the manufacturing task profile should be specified in terms of the primary manufacturing task, product characteristics, and manufacturing system characteristics of the plant, given the strategic objectives. Using data drawn from the two phases of the case study (discussed in Chapter 4), the proposed framework was exercised. The results of that work are described next.

## 5.1 Manufacturing task profile of the plant

The plant visited as part of the field work produces five product groups. The number of product types (within each product group) produced at this division is high, and varies from 6 to 15,000. The product groups manufactured in the plant typically compete on quality (reliability and conformance). The characteristics exhibited by the manufacturing system were found to be product flexibility (since most products are made to customer requirements) and delivery performance.

The plant thus manufactures a large number of product types and the business strategy emphasizes product quality and market responsiveness (product flexibility and delivery performance). The division is planning to increase the number of product types within each product group, in order to better meet customer requirements. The manufacturing system at this division therefore most resembles manufacturing task profile C, from the framework developed in Chapter 3.

Having identified the manufacturing task profile of the plant, the next step of the framework was to identify key performance measures, based on the strategic criteria on which products compete. The hypothesis of the framework was that the manufacturing function should focus on the key performance measures (those that support that strategic criteria).

## 5.2 Key performance measures

Since the division has a common plant-wide performance evaluation system, key performance measures were identified by the researcher, based on the planned process improvements to take place there in the future. The key performance measures that the plant focuses on are:

1. Delivery performance.
2. Product quality.
3. Product flexibility.

The planned process improvements with respect to each of these performance measures are discussed next.

**Delivery performance**

Improving delivery performance through reducing the manufacturing lead time was one of the primary reasons for the implementation of cellular manufacturing at this plant. According to the

Director of Manufacturing, machine utilization has been sacrificed for shorter lead-times and lower work-in-process inventory in the cells. The overall lead-time for one product group used to be 26 weeks in the job-shop, but was reduced to 10 weeks after the implementation of cellular manufacturing. Manufacturing engineering is currently involved in modifying "discrete parts balancing" (which is similar to economic order quantity (EOQ) calculations) which the division uses to compute lot-sizes. But, unlike EOQ, discrete parts balancing bases its calculations on confirmed commitments to ship. Thus the volumes used to compute lot-sizes are based on expected or in-house orders.

Due to the wide variety of part-families being manufactured in cells, set-up times constitute a major portion of the average time in the system. Focusing on the need to reduce manufacturing lead times (through reducing lot-sizes), it was discovered that discrete parts balancing results in larger lot-sizes since it gives each part-family its own set-up time and carrying cost. The modification that is planned for discrete parts balancing (to calculate lot sizes) is to have two types of set-up times: changeover time and reset time. For example, one cell, which manufactures three part-families, has product types within each part-family which vary only in diameter. Due to the similarity of part-families being manufactured in the cell, the set-up times to be considered for manufacturing product types of different part-families, with similar diameters, are only a small portion of the set-up times presently used to compute lot-sizes, which is what the Director of Manufacturing referred to as reset time. All product types of one part-family are run in a single set-up and, for the next part-family, the set-up time only includes reset time (to change tools). On the other hand, manufacturing part-families of varying diameters requires the full set-up time (changeover time).

In Chapter 3, it was hypothesized that the implications of emphasizing delivery performance were to have small lot-sizes to reduce manufacturing lead times and to reduce the work-in-process inventory to minimize the waiting times of jobs. Modifying discrete parts balancing, in this plant, will result in smaller lot-sizes and the work-in-process inventory is kept at the minimum possible level in the cells.

**Product quality**

The operators in the cell are responsible for product quality and inspection. The Director of Manufacturing is personally involved in the development of a new statistical quality control (SQC) program and gets quality "indicators" every day. The SQC program involves computing total quality cost (TQC) which consists of the following:

**Appraisal cost:** This is the cost of inspection for maintaining product conformance.

**Prevention cost:** This is the cost associated with efforts in design and manufacturing that are directed toward the prevention of nonconformance. This is typically engineering-based and involves the product and process design groups, for what the Director of manufacturing refers to as designing quality into the product.

**Warranty cost:** This includes all costs involved in service to customers, under warranty contracts. The manufacturing function reviews all warranties with marketing to determine the corrective measures needed to improve product quality, based on customer feedback.

**Scrap and rework cost:** This is divided into two categories:

Internal: This is the cost incurred due to producing defective components. The manufacturing function determines the reasons for scrap and rework and makes a sustained effort to minimize/eliminate processes susceptible to producing defective components.

External: This is the cost associated with the inspection and testing of incoming raw-materials, supplied by vendors. The division is planning to implement a vendor certification program to minimize this cost. Raw materials supplied by certified vendors will have little or no inspection.

The implications of emphasizing product quality (reliability and conformance) were hypothesized to increase total product cost and/or increase inspection time, resulting in increasing the total processing time for the products. These hypotheses were felt to be true by the Director of Manufacturing.

**Product flexibility**

To meet customer requirements effectively without significant increases in manufacturing lead times, the division is planning to switch to modular designs for their products so as to make the standardization of components "transparent" to their customers. The aim is to have a single modular bill of materials so that orders released to the shop-floor (after "exploding" the bill of materials) will be for standardized components, which will then be assembled to customer requirements.

Emphasizing product flexibility has resulted in frequent set-ups and increased manufacturing lead times at this plant (as hypothesized in Chapter 3). This plant was therefore switching to a modular bill of materials, so as to minimize set-up times and meet customer requirements more easily.

Having identified the key performance measures, the next step in the framework was to design the manufacturing system. At this plant, the primary reasons for implementing cellular manufacturing were to improve delivery performance and product quality. The manufacturing system at this plant consists of 11 cells, and one of the cells was selected by the Director of Manufacturing to exercise the AHP methodology to prioritize manufacturing objectives. The hypothesis of the framework was that each cell should focus on the key performance measures, related to the manufacturing objectives prioritized on the basis of the strategic criteria on which its products compete.

## 5.3 Prioritizing the manufacturing objectives for one cell

This cell manufactures three part-families which were assigned a priority fraction $f_i$, based on the fraction of resources used in the cell.

Priority of Part-family I: $f_1 = 0.65$.

Priority of Part-family II: $f_2 = 0.20$.

Priority of Part-family III: $f_3 = 0.15$.

Table 10 shows the matrices of pairwise comparisons of the manufacturing objectives at the third level of the hierarchy (which were derived from information gathered from the Director of Manufacturing) to determine the local priorities of each of the manufacturing objectives with respect to each part-family.

The eigenvectors of the maximum eigenvalue of each comparison matrix gave the local priorities of each of the objectives for each of the part-families manufactured in the drill-bit cell. Table 11 lists the local priorities along with the computed eigenvalues. The procedure developed by Saaty (1980) to assess the consistency of the pairwise comparisons was discussed in Chapter 3, and involved calculating the consistency index (CI) and consistency ratio (CR), for each comparison matrix.

Referring to Table 11, for Part-family I the computed eigenvalue was $\lambda_{max} = 6.344$.

The consistency index: $CI = \frac{6.344 - 6}{6 - 1} = 0.0688$.

The random index (RI) for $n = 6$ is 1.24.

Therefore the consistency ratio: $CR = \frac{CI}{RI} = 0.0555$.

Since $CR < 0.1$, the pairwise comparisons for this matrix are not inconsistent.

The first column of Table 11 gives the local priorities of the objectives with respect to Part-family I. Therefore for this part-family the most important objective was product reliability followed by product conformance. Delivery performance and product cost were considered more important than product flexibility and volume flexibility. For Part-family II, the most important objectives were product reliability, product conformance, and delivery performance. Product cost was more important than product flexibility. The most important objectives for Part-family III were product reliability and conformance, followed by product cost and delivery performance.

Table 10. Comparison matrices for the cell

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | 1 | 1/4 | 1/2 | 2 | 2 | 1 |
| 2 | 4 | 1 | 2 | 6 | 8 | 4 |
| 3 | 2 | 1/2 | 1 | 3 | 4 | 2 |
| 4 | 1/2 | 1/6 | 1/3 | 1 | 1 | 1/2 |
| 5 | 1/2 | 1/8 | 1/4 | 1 | 1 | 1/2 |
| 6 | 1 | 1/4 | 1/2 | 2 | 2 | 1 |

Part-family I

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | 1 | 1/5 | 1/3 | 1 | 2 | 2 |
| 2 | 5 | 1 | 2 | 7 | 8 | 3 |
| 3 | 3 | 1/2 | 1 | 4 | 4 | 2 |
| 4 | 1 | 1/7 | 1/4 | 1 | 1 | 1/2 |
| 5 | 1/2 | 1/8 | 1/4 | 1 | 1 | 1/3 |
| 6 | 1/2 | 1/3 | 1/2 | 2 | 3 | 1 |

Part-family II

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | 1 | 1/6 | 1/3 | 2 | 1 | 2 |
| 2 | 6 | 1 | 2 | 4 | 6 | 4 |
| 3 | 3 | 1/2 | 1 | 2 | 3 | 2 |
| 4 | 1/2 | 1/4 | 1/2 | 1 | 2 | 1 |
| 5 | 1 | 1/6 | 1/3 | 1/2 | 1 | 2 |
| 6 | 1/2 | 1/4 | 1/2 | 1 | 1/2 | 1 |

Part-family III

1-- Product cost.

2-- Product reliability.

3-- Product conformance.

4-- Product flexibility.

5-- Volume flexibility.

6-- Delivery performance.

Table 11. Local and global priorities for the cell

| | Local priorities | | | |
|---|---|---|---|---|
| | I | II | III | Global priority |
| Product cost | 0.1061 | 0.1075 | 0.1060 | 0.1064 |
| Product reliability | 0.4057 | 0.4260 | 0.4230 | 0.4124 |
| Product conformance | 0.2698 | 0.2360 | 0.2120 | 0.2544 |
| Product flexibility | 0.0593 | 0.0650 | 0.0960 | 0.0622 |
| Volume flexibility | 0.0531 | 0.0520 | 0.0880 | 0.0581 |
| Delivery performance | 0.1061 | 0.1145 | 0.0750 | 0.1031 |
| Eigenvalue | 6.3440 | 6.2064 | 6.3690 | |
| CI | 0.0688 | 0.0413 | 0.0738 | |
| CR | 0.0555 | 0.0330 | 0.0595 | |

The global priorities of the manufacturing objectives were obtained by multiplying the vector of local priorities with the vector of the priorities for the part-families (based on the fraction of resources used in the cell). For example the global priority of product cost is:
$(0.1061 \times 0.65) + (0.1075 \times 0.2) + (0.106 \times 0.15) = 0.1064$ .

Referring to Table 11 it can be seen that overall, for the cell, the primary objectives were product reliability and product conformance. Delivery performance and product cost were the secondary objectives and were considered more important than product flexibility and volume flexibility.

Having obtained a set of prioritized manufacturing objectives, the next step of the framework involved the identification of related performance measures. One hypothesis of the framework was that the manufacturing function should focus on the prioritized objectives. The implications of each of the manufacturing objectives for the FMC were also hypothesized in Chapter 3. The Director of Manufacturing was asked to identify the performance measures that he felt accurately reflect the prioritized manufacturing objectives and their implications for the cell. These are discussed next.

### 5.3.1 Key performance measures

**Product quality:** The Director of Manufacturing felt that one key performance measure for the primary objectives (product reliability and conformance) was the per cent of parts rejected. Product reliability was mainly felt to be the responsibility of design engineering, but the implication for the cell was increased inspection. For example, for drill-bits, design engineering specified close tolerances on critical angles to avoid tool-breakages. Therefore, for drill-bits, the critical angles had high inspection rates. For part-families manufactured in other cells, emphasizing product reliability resulted in design engineering's using a higher factor of safety thereby increasing product cost. The Director of Manufacturing noted that good control of the manufacturing process would ensure product conformance, and unless a process was susceptible to producing defective parts, the inspection rate was the same for all cells except on dimensions deemed critical by design engineering. Thus per cent of parts rejected accurately reflected product quality (reliability and conformance).

The Director of Manufacturing felt that emphasizing product reliability resulted in increasing the total processing time of a product and/or total product cost. The implication for cells emphasizing product conformance is reflected in the type of equipment used.

According to the Director of Manufacturing the volume of output per shift accurately reflects the secondary objectives: delivery performance and product cost. Since production schedules were made at the beginning of every month, accurately estimating the output per shift increased the predictability of delivery dates and per cent of on-time shipments.

**Delivery performance:** The bottleneck machine in the cell (machining center) determines the capacity of the cell. Production schedules planned at the beginning of every month deliberately underutilize the other machines in the cell to avoid congestion at the bottleneck machine. The work-in-process inventory is kept at the minimum possible level to minimize waiting times and the output per shift is planned based on the number of product types to be manufactured (reflected by the required changeover and reset time). According to the Director of Manufacturing, the modification to discrete parts balancing (discussed in Section 5.2) will result in reducing the manufacturing lead time, due to smaller lot-sizes.

The Director of Manufacturing felt that emphasizing delivery performance should involve minimizing the work-in-process inventory, and that increasing the number of product types produced in the cell would result in an increase in the manufacturing lead time. The number of product types (within each part-family) manufactured in the cell is restricted to the present level in order to minimize the changeover time. Thus there is a direct tradeoff between delivery performance and product flexibility, and attempting to increase product flexibility will result in increasing the manufacturing lead time (as hypothesized in Chapter 3).

**Product cost:** Focusing on the need to reduce product cost by increasing the machine utilization in the cell, the division is planning to install a robot for loading and unloading workpieces and changing tools at the bottleneck machine. This will reduce the set-up time at the bottleneck machine, enabling greater machine utilization at the other machines, without increasing congestion at the bottleneck machine. This will result in increasing the capacity of the cell and reducing total product cost. The installation of the robot will also result in decreasing the lead time.

The framework developed in this research to evaluate FMCs first involved prioritizing manufacturing objectives and then focusing on related performance measures. This was found to be true for this cell as the manufacturing function first ensured that the primary objectives (product reliability and conformance) were fulfilled and then focused on the secondary objectives (delivery performance and product cost).

A possible reason for product flexibility not being considered important for this cell is that technical specifications for the part-families manufactured in this cell were provided by design engineering. Volume flexibility was also not considered to be important for this cell since forecasting accuracy is high; unless increases in demand are long-term, the division sub-contracts excess orders.

The next step in the framework is the design of the FMC considering the key performance measures. This research only considered the preliminary analysis of the cell in terms of the operational measures. The division carries out such an analysis on a monthly basis while planning production schedules. According to the Director of Manufacturing, the division has decided to purchase new simulation software to aid in this analysis. The Director of Manufacturing noted that since managers did not receive reports regarding machine utilization, set-up time, and other operational measures, it was essential that they took an active part in planning production schedules since it would help them identify possible process improvements.

Due to the non-availability of data necessary to determine the operational measures of the above cell, the computer-based model described in Section 3.7 was used to calculate the operational measures of the FMC at Virginia Tech.

## 5.4 Determining the operational measures of the FMC

The operational measures for the FMC being developed at Virginia Tech were determined, considering the process-plan shown in Table 9 (p. 82). For purposes of of analysis this will be called the "Base Model." The operational measures for the FMC are shown in Table 12.

As can be seen from Table 12, the throughput rate for the base model was calculated to be 4.03 parts/hour. The mean processing time of a job is 23.50 minutes and the mean waiting time is 33.08 minutes. The mean travelling time is 3.0 minutes.

Due to the fact that the manufacturing objectives of this cell could not be prioritized, it is not possible to analyze the operational measures in terms of the strategic criteria on which the products compete.

As can be seen from the individual workstation performance measures, shown in Table 12, the bottleneck station is the assembly workstation (since it has the maximum utilization per server), for this hypothetical case only. The average queue length for the assembly workstation is 1.17 minutes, and the average waiting time per job is 17.46 minutes.

In order to check the logic of the model developed in this research, the above results from the computer-based model were validated by comparing them with those obtained using CANQ (Solberg, 1976).

In order to demonstrate the versatility of the computer-based model, for the analysis of the FMC in calculating operational measures, two embellishments were considered and are discussed next.

Table 12. Operational measures for the FMC

System performance measures.

| | |
|---|---|
| Throughput rate | 4.03 |
| Mean time in system | 59.58 |
| Mean processing time | 23.50 |
| Mean travelling time | 3.00 |
| Mean waiting time | 33.08 |

Individual workstation performance measures.

| | Assembly workstation | Machining workstation | Conveyor |
|---|---|---|---|
| Utilization per server | 0.81 | 0.77 | 0.05 |
| Average number of jobs processed | 0.81 | 0.77 | 0.20 |
| Average number of jobs waiting | 1.17 | 1.05 | 0.00 |
| Average processing time per job | 12.00 | 11.50 | 3.00 |
| Average waiting time per job | 17.46 | 15.60 | 0.00 |

### 5.4.1 Embellishment 1

In this embellishment, the processing time at the bottleneck station (assembly workstation) in the base model, is reduced by eliminating the kitting operation. Hence it is assumed that the pallets brought from the AS/RS have the required raw-material and proceed directly to the machining workstation. Machined parts then proceed directly to the assembly workstation. The process-plan for the two products is the same as shown in Table 9 (p. 82), except for the elimination of the kitting operation. The operational measures for this embellishment are shown in Table 13.

As can be expected, the throughput rate is higher for this embellishment than that for the base model. But the increase in throughput rate is not only due to a decrease in the mean processing time, but also due to a decrease in the mean waiting time. Therefore the elimination of the kitting operation (mean for both products = 4 minutes) resulted in a decrease in the mean time in system of 8.6 minutes. Therefore decreasing the number of operations results in a decrease in the mean time in the system by an amount that is greater than the sum of the processing times of the operations eliminated.

Table 13. Operational measures for Embellishment I

System performance measures.

| | |
|---|---|
| Throughput rate | 4.71 |
| Mean time in system | 50.98 |
| Mean processing time | 19.50 |
| Mean travelling time | 3.00 |
| Mean waiting time | 28.48 |

Individual workstation performance measures.

| | Assembly workstation | Machining workstation | Conveyor |
|---|---|---|---|
| Utilization per server | 0.6280 | 0.9020 | 0.0590 |
| Average number of jobs processed | 0.6280 | 0.9020 | 0.2400 |
| Average number of jobs waiting | 0.6250 | 1.6100 | 0.0000 |
| Average processing time per job | 8.0000 | 11.5000 | 3.0000 |
| Average waiting time per job | 7.9600 | 20.5200 | 0.0000 |

### 5.4.2 Embellishment 2

In Embellishment 1, each workstation was assumed to have one server; if a pallet arriving at either of the workstations finds that another pallet is being processed, it waits in the queue for that workstation. In Embellishment 1, the bottleneck station was the machining workstation.

In this embellishment, the two milling machines at the machining workstation assumed to be two separate workstations, with separate queues at each of the machines. Therefore it is assumed that pallets brought from the AS/RS go directly to the machining workstation, which consists of two workstations: milling_1 and milling_2. The process-plan for the two products for this embellishment are shown in Table 14 which includes the processing time (in minutes) of the two products, at each workstation. Each of the products (robots and CNC machines) consist of a base and link/s. One of the milling machines (milling_1) machines the bases, while the second milling machine (milling_2) machines the links and bases. Since the robot has two links, the machining time of links (at milling_1) is longer for the robot than for the CNC machine.

The operational measures for this embellishment are shown in Table 15. As can be seen from Table 15, the throughput rate for this embellishment is slightly lower than that for Embellishment 1. But the mean waiting time is much smaller.

Figure 7 shows the throughput rate as a function of $N$ (the work-in-process inventory), for Embellishments 1 and 2. As can be seen from Figure 5, the throughput rate is higher for Embellishment 1 for $N = 1,2,3,4$. But for $N \geq 5$, the throughput rate is greater for Embellishment 2. The mean waiting time for all $N$ were less for Embellishment 2. Therefore, for this FMC, if increasing the throughput rate with a reduction in the manufacturing lead time is essential, then the scenario considered in Embellishment 2 will be preferred over that considered in Embellishment 1.

Table 14. Process-plan for Embellishment 2

| Workstation | Operation | Robot | CNC machine |
|---|---|---|---|
| Milling_1 | machining (base) | 9 | 12 |
| Milling_2 | machining (link/s) | 6 | 3 |
| Milling_2 | machining (base) | 1 | 1 |
| Assembly | assembly | 9 | 7 |

Processing time in minutes.

**Table 15. Operational measures for Embellishment 2**

**System performance measures.**

| | |
|---|---|
| Throughput rate | 4.67 |
| Mean time in system | 51.38 |
| Mean processing time | 24.00 |
| Mean travelling time | 3.00 |
| Mean waiting time | 24.38 |

**Individual workstation performance measures.**

| | Assembly workstation | Milling_1 | Milling_2 | Conveyor |
|---|---|---|---|---|
| Utilization per server | 0.620 | 0.817 | 0.428 | 0.058 |
| Average number of jobs processed | 0.620 | 0.817 | 0.428 | 0.230 |
| Average number of jobs waiting | 0.560 | 1.110 | 0.229 | 0.000 |
| Average processing time per job | 8.000 | 10.500 | 5.500 | 3.000 |
| Average waiting time per job | 7.180 | 14.260 | 2.940 | 0.000 |

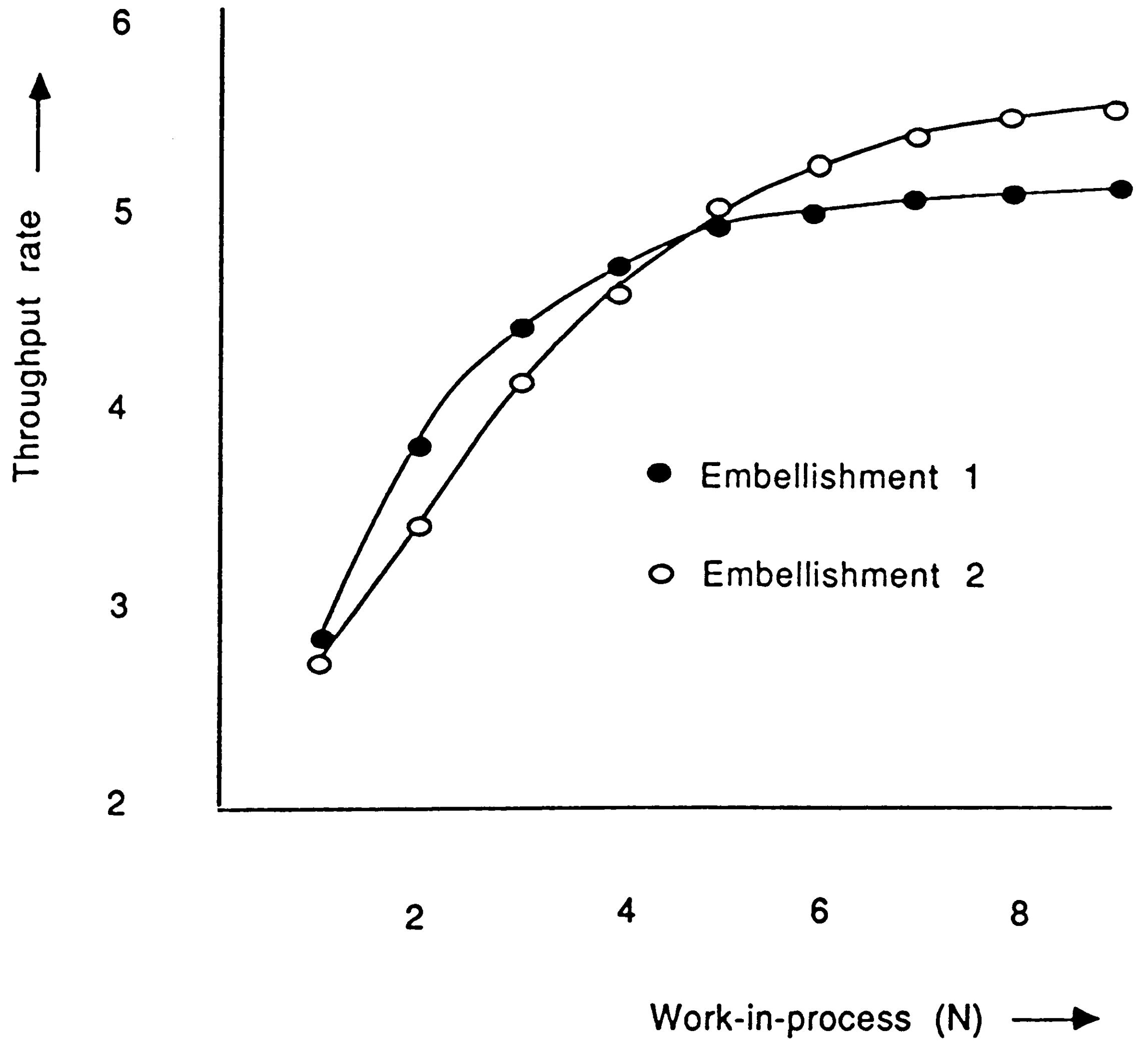


**Figure 7. Throughput rate for Embellishments 1 and 2, as a function of the work-in-process**

## 5.5 Summary of field work

The practical applicability of the conceptual framework was successfully tested by the field work. The first step was to determine the manufacturing task profile of the plant. The manufacturing system of the plant visited as part of the field-work was determined to resemble task profile C (from the framework developed in this research). The plant produces a large number of product types and the business strategy emphasizes product quality (reliability and conformance) and market responsiveness (delivery performance and product flexibility). Having determined the manufacturing task profile of the plant, key performance measures were identified for the plant based on the planned process improvements. The AHP methodology to prioritize manufacturing objectives was exercised for one cell and, based on the results of the pairwise comparisons, it was determined that product reliability and conformance were the primary objectives and delivery performance and product cost were the secondary objectives. Related performance measures, for this cell, were identified and the implications of emphasizing the above objectives were discussed. The computer-based model was used to calculate the operational measures of the FMC being developed at Virginia Tech.

# Chapter 6

# Conclusions, discussion, and recommendations

This research developed a conceptual framework for the design and performance evaluation of flexible manufacturing cells (FMCs).

Four different types of manufacturing task profiles were identified based on the primary manufacturing task, product characteristics, and manufacturing system characteristics of an SBU. Operational measures were discussed for each of the manufacturing task profiles. The task profiles of firms likely to implement FMCs were identified.

A methodology, based on the analytic hierarchy process (AHP), was developed to prioritize the manufacturing objectives of an FMC. The implications of each of the manufacturing objectives for an FMC were hypothesized. Related performance measures were also identified.

A user-friendly computer-based model, based on the theory of closed network-of-queues, was developed to aid in the preliminary design and evaluation on an FMC.

The field work carried out to determine the practical applicability of the conceptual framework included field-visits to a company in the Southeastern United States. The manufacturing task profile of the plant was determined and key performance measures for the plant were identified based on planned process improvements to take place there in the future. The methodology to prioritize manufacturing objectives was implemented for one cell in the plant and related performance measures were identified. The computer-based model was used to calculate the operational measures of the FMC being developed in the department of Industrial Engineering and Operations Research, at Virginia Tech.

This research classified manufacturing systems into four task profiles. Literature pertinent to the classification of manufacturing systems is scarce, and discrete-parts manufacturers are traditionally classified as either job shops or flow shops. This research, therefore, presents a more detailed classification based on the primary manufacturing task, product characteristics, and manufacturing system characteristics of a plant.

AHP, a multiple-criteria decision-making methodology was used to prioritize manufacturing objectives. This research hypothesized the implications of each of the manufacturing objectives for an FMC. Only a few of them were tested, due to a lack of data at the field site. It should be noted that the manufacturing objectives are not independent of each other, and the implications of emphasizing two or more of the objectives simultaneously may be different than those hypothesized in this research. The AHP methodology was exercised at the field site, and pairwise comparisons were carried out by the Director of Manufacturing (acting as the sole decision-maker). A more realistic implementation of this methodology might have been to have representatives of the various functions of the plant (manufacturing, R&D, marketing), carry out these comparisons.

The computer-based model developed in this research can only be used for the preliminary design and evaluation of FMCs, due to the assumptions made in computing operational measures.

Future research might be directed towards validating or disproving the hypothesized implications of the manufacturing objectives by extensive surveys and analyses of existing FMCs. Another possible fruitful extension to this research would be to incorporate a cost-model for the economic analyses of FMCs.

Recent developments in simulation have resulted in the creation of simulation generators, which convert user-supplied data into a simulation model and automatically run the simulation. Future research might also consider using the results of the computer-based model, developed in this research, as input-data for a simulation generator for a more detailed analysis of FMCs.

Overall, however, the framework proposed and tested in this research provides a means to evaluate FMCs based on the strategic benefits that they permit. It provides a first step towards the design of a performance evaluation system that accurately reflects the effectiveness of an FMC, relative to the strategic goals of a firm.

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# Appendix A

# Computer code

```
/*____________________________________________________________

    This is the header file and declares structures for the
    workstations, jobs, and process-plans of the jobs.
______________________________________________________________*/

struct workstation                        /* structure for information on    */
  {                                       /* the workstations in the cell    */
    char name[20];
    int number;
    int servers;
    float process;
    float total_proc;
    float visit;
    float total_visit;
    float workload;
    float buzy_servers;
    float exp;
    float id_time;
  };

 struct job_plan                          /* structure for information on    */
                                          /* the process plans of the jobs   */
  {                                       /* to be processed in the cell     */
    char machine[20];
    int oper;
    float proc_time;
    float freq;
  };
```

```
struct entities                                        /* structure for product types    */
  {
   char type[20];
   int group;
   int number;
   int num_machines;
   struct job_plan jp[50];
   float average_oper;
   float prod_mix;
   float prod_rate;
  };

void win_1(),win_2(),subwin_2(),win_3(),subwin_3(),cal_1(),cal_2();
void output(),check_1(),check_2();
struct workstation ws[50];
struct workstation *ws_ptr;
struct job_plan jp[50];
struct job_plan *jp_ptr;
struct entities jobs[50];
struct entities *jobs_ptr;

WINDOW *wp1,*wp2,*subwp2,*wp3,*wp4,*sub1_wp4,*sub2_wp4;
FILE *f1,*f2;

int num_ws;                                            /*variable for number of workstation*/
int num_jobs;                                          /*variable for number of product types*/
int num_cq;                                            /*variable for work-in-process inventory*/

int *num_wsptr,*num_jobsptr,*num_cqptr;
double PROD,TIME_SYS,TIME_PROC,TIME_TRVL,TIME_WAIT,overall_avoper;
double RELMAX,PROD_RATE[50],T_SYSTEM[50];
int WSMAX;
/*___________________________________________________________________

     This is the main program which calls the other functions
___________________________________________________________________*/

#include <curses.h>
#include "del.h"

main()
{
extern int num_ws,num_jobs;
extern int *num_wsptr,*num_jobsptr;
num_wsptr=&num_ws;
num_jobsptr=&num_jobs;
num_cqptr=&num_cq;

     initscr();
     raw();
     nonl();
     noecho();
     win_1();
     endwin();
     cal_1();
     cal_2();
```

```
	output();
}
/*______________________________________________________________

	This is the user-interface module
______________________________________________________________*/

#include <curses.h>
#include "del.h"


/*______________________________________________________________

	This function sets up the initial window on the screen
______________________________________________________________*/

void win_1()
{
WINDOW *wp1;
static char c;

	wp1=newwin(0,0,0,0);
	box(wp1,'*','*');
	mvwprintw(wp1,4,30,"WELCOME TO",c);
	mvwprintw(wp1,10,22,"PERFORMANCE BASED DESIGN FOR",c);
	mvwprintw(wp1,12,22,"FLEXIBLE MANUFACTURING CELLS",c);
	wstandout(wp1);
	mvwprintw(wp1,22,55,"Strike 'y' to continue",c);
	wstandend(wp1);
	wrefresh(wp1);

	if ((c=mvwgetch(wp1,22,77)) != 'y')
		{
		 beep();
		 win_1();
		}
	else
		{
		wclear(wp1);
		win_2();
		}
}
/*______________________________________________________________

	This function sets up window "wp2" to enable the user
	to input the system description
______________________________________________________________*/

void win_2()
{
WINDOW *wp2,*subwp2;
extern int num_ws,num_cq;
extern int *num_wsptr,*num_cqptr;
extern struct workstation ws[50];
extern struct workstation *ws_ptr;
```

```
static int i,j,k;
static char c,s[10];

          wp2=newwin(0,0,0,0);
          box(wp2,'*','*');
          mvwprintw(wp2,4,10,"Total number of workstations:",c);
          wrefresh(wp2);
          echo();
          wstandout(wp2);
          k=0;
          while(k!= 1)
           {
            mvwscanw(wp2,4,40,"%s",s);
            num_ws=atoi(s);
            if((num_ws >= 1) && (num_ws <= 49))
              {
               k=1;
              }
            else
               {
                k=0;
               }
           }
          noecho();
          mvwprintw(wp2,4,40,"%d",num_ws);
          wstandend(wp2);
          wrefresh(wp2);
          check_1();
}

void check_1()
{
WINDOW *wp2;
static char c,c1;
static int i;


          wstandout(wp2);
          mvwprintw(wp2,22,40,"Strike 'y' to continue or 'e' to edit",c);
          wstandend(wp2);
          wrefresh(wp2);
          i=0;
          while(i != 1)
          {
          c1=mvwgetch(wp2,22,77);
          switch(c1)
          {
           case('y'):
                  i=1;
                  wmove(wp2,10,10);
                  wclrtobot(wp2);
                  box(wp2,'*','*');
                  wrefresh(wp2);
                  subwin_2();
                  break;
           case('e'):
```

```
                    i=1;
                    wclear(wp2);
                    win_2();
                    break;
            default:
                    i=0;
            }
          }

}

void subwin_2()
{
WINDOW *wp2,*subwp2;
extern int num_ws;
extern int *num_wsptr;
extern struct workstation ws[50];
extern struct workstation *ws_ptr;
static int i,j,k,l;
static char c,s[10];

            i=0;
            for (ws_ptr=ws;ws_ptr <= ws + num_ws; ws_ptr++)
              {
                subwp2=subwin(wp2,9,40,10,10);
                wclear(subwp2);
                box(subwp2,ACS_VLINE,ACS_HLINE);
                if(i==0)
                  {
                    mvwprintw(subwp2,2,5,"Name of transporter:",c);
                    mvwprintw(subwp2,4,5,"Number of servers:",c);
                    mvwprintw(subwp2,6,5,"Transportation time:",c);
                    wrefresh(subwp2);
                    echo();
                    wstandout(subwp2);
                    mvwscanw(subwp2,2,26,"%s",ws_ptr->name);
                    ws_ptr->number=i;
                    l=0;
                    while(l!=1)
                      {
                       mvwscanw(subwp2,4,25,"%s",s);
                       ws_ptr->servers=atoi(s);
                       if((ws_ptr->servers >= 1) && (ws_ptr->servers <= 50))
                        {
                          l=1;
                        }
                       else
                         {
                          l=0;
                         }
                      }
                    mvwscanw(subwp2,6,26,"%f",&(ws_ptr->total_proc));
                    wstandend(subwp2);
                    noecho();
                    wrefresh(subwp2);
                    i=i+1;
```

```
          }
        else
          {
           mvwprintw(subwp2,2,5,"Name of workstation %d:",i);
           mvwprintw(subwp2,4,5,"Number of servers: ",i);
           wrefresh(subwp2);
           echo();
           wstandout(subwp2);
           mvwscanw(subwp2,2,28,"%s",ws_ptr->name);
           ws_ptr->number=i;
           l=0;
           while(l!=1)
             {
              mvwscanw(subwp2,4,24,"%s",s);
              ws_ptr->servers=atoi(s);
              if((ws_ptr->servers >= 1) && (ws_ptr->servers <= 50))
               {
                l=1;
               }
              else
                {
                 l=0;
                }
             }
           wstandend(subwp2);
           noecho();
           wrefresh(subwp2);
           i=i+1;
          }
      }
      win_3();
      return;
}

/*___________________________________________________________________

      This function sets up window "wp4" to enable the user to
      input the different product types and the work-in-process
      inventory level
___________________________________________________________________*/

void win_3()
{
extern struct job_plan jp[50];
extern struct job_plan *jp_ptr;
extern struct entities jobs[50];
extern struct entities *jobs_ptr;

WINDOW *wp3,*wp4,*sub1_wp4,*sub2_wp4;
extern int num_jobs;
extern int *num_jobsptr;
static int i,j,k,l,n,o,p;
static char c,s[10];
num_jobsptr=&num_jobs;
```

```
wp4=newwin(0,0,0,0);
box(wp4,'*','*');
mvwprintw(wp4,3,10,"Work-in-process:",c);
mvwprintw(wp4,5,10,"Total number of ",c);
mvwprintw(wp4,6,12,"Product types:",c);
wstandout(wp4);
mvwprintw(wp4,3,50,"Workstation",c);
mvwprintw(wp4,3,63,"Number of ",c);
mvwprintw(wp4,4,65,"Servers",c);
wstandend(wp4);
n=5;
o=0;
for (ws_ptr=ws;ws_ptr<=ws +num_ws;ws_ptr++)
 {
  n=n+1;
     wstandout(wp4);
     mvwprintw(wp4,n,48,"%d",ws_ptr->number);
     mvwprintw(wp4,n,51,"%s",ws_ptr->name);
     mvwprintw(wp4,n,66,"%d",ws_ptr->servers);
     wstandend(wp4);
     o=o+1;
  }
wrefresh(wp4);
echo();
wstandout(wp4);
     p=0;
       while(p!=1)
         {
          mvwscanw(wp4,3,27,"%s",s);
          num_cq=atoi(s);
          if((num_cq >= 2) && (num_cq <= 100))
           {
             p=1;
           }
          else
            {
             p=0;
             }
         }
     q=0;
       while(q!=1)
         {
          mvwscanw(wp4,6,27,"%s",s);
          num_jobs=atoi(s);
          if((num_jobs >= 2) && (num_jobs <= 100))
           {
             q=1;
           }
          else
            {
             q=0;
             }
         }
noecho();
mvwprintw(wp4,6,27,"%d",num_jobs);
wstandend(wp4);
```

```
        wrefresh(wp4);
        check_2();
}

void check_2()
{

WINDOW *wp4;
static char c,c1;
static int i;

       wstandout(wp4);
       mvwprintw(wp4,22,40,"Strike 'y' to continue or 'e' to edit",c);
       wstandend(wp4);
       wrefresh(wp4);
       i=0;
       while(i != 1)
         {
          c1=mvwgetch(wp4,22,77);
          switch(c1)
           {
            case('y'):
                    i=1;
                    wmove(wp4,10,10);
                    wclrtobot(wp4);
                    box(wp4,'*','*');
                    wrefresh(wp4);
                    subwin_3();
                    break;
             case('e'):
                     i=1;
                     wclear(wp4);
                     win_3();
                     break;
              default:
                     i=0;
           }
         }

}

/*______________________________________________________________________

       This function sets up window "sub1_wp4" to enable the user
       to input the process plan for each product type
______________________________________________________________________*/

void subwin_3()
{
WINDOW *wp4,*sub1_wp4,*sub2_wp4;
extern int num_jobs;
extern int *num_jobsptr;
extern struct job_plan jp[50];
extern struct job_plan *jp_ptr;
extern struct entities jobs[50];
extern struct entities *jobs_ptr;
```

```
static int i,j,k,l,m,n,o,p,q;
static char c,s[10];
        i=0;
        j=0;
        for (jobs_ptr=jobs;jobs_ptr <= jobs + num_jobs - 1;jobs_ptr++)
            {
             j=j+1;
             sub1_wp4=subwin(wp4,16,30,7,8);
             wclear(sub1_wp4);
             box(sub1_wp4,ACS_VLINE,ACS_HLINE);
             mvwprintw(sub1_wp4,2,2,"Name of Job %d:",j);
             mvwprintw(sub1_wp4,4,2,"Number of operations:",j);
             mvwprintw(sub1_wp4,6,2,"Fraction of ",j);
             mvwprintw(sub1_wp4,7,2,"production :",j);
             wrefresh(sub1_wp4);
             echo();
             wstandout(sub1_wp4);
             mvwscanw(sub1_wp4,2,16,"%s",jobs_ptr->type);
             jobs_ptr->group=j;
              o=0;
                 while(o!=1)
                   {
                    mvwscanw(sub1_wp4,4,23,"%s",s);
                    jobs_ptr->num_machines=atoi(s);
                    if((jobs_ptr->num_machines >= 1) && (jobs_ptr->num_machines
                          <= 100))
                     {
                      o=1;
                     }
                    else
                     {
                      o=0;
                      }
                   }
              q=0;
                 while(q!=1)
                   {
                    mvwscanw(sub1_wp4,7,17,"%s",s);
                    jobs_ptr->prod_mix=atoi(s);
                    if((jobs_ptr->prod_mix >= 0.001) && (jobs_ptr->prod_mix <= 1))
                     {
                      q=1;
                     }
                    else
                     {
                      q=0;
                      }
                   }
             noecho();
             mvwprintw(sub1_wp4,7,17,"%f",jobs_ptr->prod_mix);
             wstandend(sub1_wp4);
             wrefresh(sub1_wp4);
             k=(jobs_ptr->num_machines) - 1;
             l=0;
             for (jp_ptr=jobs_ptr->jp;jp_ptr <=(jobs_ptr->jp)+k;jp_ptr++)
                 {
```

```
                l=l+1;
                wmove(sub1_wp4,9,0);
                wclrtobot(sub1_wp4);
                box(sub1_wp4,ACS_VLINE,ACS_HLINE);
                mvwprintw(sub1_wp4,9,3,"Workstation No. :",l);
                mvwprintw(sub1_wp4,11,3,"Processing time:",l);
                mvwprintw(sub1_wp4,12,3,"Frequency:",l);
                wrefresh(sub1_wp4);
                echo();
                wstandout(sub1_wp4);
                o=0;
                while(o!=1)
                  {
                   mvwscanw(sub1_wp4,9,24,"%s",s);
                   jp_ptr->oper=atoi(s);
                   if((jp_ptr->oper >= 1) && (jp_ptr->oper <= num_ws))
                    {
                     o=1;
                    }
                   else
                     {
                     o=0;
                     }
                  }
                mvwscanw(sub1_wp4,11,21,"%f",&(jp_ptr->proc_time));
                mvwscanw(sub1_wp4,12,15,"%f",&(jp_ptr->freq));
                noecho();
                wstandend(sub1_wp4);
                wrefresh(sub1_wp4);
               }
            i=i+1;
            }
        return;
}
/*_____________________________________________________________________

      This is the computation module
_____________________________________________________________________*/
#include <curses.h>
#include "del.h"


/*_____________________________________________________________________

      This function computes the mean number of visits and the mean
      operation times at the different workstations
_____________________________________________________________________*/


void cal_1()
{
extern struct workstation ws[50];
extern struct workstation *ws_ptr;
extern struct job_plan jp[50];
extern struct job_plan *jp_ptr;
```

```
extern struct entities jobs[50];
extern struct entities *jobs_ptr;

extern int num_jobs,num_ws,num_cq;
extern int *num_jobsptr,*num_wsptr,*num_cqptr;
extern int WSMAX;
extern double overall_avoper;
double TOTAL_PROC,VISFR,RELWK,RELMAX,TEST;
int i,j,k;
double f;
    overall_avoper=0.0;
    for(ws_ptr=ws;ws_ptr<=ws + num_ws;ws_ptr++)
      {
        if(ws_ptr==ws)
          {
           ws_ptr->visit=0.0;
           ws_ptr->total_visit=0.0;
           ws_ptr->process=0.0;
           ws_ptr->workload=0.0;
          }
        else
          {
           ws_ptr->visit=0.0;
           ws_ptr->total_visit=0.0;
           ws_ptr->process=0.0;
           ws_ptr->total_proc=0.0;
           ws_ptr->workload=0.0;
           ws_ptr->buzy_servers=0.0;
           ws_ptr->exp=0.0;
           ws_ptr->id_time=0.0;
          }
      }
    for(jobs_ptr=jobs;jobs_ptr<=jobs + num_jobs - 1; jobs_ptr++)
      {
        jobs_ptr->average_oper=0.0;
      }

    for (jobs_ptr=jobs;jobs_ptr <= jobs + num_jobs -1;jobs_ptr++)
     {
       f=jobs_ptr->prod_mix;
       k=(jobs_ptr->num_machines)-1;
       j=0;
       i=num_ws;
       for (jp_ptr=jobs_ptr->jp;jp_ptr <= (jobs_ptr->jp)+k;jp_ptr++)
       {
          j=jp_ptr->oper;
          for(ws_ptr= ws;ws_ptr<=ws+i;ws_ptr++)
           {
            if(j==ws_ptr->number)
             {
              (jobs_ptr->average_oper)=(jobs_ptr->average_oper)+(jp_ptr->freq);
              (ws_ptr->visit)=(ws_ptr->visit)+(jp_ptr->freq);
              (ws_ptr->process)=(ws_ptr->process)+((jp_ptr->proc_time)*(jp_ptr->freq));
             }
           }
       }
```

```
        overall_avoper=overall_avoper+((jobs_ptr->average_oper) * f);
        for(ws_ptr=ws;ws_ptr <= ws +i ;ws_ptr++)
          {
          (ws_ptr->total_proc)=(ws_ptr->total_proc)+((ws_ptr->process)*f);
          (ws_ptr->total_visit)=(ws_ptr->total_visit)+((ws_ptr->visit)*f);
          (ws_ptr->process)=0.0;
          (ws_ptr->visit)=0.0;
          }
    }
}

/*____________________________________________________________________

    This function computes the workloads at the different workstations.
_____________________________________________________________________*/


void cal_2()
{
extern struct workstation ws[50];
extern struct workstation *ws_ptr;
extern struct job_plan jp[50];
extern struct job_plan *jp_ptr;
extern struct entities jobs[50];
extern struct entities *jobs_ptr;

extern int num_jobs,num_ws,num_cq;
extern int *num_jobsptr,*num_wsptr,*num_cqptr;
extern double PROD,TIME_SYS,TIME_PROC,TIME_TRVL,TIME_WAIT;
extern double overall_avoper;
extern double TOTAL_PROC,VISFR,RELWK;
extern double RELMAX;
extern double PROD_RATE[50],T_SYSTEM[50];
extern int WSMAX;
double G[50],F[50],PROB[50];
double AUX,SI,PB,FI;
double TEST;
double SERVE,T_SRV;
int i,j,k,l,m,n,p,x,y,z;
double f;

for(ws_ptr=ws;ws_ptr<=ws + num_ws;ws_ptr++)
  {
  if(ws_ptr->number==0)
     {
     ws_ptr->total_visit=1/(overall_avoper);
     ws_ptr->workload=ws_ptr->total_proc;
     RELMAX=(ws_ptr->workload)/(ws_ptr->servers);
     WSMAX=0;
     }
   else
     {
      if(ws_ptr->total_visit>0)
         {
          (ws_ptr->total_proc)=(ws_ptr->total_proc)/(ws_ptr->total_visit);
         }
```

```
      ws_ptr->total_visit=(ws_ptr->total_visit)/overall_avoper;
      ws_ptr->workload=(ws_ptr->total_visit)*(ws_ptr->total_proc);
      TEST=(ws_ptr->workload)/(ws_ptr->servers);
      if(TEST > RELMAX)
        {
        RELMAX=TEST;
        WSMAX=ws_ptr->number;
        }
    }
  }
```

```
/*_____________________________________________________________________

  Implementation of Buzen's algorithm to compute the matrix G
_____________________________________________________________________*/
```

```
  n=num_cq + 5;
  for(i=1;i <= n;i++)
    {
     F[i]=0.0;
     G[i]=0.0;
     PROB[i]=0.0;
     }

  for(ws_ptr=ws;ws_ptr<=ws + num_ws; ws_ptr++)
    {
    x=(ws_ptr->number);
    switch(x)
     {
      case(0):
            break;
      default:
           if((ws_ptr->workload)>0)
             {
             AUX=1.0;
             if((ws_ptr->servers)>1)
               {
                for(j=1;j <= n;j++)
                  {
                  k=n - j + 1;
                  for(l=1;l <= k;l++)
                    {
                    SERVE =ws_ptr->servers;
                    T_SRV=k - l + 1;
                    if(T_SRV < SERVE)
                      {
                       SERVE = T_SRV;
                      }
                     AUX=((ws_ptr->workload)* AUX)/(SERVE) + G[l];
                    }
                  G[k]=AUX;
                  AUX=1.0;
                  }
               }
             else
             {
```

```
            for(j=1;j <= n;j++)
              {
               AUX=((ws_ptr->workload)*AUX) + G[j];
               G[j]=AUX;
              }
            }
          }
      }
    }
      ws_ptr=ws;
      AUX=1.0;
      if(ws_ptr->servers > 1 )
        {
         for(j=1;j <= n;j++)
          {
           k=n-j+1;
           for (l=1;l <= k;l++)
            {
             SERVE=ws_ptr->servers;
             T_SRV=k-l+1;
             if(T_SRV < SERVE)
               {
                SERVE=T_SRV;
               }
             AUX =((ws_ptr->workload) * AUX )/(SERVE) + G[l];
             }
           G[k]=AUX;
           AUX=1.0;
          }
        }
       else
         {
          for(j=1;j <= n;j++)
            {
             AUX=((ws_ptr->workload) *AUX) + G[j];
             G[j]=AUX;
            }
         }
/*____________________________________________________________________

    segment of code to compute system performance measures
____________________________________________________________________*/

    PROD=(60.0*(ws_ptr->total_visit)*G[num_cq - 1])/(G[num_cq]);
    for(jobs_ptr=jobs;jobs_ptr <= jobs + num_jobs - 1;jobs_ptr++)
      {
       (jobs_ptr->prod_rate)= PROD * (jobs_ptr->prod_mix);
      }
    TIME_SYS=(num_cq*G[num_cq])/((ws_ptr->total_visit)*G[num_cq -1]);
    TIME_PROC=(G[1] - (ws_ptr->workload))/(ws_ptr->total_visit);
    TIME_TRVL=(ws_ptr->workload)/(ws_ptr->total_visit);
    TIME_WAIT=TIME_SYS-TIME_PROC-TIME_TRVL;
```

```
/*_______________________________________________________________

   segment of code to compute the throughput rate and average time in
   system, for different values of N.
_______________________________________________________________*/

   if(num_cq <= 7)
     {
      y=2;
     }
   else
     {
      y=num_cq-5;
     }
   z=n;
   ws_ptr=ws;
   PROD_RATE[1]=60*(ws_ptr->total_visit)/G[1];
   T_SYSTEM[1]=overall_avoper * G[1];
   for(i=y;i <= z;i++)
     {
     PROD_RATE[i]= (60 * (ws_ptr->total_visit)* G[i-1])/G[i];
     T_SYSTEM[i]= (i * 60)/PROD_RATE[i];
     }
/*_______________________________________________________________

   Computation of the auxillary function g, for each workstation
_______________________________________________________________*/

   for(ws_ptr=ws;ws_ptr<=ws+num_ws;ws_ptr++)
    {
     (ws_ptr->buzy_servers) = (ws_ptr->workload) * G[num_cq-1] / G[num_cq];
    }


  for(ws_ptr= ws;ws_ptr <= ws + num_ws;ws_ptr++)
    {
     if(ws_ptr->workload > 0)
      {
       if(ws_ptr->servers == 1)
        {
         ws_ptr->id_time=1.0 - ws_ptr->buzy_servers;
         PROB[1]=((ws_ptr->workload)/(G[num_cq]))*(G[num_cq-1] -
                        ((ws_ptr->workload) * G[num_cq - 2]));
        ws_ptr->exp=PROB[1];
        if(num_cq > 3)
           {
            m=num_cq-2;
            for(j=2;j<=m;j++)
             {
              x=num_cq-j;
              f=1.0;
              for(y=1;y<=j;y++)
               {
                f=((ws_ptr->workload) * f);
```

```
        }
        PROB[j]=(f/ G[num_cq]) * (G[x]-((ws_ptr->workload)*G[x-1]));
        ws_ptr->exp=(ws_ptr->exp) + j * PROB[j];
       }
      }

    if(num_cq > 2)
     {
      f=1.0;
      for(y=1;y <= num_cq - 1;y++)
       {
        f=((ws_ptr->workload) * f);
       }
      PROB[num_cq-1] = (f/G[num_cq]) * (G[1] - (ws_ptr->workload));
     }

    if(num_cq >= 2)
     {
      f=1.0;
      for(y=1;y <= num_cq; y++)
       {
        f=((ws_ptr->workload) * f);
       }
    PROB[num_cq]=(f)/ G[num_cq];
  ws_ptr->exp=(ws_ptr->exp) + ((num_cq - 1) * PROB[num_cq-1]) +
                                  ((num_cq) * PROB[num_cq]);
     }
}


else
 {
 for(j=1;j<= num_cq;j++)
  {
   AUX =1;
   if(j != 1)
    {
     l=j-1;
     for(k=1;k<=l;k++)
      {
       SERVE=ws_ptr->servers;
       T_SRV=j - k +1;
       if(T_SRV < SERVE)
        {
         SERVE = T_SRV;
        }
      AUX =F[k] + ((ws_ptr->workload) * AUX )/SERVE;
      }
    }
   F[j]=G[j]-((ws_ptr->workload) * AUX );
  }
  ws_ptr->id_time=F[num_cq]/G[num_cq];
  PROB[1]=(ws_ptr->workload) * F[num_cq -1] / G[num_cq];
  ws_ptr->exp = PROB[1];
  p=num_cq-1;
  FI= (ws_ptr->workload);
```

```
          for(j=2;j <= p;j++)
           {
            SERVE = ws_ptr->servers;
            T_SRV= j;
            if(T_SRV < SERVE)
              {
               SERVE=T_SRV;
              }
            FI=((ws_ptr->workload) / SERVE) *FI;
            k=num_cq -j ;
            PROB[j]= FI * F[k] / G[num_cq];
            ws_ptr->exp=(ws_ptr->exp) + j * PROB[j];
            }

            SERVE=ws_ptr->servers;
            T_SRV = num_cq;
            if(T_SRV < SERVE)
            {
             SERVE = T_SRV;
            }
           PROB[num_cq]=((ws_ptr->workload)/SERVE) * (PROB[num_cq -1] /F[1]);
           ws_ptr->exp= (ws_ptr->exp) + num_cq * PROB[num_cq];
        }
     }
   }
return;
}
/*________________________________________________________________________

   This function prints the input data into file "input" and the
   output data into file "output".
_________________________________________________________________________*/

#include <curses.h>
#include "del.h"

void output()
{
FILE *f1,*f2;
extern int num_ws,num_jobs,num_cq;
extern int *num_wsptr,*num_jobsptr,*num_cqptr;
extern struct workstation ws[50];
extern struct workstation *ws_ptr;
extern struct job_plan jp[50];
extern struct job_plan *jp_ptr;
extern struct entities jobs[50];
extern struct entities *jobs_ptr;
extern double PROD,TIME_SYS,TIME_PROC,TIME_TRVL,TIME_WAIT;
extern int WSMAX;
static int i,j,k,y,z;
static double f,a,b,c,d,e,g;
static char c1;

    f1=fopen("input","w");
    for(i=1;i<=4;i++)
      {
```

```
      fprintf(f1,"\n");
    }
  fprintf(f1,"Workstations\n",c1);
  fprintf(f1,"------------\n",c1);
  fprintf(f1,"\n");
  fprintf(f1,"Number of workstations=  %02d\n",num_ws);
  fprintf(f1,"\n");

  for (ws_ptr=ws; ws_ptr <= ws +num_ws;ws_ptr++)
   {
   fprintf(f1,"Workstation: %d\n",ws_ptr->number);
   fprintf(f1,"Name: %s\n",ws_ptr->name);
   fprintf(f1,"Number of servers: %d\n",ws_ptr->servers);
   if(ws_ptr == ws)
    {
     fprintf(f1,"Transportation time: %f\n",ws_ptr->total_proc);
    }
   fprintf(f1,"\n");
   }

 fprintf(f1,"\n");
 fprintf(f1,"Product types\n",c1);
 fprintf(f1,"-------------\n",c1);
 fprintf(f1,"\n");

  for (jobs_ptr=jobs;jobs_ptr <= jobs + num_jobs - 1; jobs_ptr++)
   {
    fprintf(f1,"Product type %d:%s\n",jobs_ptr->group,jobs_ptr->type);
    fprintf(f1,"---------------\n",c1);
    fprintf(f1,"\n");
    fprintf(f1,"Number of operations:%d\n",jobs_ptr->num_machines);
    fprintf(f1,"Fraction of production: %f\n",jobs_ptr->prod_mix);
    fprintf(f1,"\n");
        k=(jobs_ptr->num_machines) - 1;
        for(jp_ptr=jobs_ptr->jp;jp_ptr<=(jobs_ptr->jp) + k;jp_ptr++)
          {
           fprintf(f1,"Operation on ws:%d\n",jp_ptr->oper);
           fprintf(f1,"Process time:%f\n",jp_ptr->proc_time);
           fprintf(f1,"Frequency:%f\n",jp_ptr->freq);
           fprintf(f1,"\n");
          }
   }

  fprintf(f1,"\n");
  fprintf(f1,"Work-in-process inventory=%d\n",num_cq);
  fprintf(f1,"\n");
  fclose(f1);

  f2=fopen("output","w");
  for(i=1;i<=4;i++)
    {
     fprintf(f2,"\n");
    }

 fprintf(f2,"System performance measures\n",c1);
 fprintf(f2,"---------------------------\n",c1);
```

```
fprintf(f2,"\n");

fprintf(f2,"Throughput rate:%f\n",PROD);
fprintf(f2,"Mean time in system: %f\n",TIME_SYS);
fprintf(f2,"Mean processing time: %f\n",TIME_PROC);
fprintf(f2,"Mean travelling time: %f\n",TIME_TRVL);
fprintf(f2,"Mean waiting time: %f\n",TIME_WAIT);
fprintf(f2,"\n");
fprintf(f2,"The bottleneck station is %d\n",WSMAX);
fprintf(f2,"\n");


fprintf(f2,"Workstation performance measures\n",c1);
fprintf(f2,"--------------------------------\n",c1);
fprintf(f2,"\n");

ws_ptr=ws;
a=ws_ptr->total_visit;
for(ws_ptr=ws;ws_ptr<=ws + num_ws;ws_ptr++)
   {
   fprintf(f2,"Workstation %d: %s\n",(ws_ptr->number),(ws_ptr->name));
fprintf(f2,"Utilization per server= %f\n",(ws_ptr->buzy_servers)/(ws_ptr->servers));
fprintf(f2,"Average number of jobs being processed=%f\n",ws_ptr->buzy_servers);
fprintf(f2,"Average number of jobs waiting=%f\n",(ws_ptr->exp)-(ws_ptr->buzy_servers));
   if(ws_ptr == ws)
    {
     b=ws_ptr->total_visit;
    }
   else
    {
     b=(ws_ptr->total_visit)/a;
    }
   c=(ws_ptr->total_proc) * b;
   d=((ws_ptr->total_proc)*(ws_ptr->exp))/(ws_ptr->buzy_servers);
   e=d*b;
   f=e-c;
   if(ws_ptr == ws)
    {
     fprintf(f2,"Average processing time per job = %f\n",TIME_TRVL);
    }
   else
    {
   fprintf(f2,"Average processing time per job = %f\n",c);
    }
   fprintf(f2,"Average waiting time per job = %f\n",f);
   fprintf(f2,"\n");
 }
fprintf(f2,"\n");

fprintf(f2,"Product types\n",c1);
fprintf(f2,"-------------\n",c1);
fprintf(f2,"\n");


for(jobs_ptr=jobs;jobs_ptr<=jobs+num_jobs-1;jobs_ptr++)
 {
```

```
  fprintf(f2,"Product type %d: %s\n",jobs_ptr->group,jobs_ptr->type);
  fprintf(f2,"Average operations=%f\n",jobs_ptr->average_oper);
  fprintf(f2,"Throughput rate  =  %f\n",jobs_ptr->prod_rate);
  fprintf(f1,"\n");
 }
 if(num_cq <= 7)
  {
   y=2;
  }
 else
  {
   y=num_cq-5;
  }

 fprintf(f2,"Throughput rate for different values of N\n",c1);
 fprintf(f2,"-----------------------------------------\n",c1);
 fprintf(f2,"\n");
 fprintf(f2,"No. of jobs=1, Throughput rate=%f\n",PROD_RATE[1]);
 fprintf(f2,"                Time in system=%f\n",T_SYSTEM[1]);
 fprintf(f2,"\n");
 z=num_cq + 5;
 for(i=y;i<=z;i++)
  {
  fprintf(f2,"No. of jobs=%d, Throughput rate=%f\n",i,PROD_RATE[i]);
  fprintf(f2,"                Time in system=%f\n",T_SYSTEM[i]);
  fprintf(f2,"\n");
  }

   fclose(f2);
   return;
}
```

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