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Total performance measurement for world class manufacturing /

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Total Performance Measurement
for
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by

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Abstract

Performance measures are a vital part of a firm's strategy to achieve competitive success and to maximize profitability. They enable top management to transmit goals for company wide profits and growth in sharp, unambiguous terms. Unfortunately, most companies are managed by a set of performance measures, some or all of which are irrelevant to the strategic needs of the enterprise. This research led to the development of a generic but comprehensive set of strategic measures to evaluate total manufacturing performance. The goal of a manufacturing organization was recognized to be the maximization of profit. Profits are assumed to depend upon the cost, quality and responsiveness levels provided to the customers through the firm's products and services. Operational expenses, throughput and inventory are recognized to be global measures of manufacturing productivity. The measures developed are grouped under four heads: cost-effectiveness, quality, responsiveness and the stability of manufacturing operations. Attempt is made to relate each strategic measure to the global measures. The potential impact of uncertainty and variability on the behavior of the measures developed, is also extensively dealt with. Finally, for companies intending to develop a strategic performance measurement system, a systematic approach to determine an appropriate set of measures is recommended.

Chapter I
Introduction

Performance measures are a vital part of a firms's strategy to achieve competitive success. They enable top management to transmit goals for company-wide profits and growth to the strategic, operational and tactical levels, in sharp, unambiguous terms. Unfortunately, most companies today are managed by an inadequate set of performance indicators, some or all of which are irrelevant to the strategic needs of the enterprise. An ineffective performance measurement system can undermine superior product development, process improvement and marketing efforts. When senior management does not receive accurate information about the efficiency and effectiveness of internal operations, the organizations become vulnerable to competition from smaller and more focussed organizations (Skinner [156]). This is particularly important for large, vertically integrated or multi-divisional, diversified organizations. Also, undesirable outcomes can occur when subordinates are asked to respond to irrelevant indicators.

1.1 COMPETITIVENESS

The term competitiveness is subject to a variety of definitions. In simplest form, an industry is competitive if the price, quality and performance of its products equal or exceed that of competitors and provide the combination demanded by customers. International competitiveness is somewhat more complicated because price is more heavily influenced by exchange rates, which cannot be controlled by the individual producer. However, exchange rates are only one determinant of product price, and price is only one determinant of competitiveness. Price is also determined by production costs, quality and performance. Performance includes innovation, unique or superior design, dependability and reliability, responsiveness to the customer, which in many cases are more important determinants of competitiveness than price. If manufacturers can produce high quality goods with less labor, materials, overhead and inventory than other domestic or foreign producers, then competitive production can be ensured. These are the areas in which U.S. manufacturers have lagged [113]. Improvements in the use of these resources, as well as product quality and performance, are fundamental to improved competitiveness.

1.2 CRITICAL SUCCESS FACTORS

The success or failure of an organization depends upon how effectively it "responds" to its customer's needs. Critical success factors (CSFs) are factors that affect long term competitiveness, profitability and growth. They are the determinants of strategic success and can be determined through an objective assessment of the firm's competitive environment. Critical success factors can include things like:

- Capacity - meeting volume demand
- Capability - meeting feature demand
- Flexibility - ability to rapidly change output
- Dependability - meeting customer need dates
- Reliability - producing a product that works
- Quality - meeting product specifications
- Responsiveness - rapid product introduction
- Innovation - creating new products, processes and/or systems
- Cost - expenditures to bring the product to the customer.

Critical success factors are product specific and depend on the environment in which the firm operates. For a given product, CSFs vary as it evolves through the different phases of its life cycle. Strategies and mission statements should be derived from the firm's CSFs. No two manufacturing firms are alike. Therefore, no one strategy will work for all. Each strategy must be tailored to the environment. In a multi-plant, multi-product environment, the mission statement and objectives must be developed separately for each business unit and coordinated into the overall set of goals. Also, some of the critical success factors listed above can be mutually exclusive if taken to the extreme, for example, flexibility versus cost and cost versus reliability. Each CSF should be valued relative to the market demands vis a vis the competitor.

1.3 WORLD CLASS MANUFACTURING

World class manufacturing involves the production of goods that are competitive in a global market. Fundamental to being world class is the evolutionary creation of a lean manufacturing facility. This is done by attempting to progressively lower all uncertainties in the overall production process using only those available resources, philosophies and tools that are appropriate and make sense. Uncertainty in production stems from poor process capability, equipment reliability, vendor reliability, information accuracy and quality of incoming materials, worker absenteeism, low employee motivation and knowledge levels, schedule variations and a host of other factors. These uncertainties have a negative influence on the firm's critical success factors and therefore, on its ability to compete. It may also be seen that all uncertainties result in an increase in inputs for a given level of output.

1.4 IMPACTS OF OVERSEAS COMPETITION

Overseas manufacturers with lower labor costs will have a long term manufacturing cost advantage in the manufacture of standard products. The competitive edge for the U.S. will be in the production of items that are non-standard. The non-standard nature can arise from product customization, continual technological improvements to the manufacturing process, and/or a continuous process of innovation and introduction of new and improved products. The advent of affordable flexible manufacturing technologies will shift emphasis in the U.S. from large scale repetitive manufacturing processes to a highly automated job shop environment featuring the manufacture and assembly of customized products in short batch sizes (Gordon and Richardson [140]). Due to the high level of responsiveness demanded, a number of factors will be critical to the success of these firms. The American niche of customized production for global markets would help in gaining a competitive edge only if the evolutionary change, as well as steady state operations are managed by a diverse set of strategic performance measures that span all success factors. Traditional cost and labor productivity based indicators do not provide comprehensive measures of total manufacturing performance. New measures will be required.

1.5 STRATEGIC INFORMATION SYSTEMS

A strategic information system of an organization should serve as a means to systematically collect, organize and present on time, external and internal intelligence-information that is useful for planning and conducting business in a manner that fosters long term competitiveness, profitability and growth.

Timely external intelligence helps to keep the organization's critical success factors and mission statement up to date. This is very important since all operating strategies are justifiable only on the basis of a valid mission. External intelligence includes market and industry trends, policy changes by domestic and foreign trade/ government agencies, trade and tax laws and incentives, competitor performance and actions, advancement in product and process technologies and such others.

Internal intelligence essentially consists of measures of long term organizational health and a comprehensive set of indicators to measure total manufacturing performance in terms of the extent to which critical success factors are satisfied and how they relate to the organization's primary goal - profit maximization.

1.6 SCOPE OF THIS RESEARCH

This objective of this research was to develop a generic but comprehensive set of performance measures that could serve as a complete menu for organizations to choose from, based on their corporate mission and mix of critical success factors. Such a set of measures is a prerequisite for gaining control over planned change and steady state operations.

Chapter 2 surveys the characteristics and limitations of traditional performance measures and managerial incentive systems. The impacts of corporate missions and product life cycles on critical success factors are analyzed. The need for new performance measures and impediments to the development of such measures are discussed.

Chapter 3 presents a framework for measuring total manufacturing performance. The need for a hierarchical system is discussed and the functional requirements for strategic performance measurement are developed.

Chapters 4, 5, 6 and 7 present detailed sets of operational level measures for cost effectiveness, quality, responsiveness and operational stability respectively. About a hundred different measures are discussed. Attempt has been made to ensure that each measure reflects relevance to operational expenses, inventory and/ or throughput - the global measures of manufacturing productivity. The summary, conclusions and recommendations for the use of the proposed measures are presented in Chapter 8.

Chapter II

Research Issues in Performance Measures

This chapter surveys the characteristics and limitations of traditional performance measures and managerial incentive systems. The impacts of corporate missions and product life cycles on the critical success factors of an organization are then analyzed. Areas for further research and the desirable qualities for researchers in this field are briefly reviewed. The need for new performance measures and impediments to the development and use of such measures, that have existed in the past, are then discussed.

2.1 TRADITIONAL PERFORMANCE MEASURES CHARACTERISTICS AND LIMITATIONS

The basic problem with performance measures today is that they have little or no relevance to strategic decision making. According to a survey by Richardson and Gordon [140], productivity and cost are the most widely used performance indicators. Many firms employ measures of product quality. Some firms measure delivery performance on a regular basis. Few firms have very basic measures for flexibility in terms of volume and product specification changes and some others for process innovation. In general, indicators in use are not comprehensive enough to measure total manufacturing performance.

Measures used are not product specific. Generic measures are used for all products within a single facility. Little or no consideration is given to changes in critical success factors as a product evolves through different phases of its life cycle. Multi-product plants with products in different phases of their life cycle use a generic single measurement system across all product lines, departments and functions. The formality of evaluation increases with the size of the firm and the maturity of the product line. In small firms (sales < $5 millions) standards were less well established and the frequency of evaluation was much lower. Quality and delivery become concerns only when customers complain.

Single measures of performance are prevalent (Kaplan [91]). Single measures have myopic properties that will enable managers to increase their score on this measure without necessarily contributing to the long term profits of the firm. They do not provide insight into the variables that affect its value. Consequently, they do not provide direction for improved performance.

Cost accounting systems collect only those costs that are easy to collect. Little or no effort is made to transform non-financial measures (wherever used) into cost. Critical measures of manufacturing's responsiveness are missing. Some firms have realized that cost and productivity based yardsticks do not provide comprehensive measures of performance, but still have failed to adopt other measures. A few organizations however, appear to be in the process of developing new measures with help from consulting organizations and academic institutions (Richardson and Gordon [140]).

2.2 TRADITIONAL MANAGERIAL INCENTIVE SYSTEMS

These have traditionally been based on <u>short term</u> financial performance. According to Kaplan [91], managerial decisions are strongly influenced by the nature of incentive systems for division and senior managers. At present, they rely heavily on financial measures of performance such as earnings per share. Operating measures consistent with long term health are not used (Rappaport [138]).

During inflationary periods, firms tend to adopt practices to increase reported income through under-depreciation and understatement of the cost of goods sold. Using financial measures as a basis for compensating senior managers also tends to focus senior manager's attention on financial rather than manufacturing performance. Debt restructuring exercises like mergers and acquisitions increase financial performance in the short run, but have few demonstrable benefits for the effectiveness or efficiency of the firm.

Capital investments in new products and processes, due to the learning curve/ experience curve and other effects tend to have a short run negative impact on reported earnings. During periods of economic downturn the tendency is to reduce capital investment as well as intangible investments in research, product development, human resource development, advertising and promotion, maintenance, quality control and customer service. Workers are laid off rather than reassigned to activities suitable for slack periods such as equipment maintenance, modernization, retraining and education and redesign of work activities. These practices maintain profit levels in the short run but almost always prevent gains from new product innovation, improved processes, more skilled and loyal employees and an expanded market share.

Kaplan [91] explains the current popularity of financial measures. Financial measures provide an apparent, comprehensive measure of performance. They enable aggregation of performance across diverse operating units and divisions to get an overall measure. However, the use of financial measures as a basis for incentive systems penalize managers for sacrificing short term earnings for long term profitability.

2.3 PRODUCT LIFE CYCLE IMPACTS

Every product goes through the following phases in its life cycle:

- Phase 1: Product introduction,
- Phase 2: Market growth,
- Phase 3: Market maturity and saturation and
- Phase 4: Sales decline.

Richardson and Gordon [140] summarize their beliefs about different measures of manufacturing performance that must be employed at the different stages of a product life cycle with the following propositions:

Proposition 1

"As products move through the life cycle, the critical tasks of manufacturing change."

For products early in the life cycle, the ability to

1) innovate and introduce new products quickly,
2) vary product characteristics quickly as new customer preferences and new technological possibilities become known,

3) deliver new products at high quality levels and

4) deliver on predictable delivery schedules,

is critical to success. As products mature and markets reach a saturation stage, competition takes place along cost minimization and productivity dimensions. This is particularly true of mass produced items with stable characteristics and demand patterns.

Proposition 2

"Facilities that manufacture products early in the life cycle are less likely to have well-defined measures of manufacturing performance than those facilities with mature products."

Measures of innovation and flexibility required for products early in the lifecycle are complex and require data collected over a long time. Quite often they don't exist and if they do, they were extremely crude. Consequently, facilities that manufacture new products are less likely to have well defined measures than those with mature products.

Proposition 3

"Where manufacturing performance measures are inappropriate to a products stage in the lifecycle, dysfunctional consequences will result."

If managers introducing new products are evaluated on the basis of cost minimization and productivity, they may not be as responsive to customer needs, will freeze the design specifications and standardize the product, and may not pay enough attention to the maintenance and improvement of quality.

Proposition 4

"In multi-product manufacturing facilities product innovation will be inhibited by measurement systems designed for mature products."

Measures such as cost minimization and productivity will inhibit innovation and successful introduction of new products. This will happen because the learning curve/experience curve effects, sluggish initial market conditions and frequent design changes associated with new products result in deterioration in productivity, at least in the short term.

Proposition 5

"Managers will respond to perceived measures of their performance."

This refers to the adage that whatever is measured improves. Quite often people tend to show favorable performance numbers without regard to their relevance.

2.4 CORPORATE MISSION IMPACTS

The corporate mission provides an enduring statement of the business the firm is in, the firm's objectives and how it will compete in its markets. The statement of the mission identifies the image the firm attempts to project and reflects the values and priorities of the firm's decision makers. Subordinate to this overall mission are functional strategies (marketing, manufacturing, research and development) which should be defined by parameters that ensure that they fit the mission and so enable the firm to achieve its long run objectives (Richardson, Taylor and Gordon [141]).

Traditionally, manufacturing choices have been described as trade-offs among cost, quality, volume, delivery and design. Recently, however, declining innovation has been recognized as a major problem in firms manufacturing mature products. In response to concerns of this nature, a broader view of manufacturing strategy has emerged which includes product and process innovation [141].

Manufacturing performance should be evaluated in terms of how well it meets the goals and objectives defined for it by the corporate mission. The goal is to maximize profit and the mission represents the organizations' approach to achieve the goal. The demands placed on manufacturing by the corporate mission determines manufacturing strategy. Manufacturing tasks are derived from the manufacturing strategy and the effectiveness of operations needs to be evaluated using a weighted set of measures.

Companies in the same industry have been successful with completely different marketing and manufacturing strategies. This shows that there is a variety of corporate missions and corresponding manufacturing strategies. Some commonly observed manufacturing missions are discussed below.

2.4.1 TYPES OF MISSIONS

Richardson, Taylor and Gordon [141] identify six forms of corporate mission, differentiated on the basis of three principle characteristics: product volume, product variety(focus) and the degree of innovativeness. The missions were postulated to vary from those based primarily on innovation skills to those based almost entirely on low cost production. The different types of missions were characterized as follows:

Technological Frontiersmen

These firms are driven by research and development.

They remain on the leading edge of production technology by constantly innovating, and their ability to introduce new products is a key success factor. Markets are abandoned when they become price competitive and margins fall. Price and promotion are not significant attributes because product performance is a major selling feature.

The key factors for the sucessful implementation of this mission are:

1) Outstanding product research, development and design,
2) High product quality and
3) The ability to introduce new products continuously.

Technology Exploiters

Like technology frontiersmen, these firms attempt to introduce new products, but they follow through the complete lifecycle by manufacturing even when the product becomes price competitive. Their strategy is complex because it requires both innovation and cost minimization.

There is a broad and potentially conflicting range of factors important for the success of this mission:

1) Rapid price reduction as production reaches high volume,

2) Substantial skills in product development and design,

3) The ability to introduce new products,

4) High product quality and

5) Cost minimization skills.

Technological Servicemen

These firms are also on the leading edge of product technology but provide custom service on complex systems for low volume customers and markets. The firms must be extremely flexible and adaptable in order to respond to customer needs.

The key factors for the successful implementation of this mission are:

1) Excellence in product design,

2) High product quality and quality assurance and

3) Flexibility to customer specification changes.

Customizers

These firms are true job shop manufacturers. While they do little innovation themselves, they can accept product designs from customers and produce competitively on a low volume basis. Because they accept a wide variety of work, these firms must have considerable flexibility for changes in volume and specifications.

The key factors for the successful implementation of this mission include:

1) Product quality and quality assurance and
2) Flexibility to handle changes in specifications and volumes.

Cost-Minimizing Customizers

These firms produce low volume mature products to individual customer designs. The firm's principal skills lie in design and process engineering. Price is an important factor in the marketing process. This mission requires both job shop and cost minimization skills for successful implementation.

The key factors for the successful implementation of this mission are:

1) Low prices,
2) Cost minimization (often without the benefit of high volume production),
3) Delivery on schedule and
4) Flexibility to volume and specification changes.

Cost Minimizers

These firms are high-volume producers whose skills lie in the low cost production of mature products. Accordingly, productivity and capacity utilization will be important measures of their performance if the company can sell whatever it can produce.

The narrow set of key success factors for this mission are:

1) Low price,
2) High volume and low cost production and
3) Rapid delivery.

The relative importance of the different success factors within each mission profile may vary from organization to organization. Some forms of corporate mission, unfortunately, have conflicting critical success factors. Manufacturing strategies that satisfy all CSFs equally, may not be feasible in such cases.

2.4.2 TYPES OF MANUFACTURING STRATEGIES

Richardson, Taylor and Gordon [141] identify four different types of achievable manufacturing strategies:

New product centered strategy

The emphasis here is on innovation through the ability to adapt to varying product specifications while maintaining quality. Cost and productivity are of low importance given the innovativeness of the product.

Custom innovator strategy

The introduction of new products is important, but the fact that each job is in some way unique adds to the complexity of the task. Increased flexibility, particularly to changes in specifications and volume, is very important.

Cost minimizing job shop strategy

Productivity and cost minimization are important, but because customers demand custom production, volume and specification flexibility are also required.

Cost minimizer strategy

Long runs, productivity, and return on assets are the key parameters of manufacturing performance. New products are rarely introduced, and so flexibility is relatively unimportant.

An important factor in corporate success is the degree to which the measures of manufacturing performance match the perceived corporate mission. It can be predicted that firms where corporate mission and manufacturing performance measures are congruent will outperform those in which the two are mismatched. While developing performance indicators for any organization care must be taken to ensure congruence with the corporate mission.

This section was intended to highlight differences in corporate missions, the variations in the demands imposed on manufacturing and the need to tailor manufacturing strategies and performance measures to achieve competitive performance.

2.5 AREAS FOR RESEARCH

Research in performance measures should focus over three major areas:

- Understanding performance measurement and executive compensation practices in overseas organizations,
- Developing measures of organizational health and capabilities and
- Developing strategic performance measures, which includes relevant management accounting systems.

It is essential to understand how Japanese, German and other foreign producers noted for their manufacturing efficiencies, measure, motivate and evaluate performance of their production managers. The use of non-financial measures for evaluating operations and the benefits they have attained through the use of strategic indicators must be investigated.

Measures of health include measures for innovation, different types of flexibility. Ways to evaluate a company's ability to introduce new and improved products on a continuous basis are required.

Strategic performance measures research can be divided into development of management accounting systems and the development of physical, financial, non-financial measures for evaluating total manufacturing performance. These two systems must be well integrated and interdependent. New cost accounting systems tailored to product and process technologies and organizational structure are required. Physical measures that would provide answers to these questions need to be developed:

1) what is the value of close co-ordination between a firm and its vendors ?
2) what is the value of reduced uncertainty in the manufacturing process ?
3) what is the value of reduced lead time ?
4) what is the actual cost of quality ?
5) how do you evaluate a company's preparedness for Just-In-Time?
6) what is the opportunity cost of lost sales due to poor responsiveness ?

Comprehensive models for financial and non-financial performance measurement with well-defined exchange of information between the two do not exist. Suitable frameworks for strategic measurement systems should be developed and progressively embellished.

2.6 QUALITIES DESIRABLE IN PM RESEARCHERS

The researcher should be very familiar with the organization for which the measures are developed. He should have a good understanding of manufacturing operations and accounting procedures as well as the creativity to develop new measures. He should approach research without a rigid design in mind. However, the research should not be model free and purely descriptive. The researcher should have a variety of models in mind that should be documented and tested. He should have the capability to perform field studies, document, test and implement new systems. It is also important to document gaps in knowledge about important measurement issues pertaining to manufacturing performance.

2.7 NEED FOR NEW PERFORMANCE MEASURES

The future success of most U.S. manufacturers will depend on their ability to continuously introduce, nurture and grow new and improved custom designed products, produced quickly and efficiently in small batches using automated manufacturing equipment (Johnson and Kaplan [86]). To attain such capabilities, many companies will have to initiate and manage a program of planned change to improve their design and manufacturing facilities. The change phase as well as transformed steady state phase, if such a phase exists, must be strategically managed to remain on the trajectory to long term profitability and growth. The future manufacturing environment will be characterized by:

1) Rapid changes in technology,
2) Shortened product life cycles,
3) Differences in the organization of production operations,
4) Reduction in the direct labor content of final products,
5) Increased capital intensity of production processes,
6) Greater contribution to a firm's success provided by its stock of knowledge and intangible resources.
7) Greater need to quantify non-financial factors for justification of capital equipment.
8) Manufacturing system life cycles exceeding the product life cycle, as a result of which manufacturing capabilities will become more central to the strategic positioning of the firm. Manufacturing manager's horizons will expand. A more predictable and controllable manufacturing organization will be required to contribute to longer horizons.

Traditional management accounting systems and performance indicators are based on the mass production of a product in the mature phase of its lifecycle (Johnson and Kaplan [86]). These are primarily aimed at cost minimization. Traditional performance measures and management accounting systems do not provide comprehensive information on all financial and non-financial variables that affect the critical success factors in today's manufacturing environment. Changes in customer expectations, technological capabilities, manufacturing philosophies and global competition render traditional systems inadequate.

2.8 IMPEDIMENTS TO STRATEGIC PERFORMANCE MEASURES

There are several impediments to the development, implementation and use of strategic performance measures, particularly those that are non-financial in nature. These stem from the fact that they are different from those used to report to external financial investors. Use of these indicators initially results in erratic and unpredictable short term performance. This will occur because less attention will be paid to implementing decisions that maintain steady quarter to quarter or annual earnings growth. Other major impediments to strategic performance measures are as follows:

1) Critical variables of interest like flexibility are hard to define and capture.

2) Management's unwillingness to accept new concepts, habit and lack of understanding of alternative methods.

3) Products age and critical success factors change. Strategic performance measures also need to change.

4) Physical measures are often difficult or impossible to aggregate into a single overall measure.

5) Developing strategic performance measures requires the involvement from management accounting, design, engineering and manufacturing departments. Accounting personnel do not take pains to understand the nature of manufacturing operations. Engineering personnel often do not appreciate the importance of strategic control and look upon supplying data for accounting as a periodic ritual.

The background information in this chapter is used to develop functional requirements for strategic performance measurement and a framework for the development of a system to measure total manufacturing performance.

Chapter III
Framework for Measuring Total Manufacturing Performance

A system for measuring total manufacturing performance is one that will provide information on all factors that have a significant effect on profitability, competitiveness and market share. Such a system would be organization specific and should therefore be based on the following:

- Company's strategy,
- Product and process technologies,
- Organizational structure and the
- Marketing environment.

It should include key measures of manufacturing, marketing and R&D success. The data for these systems should not be extracted from financial management systems but from one specifically designed for strategic management. This system is intended to help the firm maintain its trajectory to long term profitability.

3.1 FUNCTIONAL REQUIREMENTS

A system for measuring total manufacturing performance should:

1) Generate timely and accurate information on

strategic performance.

2) Be product specific, logical and pertinent to the current phase of the product life cycle.

3) Ensure that the conduct of operations is consistent with long term profitability and growth.

4) Measure the effectiveness of internal processes and the profitability of product offerings.

5) Support the pursuit of competitive strategies by ensuring consistency with new technologies and philosophies.

6) Effectively capture cause-effect relationships between different activities in the enterprise and the incurrence of operational expenses.

7) Enable effective reporting of accomplishments related to cost, quality and responsiveness.

8) Enable identification of opportunities for performance improvement.

9) Promote congruence between the firm's manufacturing strategy and subsequent evaluation of manufacturing operations.

10) Encourage a certain desired type of behavior on the part of people responsible for implementing a strategy.

11) Lend credibility to capital investments through more objective post audit evaluation using

multiple qualitative and quantitative measures.

12) Enable progressive expansion of capital budgeting procedures through measures which help correlate benefits from improved quality, flexibility, rapid changeover, increased capacity etc., with improved cost performance.

13) Enable the correlation of physical productivity measures with financial profitability measures to make the capital justification task easier in future.

14) Provide a sound basis for compensation plans for personnel in the strategic, operational and tactical levels.

15) Provide the rationale for reward or penalty in stakeholder relationships.

16) Focus on solving tomorrow's problems instead of unravelling yesterday's errors.

17) Ensure that the effort required to collect data for a given measure is commensurate with the strategic importance of that measure.

18) Be dynamic- show improvement or deterioration trends instead of absolute, static or snapshot information.

19) Measure only those variables and costs that are significant.

20) Make waste and the contribution of waste visible.

21) Expose variabilities and uncertainties in manufacturing processes and systems, and their impact on the throughput of constrained resources, inventory levels and operating expenses of the firm.

3.2 HIERARCHICAL APPROACH

Strategic goals are implemented through personnel in the tactical and operational levels. It is desirable to have performance data fed back up the hierarchy through an interdependent set of subsystems, one at each level. Information from the operational level should be summarized and fed to the tactical level so that tactics can be periodically evaluated. Similarly, information with the tactical level must be summarized and sent to the strategic level so that the impacts of strategy as well its dysfunctional consequences, if any, can be understood and acted upon.

3.3 FRAMEWORK FOR MANUFACTURING PERFORMANCE MEASUREMENT

The "goal" of a manufacturing organization is to make profit. From an external perspective, profit comes from being competitive, by being fully responsive to the needs of the customer. Profitability is important both in the short term and in the long term. However, short term profitability should not be achieved at the expense of long term profitability. For long term competitiveness, the manufacturing organization should endeavor to provide the desired levels of cost, quality and responsiveness by initiating and sustaining programs of ongoing improvement in each of these factors. These success factors are the "means" to achieve the "goal". To operate strategically, it is therefore essential to monitor progress in terms of the "means" adopted and its impacts on the goal.

Goldratt's theory of constraints [43],[44] uses three global measures of manufacturing profit performance: throughput, inventory and operating expenses. **Throughput** is the rate at which the system generates money not through production but through "sales". If something is produced but not sold, then it is not throughput. Throughput is the money coming in.

Inventory is all the money the system has "invested" in purchasing things which it intends to sell. It is the money currently in the system. Investment that can be sold is inventory. By not including labor cost in WIP and treating it separately as an operational expense, the confusion over whether a dollar spent is an investment or an expense can be avoided. Depreciation is investment that cannot be sold. It is an operational expense.

Operational expense is all the money the system spends in order to turn inventory into throughput. It is the money that must be paid to make throughput happen. It is money going out. The goal is not to improve one measurement in isolation. The goal is to reduce operational expense and inventory while simultaneously increasing throughput.

From an internal perspective, profitability depends on throughput. Throughput, as already defined, is the rate at which the system generates money through sales. Throughput could be constrained by one or more resources whose capacity is less than the demand imposed on it. Besides capacity limitations, there are several events that can further limit the output from an already constrained resource. Examples of such events include material shortages, poor incoming quality, setups, equipment downtime, scrap, rework and poor scheduling. Performance indicators developed should serve as yardsticks to measure the impact of such events on the throughput of constrained resources, as well as, their impact on inventory levels and operating expenses in the plant as a whole.

The internal information on performance in many manufacturing organizations has been deficient and misleading. It is filtered several times, and it is secondary data: not process quality, but after the fact customer complaints; not how fast manufacturing can react but how responsive warehouses are; plenty of broad measures like cost variances and labor efficiencies but no details on the cause of the variances; and little, if any, measures on rates of improvement. The enterprise cannot be guided strategically based on secondary information.

World class manufacturing surely does require strategic leadership. The best strategy is to do things better and in the trenches [147]. According to Schutzenberger in [147], what we have done so far is to show that strategy is simply one of the tactics and that any tactic can be viewed as some sort of strategy. The best leadership insists on visible measures of what is going on in the trenches and on action to achieve a high rate of improvement.

There is wide agreement among world class manufacturing revisionists today that continual improvement in cost, quality, lead time and customer service is possible realistic, necessary and may be pursued in concert. In the pre-world class manufacturing era, the perception was that production could be managed by the numbers. The numbers would show what to make, what to buy and whom to blame. When variances occured, the numbers failed to show the causes. Mostly, they did not even show symptoms of real problems [147].

Numbers do serve the world class manufacturer - when they show how good the product and service are, what problems to attack next and what the likely causes are. World class manufacturing mandates simplification and direct action: Do it, judge it, measure it, diagnose it, fix it and manage it on the factory floor. The only way a factory can be steered is for the factory people to sink multiple probes. There are enough people available for it. The trick is to get them to sink the probes. Information on total manufacturing performance is the lifeblood of the manufacturing organization but certainly not the muscle. If used sensibly, it can nourish the muscle, otherwise, it can cause attrition.

Reorganizing people and machines takes boldness, which is often a commodity in short supply. Some prodding may be necessary, and the best type of prod is built into the performance measurement system. Visible measures of success are the driving force. History has shown repeatedly that whatever is measured improves. The answer to being a world class manufacturer is to choose the right goals and to organize the enterprise for continual progress against those goals [147].

The rate at which a system generates money through sales is not just a matter of internal capabilities. Market demand influences product mix and production volume. Market demand is directly dependent on the firms' performance relative to its competitors. Customers' expectations of a product fall under one or more of the following depending upon the nature of the product, the current phase of its lifecycle and the marketing environment:

- Cost
- Quality and
- Responsiveness.

Responsiveness encompasses success factors such as speed and reliability of delivery, flexibility, customer service, new product innovation, product customization and such others. Strategic performance includes performance against all factors critical to market success while the plant is operating in a stable steady-state mode. Producing products at acceptable cost, quality and performance levels does not mean a thing if the plant is always in a state of chaos in its attempt to meet the expected levels of performance. Customer expectations have to be met with proper organization and with ease. All performance evaluations must be done with this in mind.

The proposed framework for strategic performance measurement organizes the required feedback on strategic performance under four different heads:

- Measures of cost-effectiveness,
- Measures of quality,
- Measures of responsiveness and
- Measures of operational stability.

Individual performance measures under consideration must be evaluated stringently in terms of their impact on constrained resources, the operating expenses and inventory levels in the plant. It is essential to use care and consideration beforehand when identifying information that might be useful. Poor information or wrong information can be useless, whether it is collected for manufacturing or whatever else. Some important questions that must be asked are:

Why is this measure needed?
What motivation for improvement will it provide?
How relevant is this improvement to the goal?
What success factor will it favorably influence?
Who should be responsible for monitoring this?
How feasible would it be to collect data for this?
How frequently should this be reported?
How will it influence decision making?

Could it result in deviation from the goal?

When properly chosen, performance measures can help internalize a radically changed view of what constitutes factory goodness. The functional requirements, framework and rationale developed in this chapter are used as the basis for the development of specific measures in the subsequent chapters.

Chapter IV

Measures of Cost-Effectiveness

A survey by the National Association of Accountants [73] shows that the average distribution of the components of total cost is as follows:

Material	53%
Labor	15%
Overhead	32%

The actual distribution, however, would depend upon the nature of the industry, the product, the process, the organization of production operations, the customer service level and the scale of the operation. The development, adoption and termination of the use cost based indicators should be based on the following rules:

1) Don't measure costs that are insignificant.
2) Stop measuring costs that eventually become insignificant due to programs of continuous improvement adopted to reduce them.
3) Resume measurement if the need arises.

Hewlett Packard stopped measuring direct labor as a separate cost category since it was only 3 to 5% of the total cost [79]. This eliminated 100,000 journal entries per year and great amounts of worker, manager and accountants time that was consumed in labor cost tracking and analysis.

The proposed measures of cost-effectiveness are grouped under the following heads:

A. Material cost-effectiveness,

B. Conversion cost-effectiveness and

C. Lifecycle costs.

4.1 MATERIAL COST-EFFECTIVENESS

This section includes measures of cost-effectiveness of activities related to material procurement such as purchasing, vendor development, receiving, incoming inspection, raw material storage and point-of-use storage. These are activities concerned with making the right materials available for production in the right place and at the right time. Relevant indicators of material cost-effectiveness are presented below.

4.1.1 Total cost of materials purchased

The total cost of materials purchased is the cost of getting the right materials at the right time as well as the costs associated with not having the right materials at the right time. This includes the invoice cost of the material inputs, all operating expenses associated with the procurement process, expenses necessitated by uncertainties in procurement and finally, the loss in throughput caused by discrepancies in the quality, quantity, and delivery of raw materials.

Operating expenses related to procurement consist of the following:

1) Indirect overhead due to purchasing staff,
2) Vendor development costs,
3) Vendor inspection/ audit costs,
4) Incoming inspection costs,
5) Freight consolidation and transport costs,
6) Raw materials carrying costs,
7) Cost of returning defective or wrong supplies and
8) Expenses related to space, facilities and services in the purchasing office, receiving docks, raw materials stores, incoming inspection etc.,

It may be observed that most of these expenses arise out of activities aimed at reducing/ eliminating uncertainties in material inputs, that could eventually affect the throughput from constrained resources. These expenses, by themselves, do not provide any clues for ongoing reduction in operational expenses. Probes to unearth individual sources of waste and opportunities for productivity improvement in the procurement process are required.

In most companies the total cost of materials purchased has a significant impact on end-product cost and profitability. Uncertainties in procurement operations create the tendency to order more than what is required. The excess raw material inventory has a carrying cost attached to it. Bad quality material inputs can waste productive time on constraints. Material shortages and delays can starve constraints. Besides causing loss of throughput, uncertainties affect competitive performance in many other ways: poor due date performance, long lead times and post shipment product failures. The opportunity cost of lost future sales due to uncertainties in material procurement may be difficult to quantify on a regular basis, due to the complexities involved. However, a reduction in the total cost of materials purchased, as defined in this section, can be used as a global measure of improvement in procurement performance.

4.1.2 Cost to spend a dollar

This is the ratio of the purchasing overhead to the actual total invoice price of material inputs, in a given time period. The purchasing overhead in a given time period is the sum total of all procurement related expenses in that time period, as discussed in Section 4.1.1. The higher this ratio, the greater is the operational expense incurred on obtaining and providing the right materials, of the right quality and quantity, at the right time.

The only systematic way to reduce wasteful operational expenses, raw material inventory and lost throughput arising out of uncertainties in procurement is vendor development-developing vendors who could be responsive to the demand patterns and provide consistently high quality and reliable deliveries. The cost to spend a dollar is a good global measure to monitor improvements in the productivity of material procurement operations.

Fundamentally, procurement related expenses stem from activities undertaken to isolate manufacturing operations from the adverse impacts of variabilities in the quantity, quality and delivery of material inputs. These activities are non value-adding and therefore a "waste". The most serious consequences would involve starving constraints or producing scrap on constraints resulting in a loss of throughput. Lost throughput is lost profit. Therefore, a reduction in waste, uncertainty and/or throughput losses will improve cost effectiveness in manufacturing operations. Relevant indicators of the productivity of procurement operations that could expose sources of waste, uncertainty and throughput losses are presented in the following sections. These would be helpful in problem identification, problem solving and performance measurement.

4.1.3 Percentage of receipts with quantity discrepancies

A quantity discrepancy in material inputs refers either to the difference between the quantity ordered and that received or the difference between the quantity invoiced and that actually delivered. Besides affecting trust and confidence between the manufacturer and the vendor, it induces "uncertainty" in the procurement process and necessitates counting/ verification to ensure accuracy of inventory records. Incoming inspection whether manual or automated costs money and increases the dock-to-line leadtime. It is a non-value adding operational expense that can be reduced or eliminated through vendor development.

Quantity discrepancies have more serious impacts on profitability and competitiveness. They can potentially starve constrained resources resulting in loss of throughput. This, in turn, could adversely affect due date performance, leadtimes and customer satisfaction. Quantity discrepancies increase the total cost of materials purchased as defined in Section 4.1.1. The reduction in the percentage of receipts with quantity discrepancies is therefore one of the primary and dynamic measure of uncertainty reduction and improvement in the cost-effectiveness of procurement operations. To prevent short term mismanagement of this measure, it is recommended that it be used along with the previously defined measure, "the total cost of materials purchased".

4.1.4 Percentage of receipts with quality discrepancies

A quality discrepancy in material inputs is said to exist when receipts fall short of design specifications. It induces "uncertainty" in the procurement process and necessitates incoming inspection to "control" the quality of unreliable material inputs. This is a must because defective raw material has the potential to generate scrap at constrained resources and limit their throughput. Incoming inspection whether manual or automated costs money. It is a non-value adding operational expense that can be reduced or eliminated through vendor development.

Uncertainty in incoming quality encourages the creation of raw material buffers. This is intended for sustaining throughput when occasional lots of bad material escape incoming inspection and reach constrained resources. When scrap occurs at a constraint, it not only causes material losses but also profit losses due to reduced throughput. Incoming inspection also increases the dock-to-line leadtime. This, coupled with the high raw material inventory buffers, increases the dollar-days of inventory held.

In summary, quality discrepancies increase the total cost of materials purchased as defined in Section 4.1.1. Bad incoming quality can be improved through vendor SPC programs and penalties. The reduction in the percentage of receipts with quality discrepancies could therefore be used as another primary and dynamic measure of uncertainty reduction and improvement in the cost-effectiveness of material procurement operations. To avoid short term mismanagement of this measure, it is recommended that it be used with the previously defined measure, "the total cost of materials purchased".

4.1.5 Percentage of receipts rejected

Incoming materials are rejected when they fall short of specifications and cannot be corrected within the factory premises for economy or policy reasons. This is a subset of the receipts with quality discrepancies. Materials are rejected through an incoming inspection process. Rejection could involve costs associated with returning materials back to the vendors and rescheduling to sustain throughput. Besides, the delays caused by rejection could potentially starve constrained resources resulting in loss of throughput. The operational expenses associated with incoming inspection and the throughput losses arising out of bad quality can be reduced or eliminated through vendor development programs. As a rejected receipt increases the total cost of materials purchased, the reduction in the number of receipts rejected is another measure of improvement in procurement cost-effectiveness. To prevent short term mismanagement of this measure, it is recommended that it be used with the previously defined measure, "the total cost of materials purchased".

4.1.6 Percentage of receipts subject to incoming inspection

Incoming inspection, as already discussed, is a non-value adding activity, undertaken to cope with uncertainty in incoming quality. This activity could be significantly reduced in its scope or eliminated if vendors could be developed to take full responsibility for building quality into their products and for assuring consistent, good quality deliveries. This would also eliminate the tendency to buy more than what is needed and create raw material buffers to cope with bad quality. Further, this would also improve dock-to-line lead times and reduce the total dollar-days of inventory held. Though incoming inspection reduces the probability of bad materials reaching constrained resource, it does not eliminate uncertainty totally. In other words, the constraint could still waste productive time processing bad parts. The reduction in the percentage of receipts subject to incoming inspection could be used as a measure of improvement in incoming quality and procurement cost-effectiveness, if instituted along with a comprehensive cost of quality reporting system. It would then drive vendor development efforts and eventually obviate the need for incoming inspection. If incoming inspection is reduced for reduction's sake, the costs of internal and external failure and throughput losses are likely to escalate, thereby discouraging blind reductions in incoming inspection.

4.1.7 Reduction in COQ to purchase price ratio

The uncertainty in the quality of incoming materials requires some actions to isolate manufacturing operations from its adverse effects. Such actions include vendor SPC programs, on-site audits, incoming inspection and returning rejected goods back to the vendor. The cost of quality in <u>purchased materials</u> include the cost of these activities, the cost of scrap and disruptions in the production process and the loss of throughput arising directly out of defective raw materials. Success in vendor development would result in a progressive reduction in appraisal, failure and disruption costs. The ratio of the cost of quality (COQ) in materials purchased to the total invoice value of purchases, in a given time period, could be used as a dynamic measure of improvement in the quality of material inputs and the cost-effectiveness of procurement operations.

4.1.8 Reduction in late vendor deliveries

Delays in the delivery of purchased materials can cause shortages, disturb production schedules, warrant rescheduling and setup tear downs, encourage creation of raw material buffers, starve constrained resources and cause shipment delays. Delay in vendor deliveries is one of the three main sources of uncertainty in the procurement process, the others being quantity and quality. Besides increasing operating expenses and inventory levels, delays have the potential to starve constrained resources resulting in reduced throughput. Delays in material deliveries affect the company both externally and internally- externally due to poor due date performance and internally due to poor profitability. Delays increase the total cost of materials purchased as defined in Section 4.1.1. The reduction in late vendor deliveries is therefore another primary measure of improvement in procurement cost-effectiveness and competitive performance. In companies intending to become JIT producers, this measure would be particularly useful for identifying areas for improvement in material procurement.

4.1.9 Vendor base

The term "vendor base" refers to the total number of suppliers the organization is dependent upon for its production material inputs. The rationale in supplier development is simple: the quality, quantity and delivery dependability goes up and the price comes down. Since too many suppliers means too little attention to each of them, supplier development starts with supplier reduction.

According to Schonberger [147], when a supplier reduction program runs its course, the following results are observed:

1) A typical supplier plant sells in much larger volumes to a much smaller number of customers than before. Vendors and customers benefit from the economy of scale.
2) Long term contracts replace short term purchase orders.
3) The supplier receives training, advance planning, information and sometimes even financial assistance.
4) Some contracts provide for delivering to a regular daily rate rather than to irregular demands.
5) Buyers at the customers plant take over the headache of making the freight arrangements.
6) Contractual requirements are put in place to drive the supplier into the mode of continual and rapid improvement.

All these have the effect of reducing the operational expenses related to procurement as well as the purchase price of material inputs. Fewer, carefully chosen vendors could ensure dependability of quality and delivery in material inputs. With such a vendor base, it will no longer be necessary to buy more than what is needed and create safety stocks. The reduction in the vendor base is therefore a good indicator of procurement cost-effectiveness and should correlate positively with reduction in the total cost of materials purchased.

4.1.10 Percentage of qualified vendors

A vendor is usually qualified on the basis of cost stability, quality consistency and delivery dependability over a standard observation timeframe. Qualified vendors are usually exempt from incoming inspection, count/ verification and sometimes authorized to deliver directly at the point-of-use. They may be subject to occasional, random audits. Qualified vendors contribute to improved profit performance in three ways: the elimination of non-value adding activities reduces the operational expenses related to procurement; certainty in quality, quantity and delivery reduces the need for safety stocks; and dependability of material supplies to the constrained resources reduces throughput losses from starvation. All these benefits will help in minimizing the total cost of materials purchased. The increase in the percentage of qualified vendors is measure of success in vendor development efforts and should therefore correlate positively with the total cost of materials purchased.

4.1.11 Vendor proximity

This can be expressed as the average distance of vendor plants from the manufacturing plant. This could be computed by material category. Vendors located closer to the plant will find it relatively easy to make frequent deliveries in smaller quantities. This would reduce the need for large order sizes and raw material inventory. Delays in shipments from distant vendors are relatively more probable. As already discussed, delays constitute one of the three sources of uncertainties in purchased materials. Delays affect profitability from every angle. They increase operating expenses incurred to prevent disruptions, the need for safety stocks, and lower throughput by starving constraints. Besides, delays increase lead times and deteriorate due date performance. Vendor proximity is a good but indirect measure of vendors' ability to make frequent, dependable and cost-effective deliveries in small quantities. This is a good measure for companies intending to become JIT producers.

4.1.12 Raw material inventory

Raw materials are purchased and stocked for several reasons:

1) To take advantage of favorable prices,
2) To get quantity discounts,
3) High ordering cost relative to purchase price and
4) Uncertainties in the quality and timeliness of vendor deliveries.

It costs money to carry materials in stock due to financial charges, storage costs, manpower to manage, material handling in stores, obsolescence and damage. Even if cost related benefits from material purchases are ignored, it may still be necessary to hold material due to uncertainties in delivery and long lead times. However, if reliable and responsive vendors can be developed, the need to stock can be reduced. Raw material inventory cannot be reduced for reduction's sake, without starving constraints or disrupting internal operations in some way. It can only be reduced through a program of systematic vendor development. The intention of this measure is to put pressure on vendor development efforts and reduce the total cost of materials purchased. A reduction in raw material inventory dollars will therefore be a measure of the consequence of improved certainty in the quality, quantity and delivery of purchased materials. It is also a clear indicator of improvement in procurement cost-effectiveness.

4.1.13 Percentage of "point of use" deliveries

When material from suppliers goes right to the production line, that avoids the extra handling and storage that comes from putting it into a receiving stockroom, quality hold area or warehouse. This would be feasible particularly with "certified" vendors whose supplies are collected by the manufacturer's freight services. When materials are shipped at the supplier's convenience, some of the material is likely to arrive before the user needs it. It goes into a stockroom and when material is needed, it must be handled again in order to get it to the production line. These activities cost money and represent non-value adding operating expenses. If point-of-use (POU) storage areas in the shop floor are finite in size, then the increase in the percentage of POU deliveries could be used as another indicator of cost-effectiveness in procurement operations.

Constrained resources fed by material from POU storage areas run a lesser risk of being starved as direct deliveries circumvent potential delays at the receiving docks and eliminate associated uncertainties. Permitting non-qualified vendors to make POU deliveries for the sake of improving this measure can be very risky. Uncertainties in such supplies can potentially cause loss in throughput due to shortages and scrap at the constraints.

4.1.14 Reduction in area of receiving docks

The areas in a conventional receiving dock are as follows: Check-in and data entry area, incoming inspection area, count/ verification area, storage area for materials awaiting incoming inspection, quarantine area for materials awaiting clearance on disposition, and office areas. Supplier development, as already discussed, reduces the need for all receiving dock activities other than check-in and data entry. With reduction in such non-value added activities, it should also be possible to progressively downsize areas allocated in the receiving docks for such activities.

The reduction in the area of the receiving docks is a consequence of reduction in receiving dock activities, which, in turn, is the outcome of systematic vendor development. It reflects a reduction in the operating expenses associated with procurement operations. However, if the space released is not used directly or indirectly to enhance throughput, a reduction in the area does not make financial sense.

As already discussed, the reduction in raw material inventory for a given production volume indicates improvement in the certainty of quality, quantity and delivery of purchased/ outsourced materials. With reduction in raw material inventory, the space required to carry it also reduces. A reduction in the raw material storage area is therefore a consequence of progress in supplier development. It is a measure of reduction in raw material carrying costs. However, if the space released is not used directly or indirectly to enhance throughput, an improvement in this measure does not make financial sense.

4.2 CONVERSION COST EFFECTIVENESS

These are operating expenses related directly or indirectly to the process of conversion of raw material inventory into finished goods. The cost effectiveness of manufacturing operations is significantly affected by dependencies in production processes as well as statistical fluctuations in the individual processes. A dependent event refers to an event or a series of events that must take place before another can begin. The subsequent event depends upon the ones prior to it. Statistical fluctuations are caused by variances and uncertainties in the process. Relevant measures of conversion cost effectiveness should therefore expose sources of waste, non-value added costs, variabilities and uncertainties. A host of world class variabilities and uncertainties. A host of world class manufacturing subgoals can be contained with two overriding goals: one is reduction of deviation and the other is the reduction of variability.

An event is said to be subject to statistical fluctuations if its occurrence cannot be precisely predicted. A manufacturing plant can be characterized as a series of dependent events, NOT independent events as assumed for the purpose of line balancing. Further, the events are subject to statistical fluctuations, which means the actual output of each workstation will vary over time. Uncertainties arise due to variability in setup times, process yield, equipment availability, absenteeism levels, vendor delays and demand changes. Inaccuracies in planning information could also induce uncertainty. Fluctuations do not average out at the individual workstations but accumulate due to the dependencies. It is always an accumulation of slowness because dependency limits the opportunities for higher fluctuations. The overall throughput will most likely be less than the maximum potential of the individual stations. Inventory moves through the system not in manageable flow but in waves. The slowest workstation will therefore govern throughput.

It must be realized that a manufacturing organization is not a bunch of individual workstations but a pool of resources collectively responsible for attaining the required level of throughput. The goal is not to make individual workstations productive but to make the whole system productive. Strategic measures put in place must encourage this orientation. The proposed measures of conversion cost effectiveness are presented in the following sections.

4.2.1 Reduction in the average time per setup

The magnitude of setup or changeover time is a direct measure of the resistance to change from processing one product or part to another. Besides affecting flexibility, it also consumes part of the available equipment capacity and reduces potential throughput. The throughput of a constrained resource is directly proportional to its productive utilization. The reduction in the average time per setup at a constrained resource would mean an improvement in its efficiency and throughput. Also, high setup times warrant large batch sizes to justify their spreadover, which, in turn, results in high WIP levels, long lead times, poor quality traceability, poor due date performance and high purge time for design change introduction. As this affects competitiveness from every angle, reduction in the average time per changeover is a direct and dynamic measure of a company's potential for conversion cost-effectiveness and competitive performance. In organizations where flexibility is critical to success, this is a good performance measure for general use at the equipment, cell, department and plant levels and particularly for use at bottleneck workstations.

4.2.2 Ratio of external setup to total setup hours

External setup represents changeover related activities that are performed external to the machine and do not require the machine to be idle. This helps minimize actual internal changeover time and artificially enhances the flexibility of the process as well as its productive capacity. This is a good measure of changeover efficiency and is particularly appropriate for use at bottleneck stations, where production time is at a premium. This measure is likely to create an emphasis on externalizing setups and minimizing changeover time as opposed to reducing the total time per setup. To avoid dysfunctional consequences it must be used with the previously defined measure "Reduction in average time per setup".

4.2.3 Percentage of single digit setups

This is the ratio of the number of single digit setups to the total number of setups done in a given time period. This is a measure of changeover efficiency that could encourage setup reduction projects to knock setup times down to a single digit figure. In capacity constrained resources, reducing setup time can increase the "productive" capacity, throughput and inherent process flexibility. This is a measure at the plant, department and cell levels in organizations manufacturing customized products with wide fluctuations in the product mix.

4.2.4 Average batch size

The batch size for a given operation is influenced by two factors: the setup time for that operation and the availability of spare capacity in that workstation. When batch sizes are reduced by half, we also reduce by half the time it would take to "process" a batch. This means queue and wait times would be reduced by half as well. This, in turn, reduces the time parts spend in the plant by half. Lead time condenses and the speed of the flow of parts increases. With faster turnaround on orders, customers get their orders faster. With shorter lead times it is also possible to respond faster. If the response to the market is faster, it provides a competitive advantage in the marketplace. Customers who need quick deliveries will increase as marketing spreads the word about potential responsiveness levels that they could expect. This will show up as increased sales. With more business and more parts over which to spread the costs, operating expenses per unit are lowered and the company makes more profit.

Reduced batch sizes will require more frequent setups. When the batch sizes are cut in half, the number of setups theoretically double. But if the increase in setup time is well within the existing idle time or protective capacity, the time and money saved may not be of high value. However, product flow through the plant is smoothened. The above measure will tend to put pressure on setup reduction and flexibility improvement projects. Lower inventory costs and lead times would be the logical outcome.

4.2.5 Constraint utilization

Constraint utilization refers to the percentage of time the constrained resource is engaged in producing useful output. A constrained resource is one whose capacity is less than the demand imposed on it. The throughput of a system is restricted by the capacity of its worst constraint. Constrained resources determine the effective capacity of the plant. They are simply a reality. The flow through the constraint must therefore be made equal to the demand from the market. A hour lost at a constraint has the same impact as a hour lost by the entire system. Lost time on a constraint is lost throughput. The utilization of constrained resources is therefore very important. Goldratt and Cox [43] present some guidelines to improve the productivity of constrained workstations:

1) Locate constraints: Talk to expeditors. They would know the parts they are missing most of the time and in which departments to go and look for them. The parts frequently in short supply are probably the ones that would pass through a constraint.

2) Find more capacity: Try to take load off the bottlenecks by using other resources. To increase the capacity of the plant is to increase the capacity of only the constraints. Offloading could be one of the options.

3) Incoming inspection: Ensure 100 percent good incoming parts. Bad parts do not contribute to throughput and would waste time on the constrained workstation. If a part is scrapped before a bottleneck station, all that is lost is a scrapped part. But if it is scrapped after it has passed through the bottleneck, valuable time is lost that cannot be recovered.

4) Control constrained processes: Be sure that process controls on parts produced on the constraint are very good, so these parts do not become defective in later processing.

5) Avoid time wastage by making parts that are not currently required.

6) Prioritize work: Work fed to bottlenecks should be prioritized on the basis of need. For example, overdue orders should be prioritized according to

delays. This would also help prevent shortages in non-constrained workstations.

7) Reduce batch sizes on non-constraints.

Inventories must be withheld and released according to constraints, otherwise, the required performance improvements cannot be attained. With improvement in the productivity of constrained resources, throughput improves and backlogs decline. This could put more demand on other workcenters. If the demand on another workcenter exceeds its capacity, a new constraint will be created.

The goal of this measure is to maximize throughput of constrained resources. This will automatically trigger efforts to improve setup, process control, preventative maintenance and scheduling methods at the constraints. Typically constraints occur at stations with more expensive capital equipment that cannot be affordably duplicated. They are a fact of life and need to be well managed.

4.2.6 Reduction in the number of BOM levels

The number of levels in the bill of materials (BOM) represents the number of individual levels of dependent production subsystems required to produce a given end product. The flatter the BOM, the lower is the magnitude of dependency in the production system and more predictable is the product flow and throughput of end product. The product structure is largely a function of design and to a certain extent the manufacturing process. A reduction in the number of levels in the BOM can be achieved through methods such as group technology, which capitalize on similarity of parts to reduce the number of individual stages in production. This also improves the manageability of production operations. A reduction in the number of BOM levels through product improvisation or new product design is a measure of the potential for cost-effectiveness in manufacture. It is also an indicator of the quality of design.

4.2.7 Improvement in BOM accuracy

The bill of materials is an engineering document that specifies the ingredients or subordinate components required to physically make up each part number or assembly. An inaccurate bill of materials could result in one or more of the following:

1) Omission of some components and/ or sub-assemblies from the production schedule leading to starvation of constraints, delays and loss in throughput,
2) Underestimation of quantity requirements leading to starvation of constraints, delays and loss in throughput, and
3) Overestimation of quantity requirements leading to excess inventory.

In summary, inaccurate BOM's ultimately result in operating expenses which do not add value to the end product, but just more cost. The accuracy of the BOM is more difficult to measure than the accuracy of inventory records. The ratio of the number of errors found to the total number of BOM records checked in each operating time period could be used as a measure. Though this may not portray a comprehensive measure of BOM accuracy, it could still indicate improvement trends. It would also be a useful measure to evaluate the grade of MRP-2 implementation.

4.2.8 Inventory records accuracy ratio

This is defined as the ratio of the number of quantity discrepancies noticed to the total number of individual inventory checks carried out in a given time period. Quantity discrepancies in inventory records could result in erroneous production planning. When stocks fall short of records, constrained resources can potentially be starved. When stocks are in excess of records, an unnecessary inventory buildup may occur. In either case, operational expenses are incurred but no value is added. As inaccuracies in inventory records indirectly consume profit, they must be controlled and progressively eliminated. The above ratio is a good measure of inventory records accuracy for use in inventory management and MRP-2 type systems.

4.2.9 Increase in inventory turns

This is the ratio of sales to the average level of inventory, computed on an annual basis. The higher this ratio, the greater is the throughput for a given level of inventory. In other words, "earnings" improve as the "turning" improves. Lower inventory levels mean lower carrying costs, smaller lead times, better due date performance, better quality traceability and lower purge times for new product introduction. Since all critical success factors are positively influenced by an improvement in inventory turns, the increase from one period to the next is indeed a significant global and dynamic measure of profitability and competitiveness. In a multi-product manufacturing plant it would make sense to compute this measure by end product type as it will lend itself to the analysis and improvement of inventory performance by product line.

4.2.10 Reduction in WIP

Work in process (WIP) is defined as the absolute dollar value of all materials issued to production that have not been turned into end products ready for shipment. WIP cannot be zero as some units of product will have to be in the active processing stage at any point in time. WIP that is not under active processing is a waste. Therefore, it is important to minimize WIP that is not under active processing such as material waiting before operations, material moving between operations and buffers in storage. Buffers in storage are created to live through periodic shortages caused by uncertainties in material availability, process yield, unscheduled equipment downtime, absenteeism and such others. Large batches of material waiting or moving are largely responses to high changeover times and poor process flexibility. Therefore, WIP cannot be easily reduced for reduction's sake.

Associated with WIP is a high carrying cost that represents a major non-value adding operational expense. "Reduction in WIP" as a performance measure will encourage or put pressure on improvements in total manufacturing performance through reduction in uncertainties, dependencies and statistical fluctuations in a systematic fashion. This will improve the predictability of material supplies to the constraints and minimize the occurrence of holes in their buffers. In turn, this will reduce shortages at constrained workstations and enhance throughput. Low WIP also brings in all the strategic advantages of low inventory discussed in Section 4.2.9. In most companies, material costs and related overheads are a significant percentage of total product cost. Reduction in WIP will be a critical and dynamic measure of productivity, conversion cost-effectiveness and profitability.

4.2.11 Finished goods inventory turns ratio

This is defined as the ratio of sales dollars to the total cost of finished goods inventory, in a given time period, to the total cost of finished goods inventory. The total cost of finished goods inventory is the sum of the dollar value of the finished goods and all operating expenses incurred to carry it during a specified time period.

Finished goods inventory is carried for two main reasons:

1) To cope with uncertainties external to the manufacturing organization such as in market demand,
2) To isolate the marketing organization from manufacturing's inability to provide the desired levels of responsiveness, which, in turn, arises out of uncertainties and statistical fluctuations within the manufacturing system and manifests itself in the form of long and variable lead times.

The carrying cost of finished goods inventory is the price paid for not being able to deliver products as and when demand arises. In many companies this represents a large operating expense. The irony is that finished goods inventory, quite often, is perceived as the means to provide the customers with the desired level of responsiveness. In fact, it just helps to isolate marketing from internal uncertainties and does nothing to improve manufacturing performance.

The inherent level of responsiveness in the organization can be improved through work flow streamlining, process control, preventative maintenance, enhancing accuracy of information, more efficient changeovers and such others. This will enhance the predictability of end product output and as a result, the need for finished goods inventory will decrease. This is the only logical way to reduce finished goods inventory without adversely affecting sales performance. Finished goods inventory costs should be viewed as conversion costs incurred to provide the customers with the desired level of responsiveness. The finished goods inventory turns ratio is a good measure of the cost-effectiveness with which manufacturing provides the desired level of responsiveness. This measure will encourage the pursuit of projects to improve flexibility and shorten lead times.

4.2.12 Reduction in space required per unit of output

Space represents part of the money "invested" in acquiring resources to support production. This investment has an opportunity cost associated with it. The space required per unit of output is a measure of space resources that were committed to achieve a given level of output, in a given time period. Excess floor area represents a waste and encourages the building of multiple inventory buffers. Reduction in raw material, work-in-process and finished goods inventory, work flow streamlining and such others release space. However, if such space is not used directly or indirectly to enhance throughput, space savings do not make financial sense. In other words, it does not reduce the operational expenses incurred to generate one unit of output. The reduction in the space required per unit of output is a dynamic measure of improvement in space utilization from a profitability perspective.

4.2.13 Space required per unit of capacity

This is a good measure of facilities and production systems design. The use of this measure for comparing design alternatives would encourage space efficient design, while configuring new or improved production lines or cells.

4.2.14 Reduction in unplanned absenteeism

Unplanned absenteeism causes an unpredictable fluctuation in the availability of manpower to perform tasks related to production. This uncertainty has the potential to cause schedule disruptions, temporary bottlenecks, starve and aggravate the impact of existing constraints, encourage creation of buffers, reduce throughput and increase the operational expenses required to attain a given level of output. The reduction in unplanned absenteeism over time period to another is a primary and dynamic measure of uncertainty reduction in human inputs.

4.2.15 Reduction in unscheduled downtime

Unscheduled downtime is a primary measure of uncertainty in availability of production equipment. It reflects the lack of effectiveness of preventive maintenance (PM). The goal of preventive maintenance is to minimize or if possible eliminate unscheduled downtime. This calls for maintaining the equipment so often and so thoroughly that it hardly ever breaks down, jams or misperforms during a production run. There is nothing like an equipment failure to turn a continuous processor into its opposite number [147]. Unscheduled downtime at a workstation may necessitate rescheduling of all other dependent activities, render overtime necessary, and encourage creation of safety stocks. These consequences of unscheduled downtime tend to increase WIP inventory and operational expenses. The cost of unexpected downtime depends on the type of resource, its location in the production sequence and its capacity in relation to market demand. Also, disruptions in schedule that result in late shipments could mean lost future sales, the cost of which is not easily quantifiable. Unscheduled downtime is an important measure particularly for workstations upstream of the constraint and the constrained resource itself. This is because process interruptions upstream can potentially starve the constraint while downtime at the constraint means a proportional loss of throughput. In summary, unscheduled downtime can have a big financial impact on a plant's operation. The reduction in unscheduled downtime is not only a dynamic measure of improvement in PM effectiveness but also a critical measure of uncertainty reduction and conversion cost-effectiveness.

4.2.16 Reduction in total cost of maintenance (TCOM)

The goal of maintenance management is to minimize the total cost of maintenance, which is the operating expense incurred to keep production resources up and running during the scheduled operating hours of the factory. When a planned preventive maintenance takes its course, there should be a gradual shift in the cost distribution from breakdown costs to prevention costs. After a period of time the total cost of maintenance activities should begin to reduce. The reduction in the TCOM is a global measure of cost effectiveness in plant maintenance operations. It may not be very sensible to cut preventive maintenance spending for the sake of showing improvement on this measure. In the long run, this would only result in increased breakdown costs and disruptions to schedules and further deterioration in due date performance. To avoid short term mismanagement of this measure, it is recommended that it be used along with the previously defined measure, namely, "Reduction in unscheduled downtime".

4.2.17 Ratio of preventive to total maintenance cost

Preventive maintenance is maintenance that is carried out during a planned downtime period. Breakdown maintenance refers to activities related to bringing a machine back up after it goes down unexpectedly during a production run. This affects machine utilization and is particularly crucial to sustain throughput from constrained resources, where time lost is throughput lost. Also, breakdowns cost the company more due to the associated indirect costs of the disruption. The total maintenance cost is the sum of the preventive and breakdown maintenance costs. Preventive maintenance costs include all operating expenses incurred to conduct preventive maintenance operations. Breakdown costs should include the cost of repair, as well as, the cost of unscheduled downtime during the repair, at the workstation being repaired. For a given production volume, the increase in the ratio of preventive maintenance costs to the total maintenance cost is a good indicator of uncertainty reduction and improvement in the cost-effectiveness of maintenance operations.

4.3 LIFECYCLE COST

The lifecycle cost of manufacturing a product includes costs incurred on behalf of that product over its entire lifecycle. The lifecycle commences with the initial identification of a need and extends through product planning, research, design and development, equipment acquisition, startup, production, subsequent reconfiguration of facilities and equipment, logistical support, customer service, support in the field and ultimately phasing out or exiting from the market (Sodhi and Henderson [158]).

Equipment acquisition costs include purchase price, freight, insurance, engineering, installation charges and initial technical training. The capital portion of the price may be eligible for investment tax credit, reducing the net price. Startup costs include the cost of space, power, air-conditioning and other facilities required to accommodate the product. Reconfiguration costs include the cost of modifications to existing systems and lost production time while the system is being modified. Production costs include operational expenses such as energy, related labor costs, maintenance, depreciation, interest expenses, continued technical training, cost of quality, inventory costs and provision of reserve or backup capacity. Exit costs include disposal of non-repairable or obsolete physical elements of the manufacturing system.

Figure 4.1 shows product life cycle costs and revenues over time.

The idea behind using life cycle cost as a performance measure is to maximize long run profits from selling the product. Profit, in this context, is the difference between total revenues and life cycle costs to the producer, incurred in manufacturing and selling the product. The residual value of non-obsolete production equipment used for an earlier product is transferred to the next product line that uses the same equipment. It does not form part of the lifecycle costs of earlier projects. When a product manager is made responsible for the life cycle costs of the product he would therefore be mindful of the longevity of benefits from costs incurred.

Several benefits can be gained through the use of life cycle costs as a long term performance measure. First of all, while acquiring capital equipment there would be more emphasis on flexibility so that exit costs while transiting from one product to the next can be minimized. The tendency to get cheaper equipment due to the concern over payback can be averted. Functional features built into the manufacturing system may contribute to long term value in various ways:

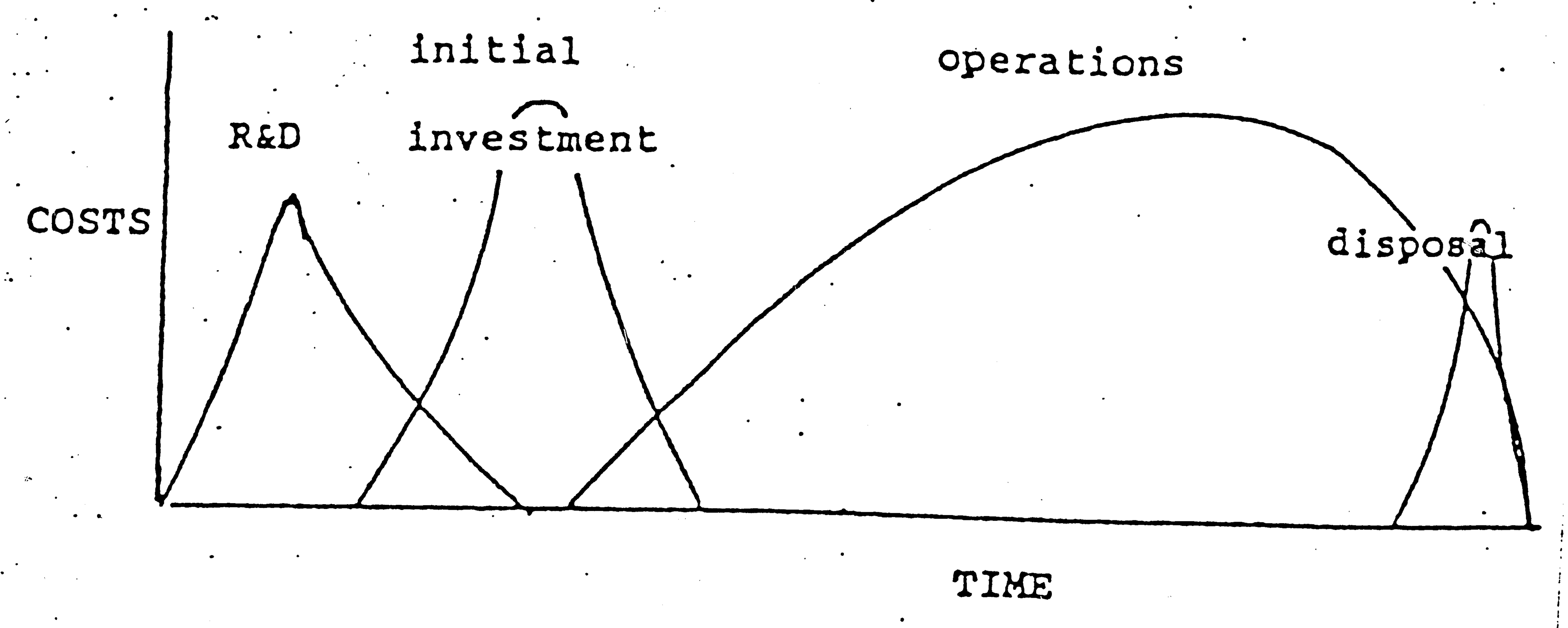

Figure 4.1: Lifecycle costs and revenues over time

- Increased production capacity or throughput,
- Ability to provide better quality and reliability in the end product and enhance value to the customer,
- Increased flexibility to change from one product to the next with minimum modification and exit costs,
- Ability to sustain continuous physical redesign to expand competitive advantage,
- Ability to add functions and permit wide product differentiation,
- Prevent the introduction of new products from rendering the installed equipment base obsolete and thereby raise concern for both entry and exit costs.

The second benefit from the use of life cycle costs and revenues is concern for long term profitability and concern for value to the customer (Forbis and Metha [32]). This is true because the price the customer pays is a function of the product's lifecycle cost. Finally, the use of life cycle costs will provide management with a tool to evaluate investment in a new product with a long term perspective.

Measures related to achieving, maintaining and improving quality in material inputs and production processes are dealt with in the next chapter.

Chapter V

Measures of Quality

Quality is a critical competitive factor in today's environment with many firms striving to improve the quality of their products. As more and more firms are successful in their efforts to improve quality, increased quality and associated productivity gains would be required to maintain market share and current profitability. Because of the impact of quality on market share and profits, quality management is an important factor in achieving productivity gains and increasing, or at least maintaining, profits.

The goal of any manufacturing organization is to maximize profits. Two important ways to attain or improve profitability are:

1) Designing a product for quality, manufacturability, testability and reliability and
2) Maximizing conformance in manufacture.

These activities help in minimizing the total cost of production and enhancing value to the customer. Cost savings come from higher yield on inventory inputs and lower operational expenses in the manufacture of the product. Higher yield improves throughput and spreads operating expenses over a large number of good production units, resulting in a lower total cost per unit. Enhancing product value to the customer, sharing cost advantages with them and good on-site product performance result in improved sales.

Fundamental to quality management are relevant indicators of quality performance. The objectives for quality performance measurement would be:

1) To understand the impacts of quality on operating costs, productivity and profitability,
2) To evaluate quality of design, quality of manufacture and field performance of the company's products and
3) To identify and solve quality problems and continually improve productivity and profitability. The scope of this task should include procurement, production, distribution, field support and customer service.

The proposed architecture for such a system consists of two subsystems of performance indicators: measures of absolute quality and measures of the cost of quality. Measures of absolute quality would include measures of the quality of design, the quality of conformance and factors that affect the value to the customer such as product reliability, field support and customer service. Measures of the cost of quality would include ratios between prevention, appraisal, internal failure and external failure costs. These could be computed by product, by division, by plant or by any other meaningful category.

5.1 QUALITY OF DESIGN

Quality of design refers to the degree of conformance between customers' expectations of a product and the design specifications for the product [126]. Today, it is reasonable to say that customers expect products of the highest quality at the lowest price delivered to them quickly with all the features and options of their choice. A product whose design allows a company to meet these expectations is a well-designed product. However, from an internal perspective, such design should also permit profit maximization, otherwise, it does not make business sense.

The quality of product design should therefore be evaluated based on its potential for profitability. A design that permits easy and economic manufacturability, requires minimum raw material inputs and provides high a functional value to the customer will provide maximum potential for profitability. Such design will minimize the total cost of manufacturing and supporting the product as well as enhance its sales potential. A set of indicators of the quality of design are presented in the following sections.

5.1.1 Number of different component parts

The number of different component parts in an end-product determine the number of different materials to be purchased, inspected, stored, moved, processed, tracked, scheduled and controlled. Purchasing a part requires identifying, developing and certifying new vendors. Inspection of some types of parts may require special purpose test equipment. Storing each type of part will require a unique bin location and separate processing of all receipts and issues. Processing each part requires a unique route sheet that is developed after extensive engineering analysis, process planning and tool design. It may often require part specific workstations, tools, fixtures and process control procedures. Scheduling, tracking and controlling parts as they flow through the factory involve transactions that are often proportional in number to the variety of parts handled. With increase in the number of different parts, the above activities result in an increase in manufacturing complexity, as well as, the operational expenses to manage that complexity. Therefore, the smaller the part variety in a given product, the more economic it would be from a manufacturability standpoint, and greater would be the potential for minimizing the total cost of manufacture.

5.1.2 Number of BOM levels

The bill of materials presents an explosion of the sub-assemblies and component parts in a given end product. Theoretically, each sub-assembly branch of a BOM can be processed independently of the other. In any bill of materials, the part numbers at any node of the tree cannot be processed or assembled until those in the branches below. So, the taller the bill of materials, the higher is the level of "dependency" in the manufacturing process for a given end product. Due to statistical fluctuations in individual processes dependency limits throughput. The higher the dependency, the lower is the throughput from the same resource base. It is therefore advantageous to have a design that is modular and has a flat BOM structure. In other words, for a given total number of parts in an end product, a BOM with few levels will provide for easier manufacturing manageability, lower lead times and operating expenses and better throughput, than one with more levels.

5.1.3 Number of threaded fasteners per product

American manufacturers often have to resort to automation of manufacturing processes to remain competitive. The adaptability of a product's design for automated manufacture becomes very important in this context. Experience has shown that it is very difficult to automate screw type fastening operations even with modern and flexible equipment such as robots. The number of threaded fasteners in a product represents the minimum number of operations that would be difficult to automate. Therefore, the number of threaded fasteners is indeed an effective indicator of design inadequacy for automated manufacture.

5.1.4 Number of component loading directions

Experience has shown that it is easy to automate the manufacture of products which are designed to be assembled bottom up. In such a design, components would be loaded from the top downward either vertically or at an angle to the vertical. Designs which require components to be assembled from multiple directions, would increase the complexity and cost of automation.

5.1.5 Total estimated cost per unit

The total cost of manufacturing a product is largely a function of the ease of manufacturability, which in turn is dependent on its design. Therefore, the estimated total cost per unit is a good index to compare alternate designs and to evaluate design improvements. These are relevant indicators for the evaluation of new products and engineering changes in existing products.

5.2 QUALITY OF CONFORMANCE

Quality of conformance refers to the degree to which a product or service conforms to its design specifications. It is assumed that the product has been designed to meet customer expectations and needs. An analysis of quality costs usually will reveal a negative correlation between quality of conformance and costs for items such as appraisal, scrap, rework, warranty repairs and product liability. High quality of conformance also means satisfied customers - a necessity for repeat business.

Productivity is a measure of the efficiency of resource use. The more productive use of resources reduces waste and conserves scarce or expensive resources. The relationship between quality of conformance, productivity and production costs can be summarized as follows:

1) Higher quality of conformance means lower rejection rates.
2) Lower rejection rates means less waste of materials, labor and higher throughput.
3) Less waste of inputs means greater output for a given level of inputs, resulting in lower costs per unit of output. Also, higher throughput enables the distribution of operating expenses over a larger number of good units, further reducing the cost per unit.

Increased productivity, achieved by producing a higher percentage of conforming products, can increase profits in a number of ways. A fundamental effect of increasing productivity is a lowering of unit costs. Furthermore, high quality products may sell at a premium. The lower unit costs and higher selling prices produce a higher unit contribution margin and increased profits. Even if selling prices are held constant and the sales volume remains unchanged, lower unit costs mean a higher unit contribution margin and, hence, increased profits. If the improved quality with unchanged sales prices results in a higher sales volume, profits will increase even more. If management elects to pass the cost reductions on to customers in the form of lower prices, the price reductions may result in increased sales volume and hence, increased profits.

Information on the quality of conformance could help in two ways:

1) It could provide a highly relevant measure of productivity, particularly that related to the consumption of materials purchased and those to which value has been added through prior operations, and
2) It could help identify and solve quality problems and institute a program of continuous improvement in

quality and profitability to sustain competitiveness.

Different types of yardsticks to measure the quality of conformance are proposed in the following sections.

5.2.1 Reduction in incoming inspection

This is defined as the reduction in the percentage of receipts subject to incoming inspection. When the quality of materials purchased is consistently good, the need for incoming inspection progressively reduces. This, in turn, reduces the need for inspection staff, space and other resources at the receiving docks. The reduction in incoming inspection staff, the reduction in floor space for incoming inspection, the reduction in the number of receipts subject to incoming inspection, the reduction in the number of receipts rejected and the increase in the percentage of qualified vendors are measures of the consequence of improvement in the conformance of materials purchased. These secondary measures reflect the quality of the firms' material inputs, the success of vendor development efforts. The reduction in incoming inspection is a primary measure of improvement in quality in incoming materials. Incoming inspection cannot be reduced for reduction's sake as it would show up as a deterioration in other in-plant quality related performance measures.

5.2.2 Improvement in yield

The yield of a process, usually expressed as a fraction or a percentage, indicates the ratio of the conforming useful output to the total input. It does not generally include output that can be reworked upon and corrected. It is a basic measure of first-time-through process productivity. Enhancement in the first time through capability of constrained resources and other resources downstream of the constraint results in higher throughput. The improvement in yield may be computed as the difference between the current yield and the original yield. It is a primary and dynamic indicator of improvement in conformance.

5.2.3 Reduction in scrap

Scrap refers to items produced that do not conform to design specifications and which cannot be corrected through rework for economic or technical reasons. Scrap is a measure of wasted input. The occurrence of scrap has two implications: one is the wastage of raw materials and the other is the loss in throughput. Throughput is lost if scrap occurs at the constraint or at operations downstream of the constraint. Since reduced throughput means reduced profits, the actual financial implication of scrap is much higher than the cost of materials wasted. Scrap also has the tendency to mask the clarity of manufacturing operations. Therefore, reduction in scrap could also be used as another indicator of reduction in process uncertainty. Scrap expressed in terms of absolute dollars, would be a good measure to prioritize areas for corrective action. When expressed as a percentage of total inputs (percentage scrap), it provides the relative magnitude of inputs wasted. Improvement in conformance is best expressed as percentage reduction in scrap.

5.2.4 Reduction in rework

Rework refers to non-conforming output from a process that can be economically corrected into useful output. Experience has shown that reworked items, particularly in the electronic industry, lower the functional reliability of the systems they form part. In general, rework is additional work and represents a waste. Reworked items could cost the company even more due to internal and external failures. Rework expressed as a percentage of total useful output is a measure of the magnitude of rework. Reworking may or may not be more cost-effective than scrapping. Reworking bad parts that have already passed through constraints may increase throughput and help secure profits from sale of products which could have otherwise been lost. This is another useful measure to help direct quality improvement efforts aimed at enhancing first-time-through capability. The percentage reduction in rework is a primary and dynamic measure of improvement in first-time-through capability.

5.2.5 Defects per million parts

A defect is a deviation in a quality characteristic from design specification. It could be minor, major or critical. Minor defects may not result in defective output. In other words, products could leave the factory that have one or more defects that do not affect the functionality of the product in any significant manner. However, in the interest of better quality, stricter standards, better product reliability and repeat sales it is essential to reduce or eliminate occurrence at the source. Companies have used data on defects to identify and solve quality problems and successfully reduced defect levels to few defects per million parts produced. For a given production volume, the percentage reduction in the number of defects per million parts, is a good customer oriented measure of improvement in conformance. It can enhance the visibility of numbers pertaining to defect occurrence. When statistics on "defects per million" are maintained by organizational unit or by defect type, it could serve as a problem identification and prioritization tool.

5.2.6 Reduction in defects per unit shipped

"Defects per unit shipped" is the ratio of the total number of defects reported by customers in a certain time period, to the total output of end product in units, during the same time period. The reduction in defects per unit shipped is a not only a dynamic measure for improvement in the quality of conformance in goods sold but also a critical indicator of customer satisfaction. When defects are classified into different categories, the data on this measure can provide the focus for corrective action.

5.2.7 Reduction in returned goods

This includes products sold to the customers that for some reason have failed to meet the specified levels of performance and were rejected by the customers. The percentage reduction in the number of such occurrences or the dollar value of such occurrences is a primary and dynamic measure of improvement in customer satisfaction and in the functional performance of the goods sold.

5.3 PRODUCT PERFORMANCE

This term "product performance" is used to refer to the functional performance of the end product under normal working conditions. This should relate to the level of satisfaction or dissatisfaction the customer is likely to derive from the use of the product. Some measures pertinent to product performance are proposed in the following sections.

5.3.1 On-site reliability

The reliability of any product or equipment is the ratio of mean time between failures to the mean time to repair. The on-site reliability of a given product may be computed as the average of reliability levels reported by individual customers. The only drawback of this measure is that it is based on external data. However, it is a good primary measure of functional performance for products where availability is an important factor for customer satisfaction. Examples of such products would include main frame computers, CNC machine tools, automated production machinery, automobiles and such others. On-site reliability is a customer oriented measure of a product's functional performance.

5.3.2 Reduction in calls for service

The reduction in the number of calls for after sales service excluding those for periodic preventative maintenance and failures cause by factors external to the product (like accidents in automobiles), is a good primary and dynamic measure of customer satisfaction. It is the consequence of improvement in product performance and reliability. If this customer-oriented measure is computed and monitored by product, it could help focus problem identification and solving.

5.4 COST OF QUALITY

Quality, as already discussed, has a big impact on market share and costs. The measurement, planning and control of quality costs can yield many benefits to an organization interested in improving the quality of its products and services. A quality cost system helps management determine the financial importance of quality and provides clues to the areas in which resources should be spent to improve quality. Improved quality can lead to lower costs, higher productivity and greater profits. Quality costs provide the economic common denominator through which plant management and quality control practitioners can communicate clearly and effectively in business terms. Quality costs also provide the basis for evaluating investments in quality programs in terms of cost improvement, profit enhancement and other benefits [126].

Understanding the nature and classification of quality costs is a prerequisite to the development of relevant cost based measures of product quality. Also, the utility of such performance measures depends on the way quality cost data is summarized and presented.

Quality costs are costs incurred either because poor quality may exist or because poor quality does exist. In defining and measuring quality costs, a quality product is one that conforms to design specifications. Quality costs are grouped into two broad categories:

1) Costs incurred because poor quality of conformance can exist - prevention costs and appraisal costs.
2) Costs incurred because poor quality of conformance does exist - internal failure and external failure costs.

Prevention costs are incurred to prevent defects in design, procurement and delivery of products. Appraisal costs are incurred to identify nonconforming units before they are shipped to customers. They also include the cost of activities required to appraise the design of a product or process. Internal failure costs are incurred when materials, components or products are identified as nonconforming before they are shipped to customers. External failure costs are incurred when nonconforming products are shipped to customers.

5.3.1 Quality cost classification scheme

A quality cost classification scheme is presented in Table 5.1 below. This could vary widely among different organizations and depends both on the needs of users and the imagination of personnel who develop reporting formats. The actual classification is less important than the proper identification and measurement of quality costs, as long as the classification scheme is consistent across all quality cost reports subject to aggregation or comparison.

Table 5.1: Quality Cost Classification Scheme

1) Prevention costs
   - Design review
   - Vendor quality support
   - Quality planning and administration
   - Quality circles
   - Quality engineering
   - Quality training
   - Quality systems audit
   - Statistical process control
   - Experimental design studies
   - Systems development
   - Supervision of prevention activities

2) Appraisal costs
   - Vendor inspection
   - Incoming inspection and test
   - Maintenance and calibration of test equipment
   - In process inspection and test
   - Final inspection and test

- Reliability testing
- Depreciation of test equipment
- Supervision of appraisal activities

3) Internal failure costs

- Design revisions and corrections
- Vendor product rejects
- Material reviews
- Net cost of scrap
- Rework labor and overhead
- Reinspection/ retest of reworked product
- Net cost of downtime due to quality problems
- Disposal of defective product
- Defect cause analysis and investigation
- Opportunity cost of products classified as seconds

4) External failure costs

- Cost of responding to customer complaints
- Investigation of warranty claims
- Warranty repairs and replacements
- Product liability costs
- Product service
- Traffic damage
- Product recalls
- Cost of goods rejected by customers

The elements of the cost of quality listed in the classification above are self explanatory and no attempt is made to elaborate on them. Trends in quality costs are a key indicator of the success of an organization's quality improvement efforts. They determine whether or not quality improvement programs have shifted the mix of quality costs among the four categories and resulted in an overall reduction in quality costs. When there are period to period changes in the level of throughput (activity level), trends in quality costs are shown more meaningfully by restating quality costs as a percentage of some standard measure that reflects true output.

5.3.2 Uses of quality cost information

Quality cost information can be used to:

1) Indicate the financial significance of quality costs,
2) Help identify the relative importance of quality problems,
3) Indicate if there is a maldistribution of quality costs,
4) Establish goals or budgets for quality costs,
5) Evaluate the performance of quality improvement activities and
6) Evaluate capital expenditure proposals.

The most important use of quality cost information is to indicate the financial significance of quality. An awareness of the of the real size of quality related costs will motivate managers and other employees to improve product quality. Studies have indicated that quality costs for many U.S.companies range between 10% and 20% of total sales, while careful management can reduce quality costs to 2.5% of sales [126].

Quality cost information can help prioritize quality problems only through a cost database that accumulates quality costs by organizational unit and by product. The important point is that a detailed analysis of quality costs can direct management's attention to the quality problem that is most important from the standpoint of profitability. Once this problem is solved, attention can be directed to the next most financially significant problem.

Quality cost information is useful in indicating a maldistribution of quality costs. Figure 5.1, often discussed in quality control literature [126], shows a line graph depicting possible shifts in quality costs as an improvement program is introduced. In Period 1, little effort is made to prevent or detect nonconforming products. Prevention and appraisal costs are low. Because few defective products are identified prior to delivery, internal failure costs are low, while external failure costs are quite high. Efforts to identify defective products increased during Period 2. Consequently there was a significant increase in appraisal and internal failure costs, accompanied by a decrease in external failure costs. In Periods 3 and 4, quality improvement efforts are expanded to include prevention. These efforts to "do it right the first time" begin to pay off in Periods 5 and 6 as total quality costs decline, especially in the categories of internal and external failure. Because there is a smaller probability of producing defective units, appraisal activities are also reduced. Increases in prevention are financed by a portion of the savings in failure and appraisal costs. The net result is a substantial reduction in the cost of quality and an increase in the level of quality.

Once management understands the financial significance of quality costs, the relative financial importance of quality problems, and the distribution of quality costs among the categories: prevention, appraisal, internal failure and external failure, it can begin to establish goals or budgets for quality costs. Budgets for quality costs are a potentially significant way of controlling quality costs. Management can plan for reductions and shifts in the distribution of quality costs. The process of budgeting provides the benchmark for gauging the progress that results from quality improvement efforts.

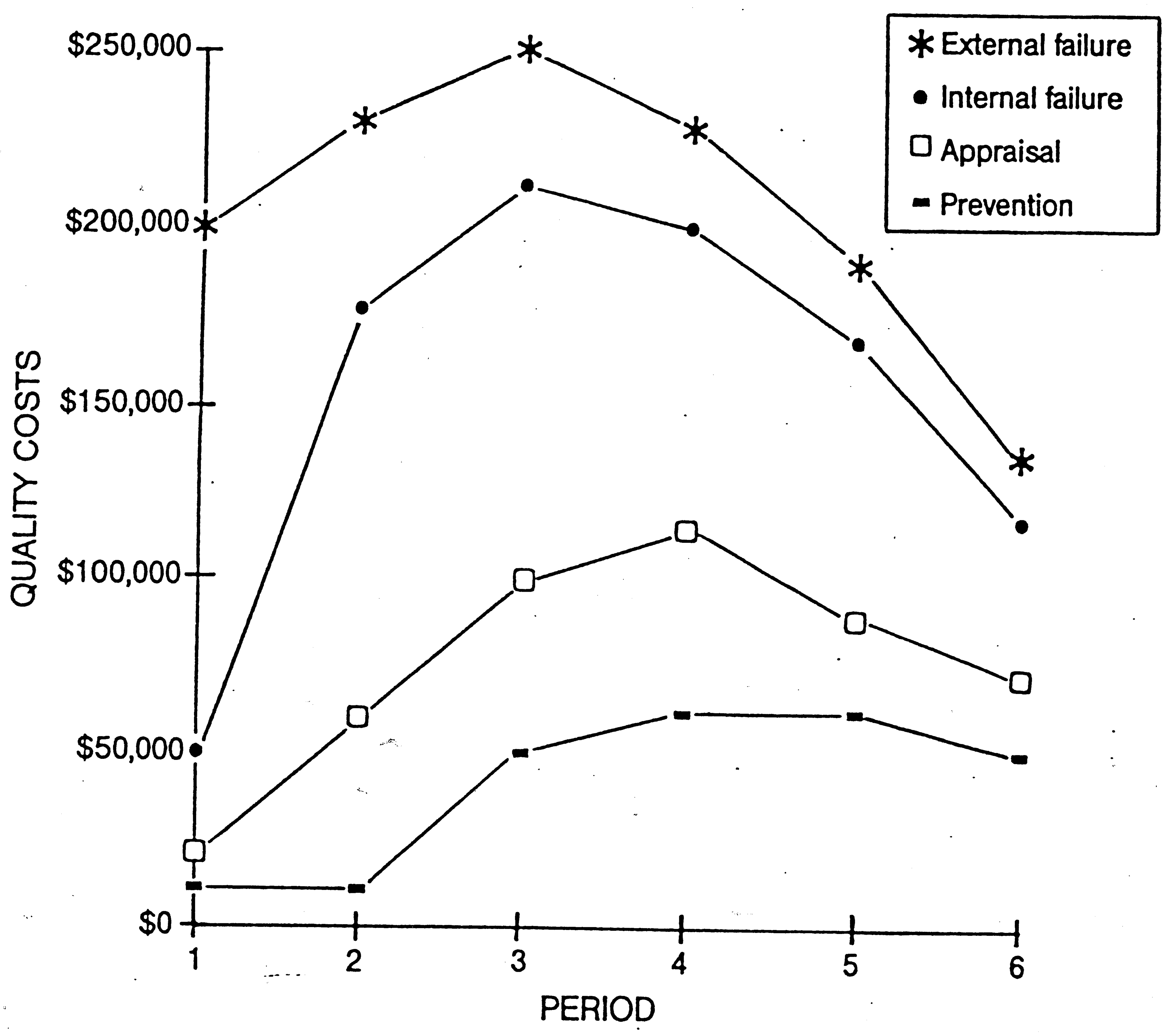

Figure 5.1: Shift in distribution of quality costs

Past quality cost information could help budget for savings from major capital expenditures. The cost classification scheme can serve as a checklist to make sure that management considers all relevant costs and determines whether each cost will be affected by the proposed expenditure. It can also be used to predict possible savings.

5.3.3 Measures based on quality costs

The distribution of quality costs changes when a quality improvement program takes its course. Measures based on cost offer a convenient means to track trends in individual cost types as well as shifts in total quality costs with time. Three such measures are proposed below.

5.3.3.1 Total cost of quality (TCOQ)

The total cost of quality could represent a major operational expense and a fairly significant percentage of the total cost of sales. The goal of quality improvement programs such as SPC and TQC is to maximize quality of design and conformance and progressively minimize the total cost of quality. A reduction in the TCOQ shows up as a corresponding increase in gross profits. This measure may be susceptible to short term mismanagement. There may be a tendency to cut down prevention and appraisal activities to show reductions in the total cost of quality. However, such reductions increase internal and external failure costs and often outweigh the short term cost savings. As discussed in Section 5.3.1, the total cost of quality declines only after quality programs reach a certain level of maturity. Cutting down on prevention and appraisal programs may reduce quality costs in the short term but certainly without improving quality. In the long run, the reduction in the total cost of quality will be a positive and dynamic measure of improvement in the quality of goods produced. It is also a global measure of the maturity and accomplishment of a quality improvement program.

5.3.3.2 Increase in ratio of prevention costs to TCOQ

According to a survey conducted by the National Association of Accountants [126], major cost savings are realized by identifying quality improvement projects that will cause costs to shift from appraisal and failure categories to prevention. Once these projects are identified and implemented, total quality costs often are reduced, but even if they are not, the shift in costs is perceived to be beneficial. A shift in costs from appraisal and external failure to prevention usually means higher quality products are being produced or that quality is built into the product. This will have a favorable impact on future productivity and profits. The increase in the ratio of prevention costs to the total cost of quality, hence, is a direct and dynamic measure of improvement in product quality and potential for long term profitability.

5.3.3.3 Increase in ratio of conformance costs to TCOQ

Conformance costs are the sum of prevention and appraisal costs. Nonconformance costs are the sum of internal failure and external failure costs. The total cost of quality (TCOQ) is the sum of the conformance and nonconformance costs. An increase in the ratio of conformance costs to the total cost of quality indicates a trend towards building good quality into the product. This measure would become relevant only when a quality improvement program takes its course and a shift in the distribution of quality costs from nonconformance costs to conformance costs begins to occur.

5.3.4 Limitations of quality cost information

Quality cost information has some inherent limitations. Some frequently cited limitations include:

1) Quality cost measurement does not solve quality problems,
2) Quality cost reports do not suggest specific actions to improve quality,
3) Quality costs are susceptible to short-term mismanagement,
4) It is difficult to match effort and accomplishment,

5) Important costs may be omitted from quality cost reports,

6) Inappropriate costs may be included in quality cost reports and

7) Many quality costs are susceptible to measurement errors.

It is most important to recognize that quality cost management and reporting does not solve quality problems. Management action is required for improvements in quality. Quality cost analysis is merely a tool that can facilitate better quality and productivity.

Quality costs are susceptible to short term mismanagement. If immediate cost reduction is the stated objective of quality improvement and quality cost measurement programs, often it is possible to reduce quality costs in the short run without improving product quality. In fact, quality may suffer as cutbacks in prevention and appraisal result in immediate short-term cost savings. The long run consequences are likely to be increased failure costs. Reduction in the total cost of quality and improvement in profits should be regarded as long run goals of a quality improvement program. The short-run goal must be to improve quality and productivity. Reductions in quality costs occur as a consequence of successful quality management.

Important quality costs are often omitted from quality cost reports. Costs often excluded include the opportunity cost of lost sales or customer ill will, the profit lost from lost throughput, manufacturing overhead costs and administrative costs. The omission of these costs can significantly understate external failure costs.

Inappropriate costs may be included in quality cost reports although this problem is not likely to be as significant as omission of relevant costs. Write-offs on obsolete goods that happen to be nonconforming, cost of rework due to changes requested by a customer are some examples of inappropriate costs.

Like many other kinds of cost accounting information, quality cost information is subjective and susceptible to measurement errors. The determination of the portion of a supervisor's time assigned to prevention, appraisal and failure is likely to be based on percentage estimates made by individual managers rather than detailed time reports. Overhead costs included in quality cost reports are subject to the same measurement and cost allocation problems that plague all overhead calculations. If the opportunity cost of lost sales or customer ill-will is included, it is again based on subjective estimates.

In light of the above, it may be concluded that while quality cost information is a useful portion of a total quality improvement program, an overemphasis on quality costs as the single measure of success in quality improvement programs must be avoided.

In summary, measures of quality of design can be used for the evaluation of competing product designs. Measures of the quality of conformance can be used for shop floor problem identification, problem solving and for evaluation of improvements in process quality. Indicators based on quality costs can serve as global measures for determining the effectiveness of a quality improvement program.

Chapter VI

Measures of Responsiveness

There are some factors related to operational performance that are seemingly non-financial and significantly affect the organization's responsiveness to the customer. Performance against these customer oriented factors strongly influence operating costs, current profits, potential for future sales and market share. Measures of responsiveness can be grouped under five main heads:

1) Cumulative lead time
2) Delivery performance
3) Customer service performance
4) Flexibility
5) New product innovation and introduction

6.1 CUMULATIVE LEAD TIME

Cumulative lead time, for the purpose of this research, is referred to as the total time that elapses from the instant a prospective customer shows interest in the firms products to the time goods are delivered and payments are collected for the sale of goods. During this period, a number of value adding and non-value adding activities take place, each causing a certain amount of "delay". An awareness of the components of cumulative lead time is essential to plan and reduce it and thereby improve responsiveness to the customer. A list of the components is presented below:

Components of cumulative lead time

A. **Marketing lead time**

1. Responding to inquiries
2. Contract acceptance
3. Sales booking/ order entry

B. **Manufacturing lead time**

1. Design/ engineering
2. Design approval
3. Production planning and scheduling
4. Purchase order release
5. Vendor lead time
6. Receiving
7. Incoming inspection
8. Stocking
9. Order kitting/ staging
10. Dock to line/ stores to line move time
11. Fixturing/palletizing and defixturing/ depalletizing
12. Queue time before operations

13. Setup or changeover time
14. Run time or actual processing time
15. Process control time
16. Delay or wait time during/ between operations
17. Quality assurance/ control
18. Packaging
19. Invoicing/ dispatch
20. Shipping and transportation

C. **Post shipment lead time**

1. Installation and commisioning
2. Customer acceptance
3. Collecting payments for sales

The above list may vary from company to company and industry to industry. In any case, the most important concern customers have with respect to delivery is lead time. Excessive lead times can downgrade factors like cost and quality in importance and adversely affect the potential for future sales. Meeting internal due dates does lead to meeting external due dates, and that made yesterday's undemanding customer happy. Today's customer expects that it will be on time; the competitive issue is, "What is the lead time?". Managing lead times can therefore provide an enormous edge on competition.

Traditionally, marketing and manufacturing objectives have been opposed to a large degree. Marketing, on the one hand, wants a fast response to shifting demand that often cause quick production schedule changes and greater expense in overhead and in premiums to vendors to accelerate on their deliveries. Manufacturing, on the other hand, wants gradual schedule changes in order to minimize product cost, inventory and operational expenses and maximize throughput. But this posture reduces responsiveness. The answer to this problem is to maintain the shortest possible lead times for processing, assembly and test in order to allow maximum responsiveness to schedule changes without harming inventory, cost and throughput objectives.

The interrelationships between production lead times and the objectives of schedule performance, inventory and operational expenses are often ill understood. Lead times affect manufacturing-marketing relationships, production planning and control, distribution performance, and, as a result, are highly important to a company's success. Shorter lead times improve responsiveness to schedule changes, thereby softening the effects of economic cycles and forecasting errors. Shortening lead times can also improve customer service, reduce inventory and reduce product costs.

One by one, top companies are coming to the conclusion that reducing lead time is a simple and powerful measure of how well they are doing. Lead time is a sure and truthful measure because a plant can reduce it only by solving problems that cause delays. These problems cover the entire gamut: order entry delays and errors, wrong blue prints or specifications, order backlogs, long and variable setup times, large lots, high defect counts, machines that breakdown, operators who are not well trained, supervisors who do not coordinate schedules, suppliers that are not dependable, long waits for inspectors or repair men, long transport distances, multiple handling steps, multiple queues and buffers, and stock record inaccuracies and inadequacies. Lead times drop when problems are solved. Lead times drop fast when problems are solved fast [147].

6.1.1 Lead time measures

Performance measures for lead time, like all other performance measures, have a three fold objective:

1) Problem identification,
2) Setting targets for improvement and
3) Providing direction and motivation for problem solving.

Problem identification requires detailed information on the relative impact of different activities on lead time. Understanding the relative magnitude of the different components of lead time will help identify and prioritize areas for improvement. Secondly, performance measures should serve as tools to set measurable targets for improvement in lead time. Finally, measures related to lead time should encourage progressive reduction of lead time. They should focus on lead time improvements in areas that cause the biggest delays and bottlenecks. Some performance measures related to lead time are proposed in the following sections.

6.1.1.1 Reduction in manufacturing lead time

For the purpose of this research, this is the total time taken to design, engineer, produce and ship the product. All activities that affect manufacturing lead time (MLT) take place within the factory premises. Therefore, reduction in MLT is a good measure of improvement in total plant operations.

6.1.1.2 Reduction in design lead time

Lead time to get ready for manufacture is often overlooked. Short lead times to produce the designs and specifications are vital to the world class manufacturer. This is particularly important for firms whose niche is to customize products to individual customer needs. These firms must endeavor to continuously reduce the design and engineering times that go into the customization process through the use of appropriate technologies. The reduction in the average design lead time would be a good dynamic measure of improvement in pre-production responsiveness.

6.1.1.3 Reduction in production lead time

Production lead time includes the time taken to procure materials, plan, schedule, produce and ship products to the customer. These include components B3 - B20 of manufacturing lead time. These are essentially shop floor activities. The reduction in the production lead time is a good dynamic measure of improvement in the responsiveness of shop floor operations. If this measure is reported at the department or cell level, it can help assess the relative impact of different shop floor activities on lead time and prioritize them for lead time improvement projects.

6.1.1.4 Reduction in dock-to-line time

The dock-to-line time refers to the average time taken by purchased material to reach the production line from the instant it is delivered at the receiving docks. This could include elements like transaction accounting, incoming inspection, counting, verification, quarantine, handling and raw material storage. "Reduction in the dock-to-line time" is a good operational level performance measure to encourage development of vendors who can be trusted to make direct deliveries to the point of use, the deliveries being of the right quality, quantity and timing. Raw material storage is resorted to primarily to cushion the shocks arising out of vendor uncertainties. Developing qualified vendors can significantly reduce procurement and dock-to-line lead times.

6.1.1.5 Reduction in post-shipment lead time

A manufacturing organization earns money only on receipt of payments made against goods delivered. The collection of payments could be delayed for a number of reasons: product not meeting expected levels of performance, incomplete or unsatisfactory installation and/ or non-adherence to customer acceptance criteria of some sort. It must be realized that finished goods that have not been paid for are as good as inventory. The opportunity cost of money locked up in goods delivered is an operational expense. It is therefore necessary to eliminate causes that delay payments. Post shipment lead time is the time that elapses from the instant goods are physically delivered at the customer's premises to the time customer's acceptance criteria are met and payment is received for the goods supplied and services rendered. The reduction in post shipment lead time is a good measure of improvement in the responsiveness and cost-effectiveness of post shipment operations.

6.1.1.6 Reduction in constraint cycle time

A constrained resource is one whose capacity is less than the demand. It restricts throughput and time lost on this resource is time lost on the entire system. Similarly, production time gained on this resource is time gained on the entire system, until the capacity on the constraint just equals the capacity of the resource with the next higher capacity. One way to gain capacity on a resource is to reduce the cycle time, hence the above measure.

6.1.1.7 Reduction in flow time, by organizational unit

The term organizational unit, for the purpose of this research, is used to refer to a production cell, line, shop or department that contributes to the total manufacturing lead time. Flowtime refers to the time taken by a given production order to flow through a certain segment of the plant. Measuring flowtime by organizational unit helps to segment the total lead time into components. The goal is to expose the relative impact of different organizational units on lead time. This will help identify and prioritize areas for improvement in lead time. Also, the reduction in flow time is a good operational level measure to evaluate the responsiveness of the individual organizational units.

6.1.1.8 Average vendor lead time

This refers to the average time taken by vendors to make a delivery after the receipt of a firm order. As this is one of the components of total manufacturing lead time, it affects the responsiveness of the firm. When vendor development programs take their course, sharp reductions in procurement lead times have been observed. The average vendor lead time is a good operational level measure of vendor responsiveness. It is also useful for evaluating progress in vendor development program. In instances where incoming material is rejected and sent back to the vendor, the vendor lead time should be computed as the actual time taken to receive an acceptable delivery.

6.1.1.9 Number of BOM levels

The number of levels in the bill of materials typically indicate the number of individual, dependent stages in the manufacture of a product and the number of waiting queues associated with it. Cutting down the number of BOM levels, reduces the number of dependent processes in a series. For a given level of statistical fluctuations, this has the tendency to reduce lead time. Increasing the modularity of the design flattens the bill of materials structure. The number of parallel processes may increase but the number of consecutive steps within each parallel process will decrease. The number of BOM levels is a good measure of the susceptibility of a product's design for quick manufacture.

6.1.1.10 Reduction in WIP inventory

This is a secondary measure of lead time reduction. Work-in-process (WIP) reduction is an almost unrecognized benefit of lead time reduction. The size of WIP inventory is related to manufacturing lead times. If lead times are reduced by a week, we would need one week's less material requirements to support the same scheduled output. This means that no material will be released at the gateway (initial) workstations for a week. This suspension also relieves some of the workload of personnel assigned to the gateway workstations, who would otherwise keep busy producing to stock. Reduction in WIP inventory is a useful measure to correlate improvements in lead time with improvements in inventory levels and understand their interrelationship better.

6.1.1.11 Reduction in average batch size

The average batch size is the mean of the lot sizes used during a given time period. The smaller the batch size, the smaller is the queue time before each operation and faster is the flow of product through the entire production sequence. This shows up as reduced lead time. The reduction in the average batch size during a given time period is an indirect measure of lead time reduction and is also useful for correlating reductions in batch sizes with improvements in WIP and lead time. This will help gain a better understanding of their interrelationships.

6.1.1.12 Reduction in shortages

A shortage refers to non-availability of materials for an operation, that was unexpected. Shortages disrupt production plans, necessitate rescheduling and setup tear downs, often starve constrained resources and increase the lead time to achieve the target throughput levels. In summary, shortages cause delays and increase the production lead time. The reduction in the number of material shortages, when used as a performance measure, will put pressure on projects to improve production planning methods, vendor development, preventive maintenance and process control and thereby minimize the extent of variabilities and uncertainties that affect lead time.

6.1.1.13 Reduction in flow distance

The flow distance for a given product refers to the total distance materials flow through the plant during the course of processing, assembly and test. This decides the total material handling time, which could often be a substantial fraction of the production lead time. The reduction in flow distance is good measure to evaluate alternative layout configurations, and cell or line designs from a lead time perspective.

6.1.1.14 Reduction in processing lead time

Processing lead time refers to the total flow time through the processing shops. Typically the initial production stages in discrete manufacturing are processing operations. Some of the components to be eventually assembled are made in this stage, while the rest are bought out. Flow times through processing, assembly and test could significantly vary in duration. For problem identification and prioritization purposes, it therefore makes sense to measure lead times in each of these areas, independently. The reduction in processing lead time is a measure of improvement in the responsiveness of the process shops.

6.1.1.15 Reduction in assembly lead time

Assembly lead time refers to the total flow time through all the assembly operations. Assembly flow time could be affected by capacity constraints in processing shops besides factors specific to assembly. Monitoring assembly lead time with causes for delays could provide good leads for constraint management and help reduce total assembly time. The reduction in assembly lead time is a measure of improvement in the responsiveness of assembly shops.

6.1.1.16 Reduction in test lead time

Test lead times are often affected by high test cycle times, the need to group several end products together to collectively administer the test procedures and/ or capacity constraints of some sort. It is desirable to monitor test lead time as a separate variable to understand its impact on manufacturing lead time. The reduction in test lead time is a measure of improvement in the responsiveness of product testing departments.

6.1.1.17 Lost sales due to excessive lead time

This should be an unbiased record of sales believed to be lost as a result of customers' unwillingness to tolerate quoted delivery times. This should be maintained by product. Information on this could help understand the criticality of short lead times to the product line under consideration as well as to put pressure on efforts to take focussed, corrective action. This is a fundamental measure to assess impacts of long lead times on competitiveness.

6.1.1.18 Production lead time to work content ratio

The work content in a product refers to the actual processing time, the time during which value is added to the product. The lead time to work content ratio is a measure of the efficiency of time usage in responding to customer needs. The ideal is 1 to 1. According to Schonberger [148], a good ratio, which is not often achieved, is 2 or 3 to 1. Bad and typical is a ratio of 5, 10, 20, 100, 1000, or more to 1. In order to reduce this ratio, problems related to transport, setup, down time, raw material, machine variation, operator methods and such others need to be solved. The use of this ratio as a performance measure will therefore force reduction in non-value added times. This ratio can be used at the workstation, cell, department or plant level as part of a drive to create a low inventory environment.

6.1.1.19 Process rate to demand rate ratio

This is the ratio of the actual processing rate to the demand rate at the next process. The process rate is not the average output rate, which would include stops for setups, down time and breaks, but the functional rate. Furthermore, the ratio applies to a single part number, not to several different part numbers processed through the same workcenter. According to Schonberger [148], the ideal ratio is 1 or 2 to 1. A ratio of 2 or 3 to 1 is good. Bad and typical ratios are 5, 10, 20, 100, 1000 or more to 1. This ratio improves (tends closer to unity) when process rate differences between consecutive processes are smoothened which, in turn, reduces inventory accumulations between processes and increases throughput. This is a good local measure at the workstation or cell level particularly for the management of critically constrained resources and other resources for which there is a mismatch between production and use rates.

6.1.1.20 Pieces to workstations ratio

This is the ratio of the number of pieces to the number of workstations or operators in a production line or line segment. Every idle job, every idle piece, every container in transit or in queue between processes raises this ratio. This ratio is an effective tool to analysis of office work and production systems. According to Schonberger [148], the ideal is 1 or 2 to 1. Good ratios are 2 or 3 to 1. Bad and typical are 5, 10, 20, 100, 500, or much more to 1. Reducing the physical distance and buffers between consecutive processes, reducing lot sizes, quicker material handling and such others improve this ratio. Like the preceding two ratios, this ratio is particularly helpful in setting targets for improvement.

6.1.1.21 Reduction in storage steps

Work-in-process stockrooms are the biggest obstacles to smooth production flow. Stockroom steps between consecutive operations, besides disrupting production flow, result in additional load and unload steps, require move tickets to be prepared, increase travel distances, cause stock room delays, increase inventory transactions, cause damages during transit and storage, lengthen lead times and do not allow the use of simple, lighter types of material handling equipment to link consecutive processes. It therefore makes sense to have the normal flow of the product be direct from workcenter to workcenter. This would result in a close time linkage of processes in the flow and the absence of stockroom delays would further reduce lead time. The reduction in the number of storage steps would be an effective operational level measure to encourage steps toward lead time reduction.

6.1.1.22 Reduction in average time per setup

The total amount of time spent on setting up the workstation represents a significant percentage of the available capacity in some processes. It is not always possible to schedule materials to arrive just after setup. Materials do tend to wait before machines while they are being setup. This delays flow and increases lead times. Reduction in the average time per setup is a good operational level measure at the workstation, cell or department levels. The use of this measure would place an emphasis on reducing changeover times and improving flexibility.

6.2 DELIVERY PERFORMANCE

The need to improve due date performance is felt by many plants. The causes of poor due date performance are seemingly external to the plant: unreliable vendors or customers who are constantly changing their minds by adding orders, canceling orders and changing due dates. These conditions do exist and heavily impact a plant's ability to deliver on time. However, according to Goldratt [44], the real problem lies in the level of work-in-process inventory.

A typical production forecast is quite reliable for some period of time into the future, then the validity of the forecast drastically deteriorates within a very short period of time. Customers do not place orders and commit themselves to specific due dates before the commonly observed lead time for the delivery of the product offered. Consequently, production forecasts for the product will not be reliable beyond the valid forecast horizon for the industry. The length of the horizon will be dictated by the low inventory competitors in the industry because their lead times will be the shortest.

If operating inventory levels are higher relative to the competitors, it means that the production lead time is longer than the valid forecast horizon of the industry. As a result, a high inventory company's production plans are based on pure guesses and not on a reliable forecast. When operating inventory levels are lower than the competitors, the firm can enjoy an enviable position that gives it an inherently more accurate forecast. When production is started, a firm order or a valid forecast, which is much less likely to change, is available. Since production plans are driven by more reliable information, it would be possible to give reliable requirements to the vendors. A prime reason that vendors cannot deliver reliably is because manufacturers keep changing their requirements on them, the same way customers are changing their requirements on the manufacturer.

In summary, meeting due dates or alternatively, the ability to adhere to delivery dates is aided by short lead times, which, in turn, is heavily dependent on work-in-process levels. Therefore, performance related to lead times and due date performance are cross related. Some direct measures to keep a tab on due date performance are proposed in the following sections.

6.2.1 Percentage of on-time deliveries

This is the percentage of deliveries made within the agreed time frame. Delivery, in this context, does not refer to shipment from the factory, but delivery and installation at the customers' premises as promised.

6.2.2 Percentage of correct shipments - quality & quantity

This refers to the percentage of total shipments for which no quality or quantity discrepancies were reported by the customer. Often, this could be a good measure of customer dissatisfaction. Due date performance does not mean a thing, if the quality and quantity of goods delivered or services rendered fall short of customer expectations. This is a critical performance measure and prompt action should be initiated to favorably influence this number.

6.2.3 Reduction in lead time variance

Statistical fluctuations in manufacturing lead time (MLT) indicate two things: firstly, uncertainty in the actual duration of activities that constitute manufacturing lead time and secondly, the possibility of not conforming to an agreed delivery date. Considering the numerous activities that affect MLT, a certain amount of variability is to be expected. However, the key issue is that variability should not result in late shipments. The reduction in the variance (square of the standard deviation) of MLT is a good measure of improvement in the predictability of shipping dates, as well as, the chances of adhering to the predicted dates.

6.3 CUSTOMER SERVICE PERFORMANCE

These are measures intended to evaluate promptness of service to the customer in areas such as providing information on products and prices, field support, supplying spare parts and such others. These services can dramatically influence customers' perception of quality, service and the firm's people. Monitoring customer service is therefore of strategic importance to the firm.

6.3.1 Inquiry response time

This is the time taken by the organization to respond to customer queries related to products, specifications, options, pricing, customization possibilities, delivery period and such others. All this requires timely and accurate information. This is particularly critical for manufacturers of customized products with numerous options. For such companies, response to inquiries can be a real strain, if proper information is not available or difficult to retrieve. The delayed response may be perceived as lack of enthusiasm and could result in losing a prospect. The reduction in inquiry response time would be a useful measure of front end responsiveness, if the data required to compute it is collected without bias.

6.3.2 Spare parts lead time

Customers are likely to order spare parts to meet an emergency need. Long lead times for spare parts could mean a lot of inconvenience and may be perceived as poor after-sales service. This could in turn affect future sales. The reduction in spares parts lead time one of the good measures of improvement in the quality of after sales service.

6.3.3 Average response time on service calls

This is the average time taken to respond to a request for after sales service. The information on this measure could be segregated under routine service and emergency service to get a better quantification for customer's perception of service quality. The reduction in the average response time is another good measure of after sales service.

6.4 FLEXIBILITY

Flexibility comes from the Latin word for bendable (Zelenovic [175]). A flexible system has a capacity to change which is built into the system and does not require any external resources to adapt itself. It can operate efficiently in many different circumstances or continue to function efficiently despite change. Such a system has built-in absorbency, robustness or tolerance to change.

In industry, the word flexible means adaptable and capable of change. Changes could occur in product design, the state of the production system (including machinery, production methods, information systems and personnel) and in the nature of market demand. Changes such as these impose demands on various subsystems of the manufacturing organization either in the short term or in the long term. Flexibility, therefore, is a measure of a system's ability to adapt to these "demands of change".

Short term demands include the need to quickly replan in order to manage equipment breakdowns, material shortages, absenteeism, schedule changes and such others. Design changes and production rate fluctuations allow relatively larger response times but could also demand effective adaptation in the short term. Medium to long term demands could include the need to initiate production of new models with minimum exit costs and additional investment. It has always been difficult to fully understand the nature and scope of internal and external uncertainties. Therefore, to manage these uncertainties effectively and remain competitive, appropriate types and levels of flexibility must be "built into" the various subsystems of the manufacturing enterprise.

6.4.1 Types of uncertainty

Kumar and Kumar [100] classify uncertainty in terms of the uncertainty related to the four elements of the manufacturing system: the inputs, the outputs, the manufacturing process and the environment. They suggest that unifying various types of flexibility on the basis of uncertainty will

1) help understand the relationship between various types of flexibility,
2) eliminate ambiguity and confusion in definitions and terminologies used by different researchers and
3) help develop measures of flexibility.

The uncertainty of the external environment primarily affects the nature and volume of demand. Uncertainties associated with inputs usually affect incoming material quality and the availability of inputs. Uncertainties in outputs are caused by changes made by customers in end-product specifications, delivery dates and delivery quantities. Process uncertainty results from low yield and unscheduled downtime.

6.4.2 Types of flexibility

The uncertainties in a manufacturing organization are many and varied. So are the types of flexibility to manage those uncertainties. Some important types of flexibility are discussed in the following sections.

6.4.2.1 Volume flexibility

This is a measure of the capability of a given production system to operate profitably at a wide variety of volume levels (Brown et al [12]). Frazelle [34] and Gerwin [38] define volume flexibility as the capability of a system to respond to changes in aggregate product demand.

Brown et al [12] define expansion flexibility as the ability of a system to vary its volume capability as needed, easily and in a modular manner. This could also be defined as the ability and ease with which capacity can be adjusted, either through building new capacity or eliminating unnecessary capacity. Frazelle [34] and Gerwin [38] define design change flexibility and design flexibility as the ability to redesign the manufacturing process including expanding it.

6.4.2.2 Process flexibility

This is a measure of the ease with which a production system (comprising machinery, fixtures, tools, layout, methods, software etc.,) can changeover from processing one "task" to another, without any or significant modification to its configuration. In other words, it is the ability of a process to deal with changes (additions or deletions) from the product mix over time. The word "task" could refer to a part type or a product family.

The changeover flexibility defined by Frazelle [34], the parts flexibility of Gerwin [38], the product mix flexibility of Slack [157], the production flexibility of Brown et al [12], the job flexibility of Buzzacott [14], the process flexibility of Falkner [31], and the modification flexibility of Gerwin and Leung [39] are not different from each other. These simply have different terminology and different views of the same concept.

6.4.2.3 Material flexibility

This is defined by Gerwin [38] as the flexibility needed to accommodate uncontrollable variations in material specification. This depends upon the adaptability of the machine, the fixturing and the tooling to such variations. However, adaptation to such variations may violate some basic TQC principles.

6.4.2.4 Sequencing flexibility

This is the ability to rearrange the order in which different kinds of parts are loaded into the system in response to short term disruptions in the availability of input materials. It also refers to the capability to expedite or delay the production of a certain batch (or certain batches) of parts of one or more part types, when the customer requests a change in product delivery time.

6.4.2.5 Re-routing flexibility

This type of flexibility is required to respond to unscheduled non-availability of production machinery or material handling equipment. This is defined as the degree to which the part routing sequence can be changed, and the degree to which the system can continue to produce the given set of part types. This in turn requires machinery flexibility, material handling flexibility and process plan flexibility. Machinery flexibility refers to the capability of a machine to handle a variety of operations in one setting and the ease of changeover between different part types. Chaterjee et al [18] define material handling flexibility as the ability to move parts freely between machines. Process plan flexibility refers to the ease with which the order of operations on a part can be changed. This enhances re-routing flexibility.

6.4.2.6 Layout flexibility

This is a measure of the ease with which a variety of parts, sub-assemblies or end products can flow through a given factory. A flexible layout allows for flexible routing and requires minimum reconfiguration cost and time when new products are introduced.

6.4.2.7 Labor flexibility

This is a measure of the ability, mastery and willingness of personnel to handle a variety of tasks both directly and indirectly related to their main task.

6.4.2.8 Product flexibility

This is a measure of the capability to customize a product with just the desired mix of features and options demanded by the customer. To a large extent, this is a function of product design, particularly its modularity.

6.4.3 Economy of scale

A traditional factory based on economies of scale derives its productivity from a combination of physical and organizational size which reduces the investment cost per unit of installed capacity; volume which spreads fixed costs over a large number of units; standardization which reduces information requirements; and experience which reduces costs through repetition over time [41].

Unfortunately, this highly productive factory comes on-stream just as the product reaches the maturity phase of its lifecycle. The result is a "beautiful" but rigid factory and a rapidly aging product - a factory that is a barrier to further product innovation.

Companies facing such scenarios often attempt to lengthen the utilization of the high capital investment in their production and service systems. They do this by lengthening the product lifecycle through the development of new market segments or small product changes. However, a dying product cannot be kept alive too long as competitors will introduce newer and better products to take its place. Besides, profit margins have been known to rapidly erode during the last phase of the life cycle.

In operations based on scale economies, productivity (as it is traditionally defined) has often been achieved by trading off flexibility. This literally strips the company of the abilities to serve today's market place where intangible values such as variety, uniqueness in design, customization, quality, reliability, just-in-time delivery are required besides low price. Further, when the factory is a bottleneck to the flow of new products, it provides room for research and engineering to hide behind the constraints of the factory. This can be deleterious to the strategic positioning of the firm.

A new manufacturing era has dawned. There is less time to get ready to manufacture a new product. There is less time to recoup the investment in any specialized kind of equipment and tooling required to manufacture that product at a reasonable price. These demands can only be met with "flexible" production and service systems. Economies of variety makes more sense today than economies of scale.

6.4.4 Economy of scope

An "economy of scope" factory can produce a continuous stream of different product designs at the same cost as an equal stream of identical products (Goldhar [42]. This factory derives its competitive advantage from the flexibility created by the variety of different tasks it can perform and the speed with which it can change designs and processes.

Economy of scope, in short, allows for low cost variety of output. Its economies are not in size but in the variety of products produced. This is the basic difference between factories based on economies of scope and those traditional factories based on the economies of scale. It is just as cheap (or cheaper) to produce a variety of products on the same equipment as it is to produce only one item or produce the range of products on separate equipment.

Economies of scope provide technical capabilities such as:

1) Extreme flexibility in product design and product mix, which allows for an almost unlimited variety of specific designs within a reasonable family of options, including alternative materials.
2) Rapid response to changes in market demand, product design and mix, output rates and equipment scheduling.
3) Greater control, accuracy and repeatability of processes, all of which lead to better quality products and more reliable manufacturing operations.
4) Reduced waste, lower training and changeover costs, and more predictable maintenance costs.
5) Greater predictability in all phases of manufacturing operations and more information, both of which make possible more intensive management and control of the system.
6) Faster throughput due to more productive use of all machines, less in-process inventory, fewer stoppages for missing parts or materials, or machine breakdowns.
7) Distributed processing capability made possible and economical by the encoding of process information in easily replicable software.

These capabilities directly challenge the notion of economies of scale, particularly that larger volumes mean lower unit costs than lesser volumes.

6.4.5 Importance of flexibility

Flexibility is now of overriding importance for long-term profitability for a number of reasons:

1) Ever shortening product life cycles,
2) Demand for larger product variety,
3) Demand for greater customization,
4) Need for large investments in automation to remain competitive. Large fixed costs could be a deterrent to new product innovation if equipments purchased are not flexible,
5) Demand for shorter manufacturing lead times. This requires shorter flow times which is possible only through rapid changeovers and flexibility in the organization of production operations,
6) Uncertainties in the timing and extent of demand changes,
7) Changing product mix due to changing customer preferences and competition,
8) High level of worker education and their ability to handle a variety of tasks demand task flexibility to sustain job satisfaction,
9) Development of modern communication, computing and control systems and their integration with production processes have enhanced process flexibility and allow

for economies of scope,

10) Need to slash all non-value added costs to be price competitive and

11) The proven effectiveness of continuous and rapid change as a strategic weapon in many markets.

It may be observed that most of the reasons listed above are market oriented. In other words they are centered around the needs of the customer.

6.4.6 Achieving flexibility

Flexibility must be built into a system as quality must be built into a product. A system to be labelled "flexible" should depend only on itself to provide the adaptability to change it is expected to provide. The dependency of a system on external resources to "cope" with change (which will be discussed later) is a clear sign of lack of inherent flexibility. Some ways to achieve specific types of flexibility are discussed below.

6.4.6.1 Process flexibility

External setup of tooling and fixturing, commonality of tooling and fixturing between parts, programmability of process equipment and rapid downloading of part programs help reduce the time to changeover from one part type to another. Process flexibility is directly proportional to the rapidity with which a changeover could be made.

6.4.6.2 Layout flexibility

Grouping parts that have commonality of process equipment, routing, fixturing, tooling and methods together and producing them in one location based on group technology cell concepts, significantly reduces the material handling distance between consecutive processes, besides many other benefits. This permits cost effective transfer of small batch sizes or even individual units between processes. Besides, it also reduces product flow times and enhances the flow rate for an entire family of parts. Incidentally, these are indicators of a flexible layout.

6.4.6.3 Volume flexibility

Volume flexibility can be attained by building modular small units and by making it easier to add and subtract capacity. The infrastructure to support the use of modular units should also be provided.

6.4.6.4 Labor flexibility

Schonberger [147] shows that labor flexibility can prevail in a number of ways:

1) Workers moving on their own or directed to move to whatever task that arises over time,

2) Removal of workers off the line when a line is running too smoothly,

3) Moving of whole crews from one dedicated line to another as the model mix changes,

4) One worker handling a variety of tasks in a single work center and

5) Moving people to rebalance lines when a change is made from one part to another.

Creating flexibility of this nature requires good labor-management relations and an appreciation of the value of flexibility to the prosperity of the organization, by all concerned.

6.4.7 Pseudo flexibility

Some organizations adopt wasteful practices to cope with change and also live with the problems associated with it. By doing so they think that they have acquired "flexibility" when in fact they have not. Two such methods are discussed below.

6.4.7.1 Buffers

When the volume of demand or the product mix varies significantly buffer stocks are built to quickly meet customer needs. It may be observed that this does not enhance the capability of the production process to respond quickly to customer needs. The production process depends on an external entity, namely the "buffer" to meet the need. In some situations it may make good business sense to have buffers in front of the market. However, it must be realized that building buffers does not enhance the inherent flexibility of the manufacturing system, but just serves to isolate marketing from manufacturing's lack of responsiveness.

6.4.7.2 Excess capacity

When the volume of demand varies significantly, excess production capacity is built up to cope with fluctuations on the high side. It may be noted that by doing so, individual pieces of equipment have not enhanced their inherent flexibility in any way, to respond to volume fluctuations. Busy units of production equipment "depend" on excess capacity of the same type of equipment to respond to such fluctuations. Moreover, excess capacity is an idle and wasted resource that has already been paid for. In some situations, it would make perfect business sense to build in some protective capacity. However, it must be realized that it does not enhance the inherent flexibility of the production system.

6.4.8 Measurement of flexibility

The management of flexibility involves the identification of the needs for appropriate types of flexibility, effectively building it into the system, measuring it and improving it on a continuous basis to sustain competitive advantage. The strategic importance of flexibility requires that it be well managed. The measurement of flexibility is fundamental to its management. However, the firm must be clear about how it intends to use measures of flexibility. Otherwise, it might end up measuring for measurement's sake.

Flexibility measures may be used as follows:

1) To understand its consequences qualitatively and quantitatively - the way in which and the extent to which it affects business related variables like costs, lead time, responsiveness to the customer, revenue enhancements arising out of flexibility etc.,
2) To identify areas for flexibility improvement and to support decision making pertaining to new capital investments.
3) To monitor improvement in flexibility arising out of new investments and projects undertaken to achieve certain economies of scope. This is very important for the strategic management of change.
4) To compare one system with another. Measures that only indicate whether one system is more flexible than another, ordinal measures, may provide abstract measures of health but may not be of much use for the

management of change or steady state operations.

A flexibility measure is supposed to indicate the ease with which, or alternatively, the "degree" to which a system can adapt to a certain "type" of change. Measures developed should be fit for use by operations management and not too mathematically complex to be of practical use. Measures should be developed for each of the different types of flexibility as their relative importance varies from one organization to another, depending upon business needs. Also desirable are measures of overall system performance. Measures of flexibility may be classified into indirect measures and absolute measures.

Indirect measures are a set of indicators which reflect the sources of flexibility or the consequences of it, which are measurable. They can indirectly show the existence of flexibility and improvement or deterioration trends. They could also be used to compare systems that perform the same or similar tasks. Flexibility is a dependent variable. It can therefore be described by the independent operational variables that are responsible for its existence, like low setup time for example, or alternatively, by other dependent variables that are also influenced by the same independent variables, like economic batch size for example.

An absolute measure of flexibility is one that does not require comparison to other systems to determine its value. Such measures do not exist at this point and are likely to be very system specific, when developed. It is not clear if they would be able to support technical decision making pertaining to building and improving flexibility. However, they could provide a common yardstick for organizational health or competitiveness within a certain industry type. The practical uses of such measures are not very obvious and require further research.

While developing absolute measures care must be taken to differentiate capability from flexibility. Consider the following example: Drilling machines A and B can drill at speeds ranging from 100 rpm to 5000 rpm. Machine A is manually operated and needs a gear change (setup) to step up after every n x 1000 rpm where n=1,2,3,4. Machine B allows automatic and instantaneous speed selection within the entire range (100 to 5000 rpm) through a touch screen. Both machines A and B have the "capability" to handle drilling between 100 and 5000 rpm but machine B is more flexible. Now consider machine C which allows automatic, instantaneous speed selection within a possible range of (100 to 4000 rpm). Machine C has a lower rpm capability than machines A and B. It is definitely more flexible than machine A but is it less flexible than machine B or does it have the same flexibility as B? It depends on how the absolute measure is defined.

6.4.9 PROPOSED MEASURES

A set of measures are proposed under each major type of flexibility. These are indirect measures intended to assess manufacturing performance.

6.4.9.1 Process flexibility

1. Average time per setup

The magnitude of the setup time to change from one part type to another is a measure of the resistance to changeover. The higher the average time per setup for a given cell or shop, the lesser is the average process flexibility.

2. Reciprocal of (1 + average setup time).

This measure expresses process flexibility on a scale of zero to one. A rigid system such as a transfer line has a very large changeover time. The flexibility measure in this case will be very close to zero. In a CNC machine, the setup time, depending on its configuration will be very small. The resulting flexibility figure will be close to unity.

3. Machinery or equipment flexibility

This can be computed as the ratio of two factors as shown below:

$$\frac{\text{Residual value of investment for the next model}}{\text{Original investment for the existing model}}$$

The residual value of the investment for the next model is a measure of the value of current production equipment that is considered flexible enough to support the manufacture of proposed new products. The higher this value, the greater would be this measure, which is indicative of the flexibility of the existing plant for introducing new products.

4. Operation flexibility

The operation flexibility of an entity such as a machine, cell or production system can be computed as the ratio of two factors as shown below:

$$\frac{\text{Number of processes the entity can deal with}}{\text{Total number of processes on the part}}$$

This measure of flexibility will have a value of one for a given part-machine combination, if all operations on the part can be performed on the same entity in one setup.

5. **New product introduction flexibility**

This measure has the same intent as (3) above. This expresses the loss incurred in tearing down and removing items of existing plant and machinery that have been rendered inflexible or unfit for the manufacture of the proposed new product(s) as a percentage of the total cost of new product introduction. It is a measure of the flexibility of an existing plant and may be expressed as:

$$\frac{\text{Exit cost}}{(\text{Exit cost} + \text{Cost of new additions})} \times 100$$

6. **Flexibility horizon**

It is the minimum time window a production system remains capable of adapting itself to schedule changes, without loss of throughput. The higher the flexibility, the smaller will be the time window.

7. **Total number of parts per part family or per cell**

This is a measure of the variety of parts processed within a single production entity such as a cell or a flexible manufacturing system.

8. **Average number of part types per fixture**

This is an indicator of workholding flexibility. The higher the number of part types a given fixture can locate, the greater is its universality and lesser would be the time spent on setting up and removing the fixture from the bed of the machine.

9. Mixed model capability

The maximum number of part types that could be produced per day (or in a specified time period) could be used as a measure of mixed model capability. This is a consequence of process flexibility. The number of models that can be simultaneously produced in a given time period, profitably, is a function of the built-in flexibility. This capability improves with decrease in setup times.

10. Versatility of geometric specification

This is process specific measure that could be expressed as the number of different part features that the machine can generate or process, and/ or the tolerance limits it can handle.

6.4.9.2 Volume flexibility

1. Volume capability variance

The standard deviation of the discrete volume levels in which the plant can operate is a measure of volume expansion and contraction flexibility.

2. **Stretch capacity as percentage of normal volume**

This is defined as the ratio of the maximum range of volume to the normal operating volume and may be expressed as:

$$\text{Stretch capacity} = \frac{\text{Maximum volume} - \text{Normal volume}}{\text{Normal volume}}$$

This is a measure of the expandability of a production system to meet occasional surges and drops in volume demand.

6.4.9.3 Labor flexibility

1. **Average number of jobs mastered/ operator**

The ability each member of the workforce to perform a variety of tasks (operation of different machines, preventive maintenance, housekeeping, process control, setup, tool maintenance etc.,) significantly enhances the flexibility with which he or she can be used to meet changing demands for labor. The above is a basic but strong indicator of labor flexibility.

2. **Number of organizational levels or grades**

As the number of organizational levels increase, the flexibility with which personnel can be used across levels decreases. The smaller the number of levels, the higher should be the flexibility, particularly within the labor ranks.

6.4.9.4 Routing flexibility

For a given cell, this is the ratio of the number of feasible inter workstation routes to the maximum mathematically possible number of routes (expressed as a factorial). The higher this measure, the greater would be the routing flexibility. Expressed as a formula,

$$\text{Routing flexibility} = \frac{\text{Feasible routes in the cell}}{(\text{No of work centers})!}$$

6.4.10 Benefits of flexibility

The benefits of flexibility are many and varied. Those commonly observed and of strategic importance are as follows:

1) Lower indirect costs due to lower setup times, batch sizes and product flow times.
2) Custom products can be produced at close to mass production costs.
3) Improved cost stability with volume and mix changes.
4) Shorter manufacturing lead times which permits quicker order execution.
5) Capability to produce mixed models cost-effectively.
6) Increase in productive capacity of available resources.

7) Forecasting errors have a less drastic effect.

8) Reduced tendency to create buffer stocks.

9) No cost penalty for producing variety.

10) It helps the firm update products, incrementally increasing their complexity and technological content.

11) Helps create protective barriers against competition.

12) Increases the range of the product line, complexity of products, and provides for greater responsiveness.

13) Flexibility opens up new markets, customers and demands of distribution and, along with them, new opportunities for revenue enhancement and new routes to competitive advantage and

14) Flexibility allows competition on perceived special options. This regenerates competition on product characteristics, not simply on price.

6.4.11 Value of flexibility

The value of flexibility is the extra profit or the decrease in loss that the flexible system can achieve in comparison to a less flexible system. It is not a measure of flexibility but a measure of its consequences.

6.5 NEW/IMPROVED PRODUCT INNOVATION AND INTRODUCTION

The purpose of product engineering changes is to improve existing products, to make them superior to those of the competitors. If the firm can offer products with the latest functions and features desired by the marketplace, it can gain a competitive edge. The potential of the company to be the first in the market with new or improved products also makes it attractive to investors. Being the first in the marketplace with an improved product is clearly an obvious competitive advantage. Unfortunately, many manufacturing people have the feeling that engineering changes are simply made to make their life more difficult.

In a large batch size environment, the work-in-process level is high. Consequently, introduction of a design change would involve purging a lot of material in the system. However, in most cases, the cost of scrapping or reworking old designs in process forces managers to "delay" the implementation of the engineering change until the next production order for the product. In a small batch size environment, orders are released to production in small portions. The amount of superceded designs in process that must be purged will be much smaller, and the new designs can be introduced much faster. The company with the low batch size environment can therefore make the superior product available to the marketplace for a significant period without competition and should be able to gain additional sales and market share. As product life cycles are continually reduced, these advantages become more and more important.

The following sections present measures of a company's ability to efficiently and quickly innovate and introduce new products and design enhancements.

6.5.1 Reduction in R&D manhours per new product

The number of manhours that goes into research and development associated with a new product is a measure of the effort expended to introduce it. Efficiency in new product introduction is vital to the world class manufacturer, whose success depends on continuously introducing new and improved products. Past experience has shown that mature and flexible R&D organizations introduce newer products with greater ease. The reduction in the manhours per new product could be used as a measure of improvement in the efficiency of innovation.

6.5.2 Reduction in new product introduction lead time

The ability to continuously introduce new and improved products is critical to the success of many organizations. The lead time to conceive, design, test, develop and get ready for manufacture is an important variable that affects their success. Short lead times to introduce new products are vital to the world class manufacturer. In halting its declining fortunes in the copier industry, Xerox, has vastly improved its ability to get new products to the market.

Fewer than 350 R&D people spent just two and half years developing Xerox's top of the line 9900 copier, as compared with five years and four times more people for such products in the past [147]. The reduction in average new product introduction lead time could be used as a measure of improvement in an organization's capability to quickly innovate and introduce new products.

6.5.3 Reduction in lead time for ECO implementation

In many organizations, short term or periodic improvements in the product are introduced in the form of an "engineering change order" (ECO). The production order backlogs, the size of work-in-process inventory, capital resource requirements and the inflexibility of production personnel could delay the implementation of the engineering change. To sustain and improve competitiveness, it is essential to bring superior products to the marketplace long before competitors do, to be able to gain additional sales and market share. As product life cycles are continually reduced, this is becomes more and more important. The lead time for implementing an engineering change is the time that elapses from the instant an engineering change order is received to the time it is fully implemented with all the associated resources. The reduction in the lead time for implementing an ECO, could be used as a measure of improvement in the organizations' ability to introduce periodic product enhancements in product design.

In summary, the critical variables that determine an organization's responsiveness to its customers are lead time, delivery dependability, customer service, product and process flexibility and the ability to quickly and continuously innovate and introduce new and improved products. These factors markedly influence customers' perception of a company, its products and its people. Consequently, they have strategic importance and need to be managed through an appropriate set of measures. Measures of the stability of production operations are presented in the next chapter.

Chapter VII

Measures of Operations Stability

The stability of manufacturing operations may be defined as the state of affairs that permits full, productive use of all capacity constrained resources, as well as, the uniformity of end product shipments over a billing period.

The stability of production operations is an important issue because lack of it adversely affects cost-effectiveness, profit margins and competitiveness. The company with high margins has the flexibility to selectively lower prices or use its high margins to gain a competitive edge in other ways such as increasing its sales force, advertising or product engineering.

Lost time on constraints is lost throughput. Throughput, as defined earlier, is the rate at which the system generates profits through sales. So lost throughput is profit lost. Loss of productive time at the constraints can occur in a number of ways: shortage of labor or material inputs which starve the constraints, defective material inputs which reach the constraints and get processed only to become scrap, nonconformance at the constrained resources due to their own variability, and finally breakdowns of the constraints which result in unscheduled downtime. The relative impacts of the different causes may vary from situation to situation. However, all the causes originate from uncertainties and variabilities in manufacturing operations.

Labor shortages are the result of unplanned absenteeism or temporary absence from the workstation during scheduled production time. Material shortages at the constraints occur due to variabilities in the yield of processes upstream of the constraint, uncertainties in material availability in upstream processes and uncertainties in the availability/ uptime of process equipment upstream. These variabilities and uncertainties coupled with poor process flexibility and large setup times encourage the use of large batches and making more upstream than what is actually needed downstream. Large batches and WIP inventory buffers upstream cause the material to move sluggishly and unpredictably through the plant in discrete jumps. Often, there is virtually no flow.

Defective materials reach the constraints due to poor process control and inadequate inspection upstream. Nonconformance at the constraints originate from their own process variabilities and inadequate process control. Unscheduled downtime at the constraints occur due to poor, inherent process reliability and poor preventive maintenance. Typical of an unstable environment is the "end of month syndrome", which is discussed in the section below.

7.1 END OF MONTH SYNDROME

In an unstable production environment, it is not uncommon to encounter major differences between planned production levels and actual output. No matter how well plans are made, even with large measures of safety built in, orders are still constantly expedited and lavish amounts of overtime are expended to get orders shipped on time. This problem is so widespread that it is often referred to as the "end of the month syndrome". Somehow through special efforts, more than half of the month's production are shipped in the last few days. Whenever there is trouble with shipping on time, invariably always, there is heavy dependence on overtime, premium freight and other expensive and unplanned actions. The end result is that orders may or may not get out on time, but additional operating expenses are certainly incurred and profit margins shrink as a result. All this could be attributed to a relatively higher level of inventory as compared with the competitors.

If the competitors have lower inventory, their lead times would also be lower. To win orders against such competition, marketing will be forced to quote shorter lead times than manufacturing is capable of. Manufacturing will be forced into considerable overtime and possibly other additional costs to meet the delivery date. Inventory is not generally recognized as causing overtime, but it quite often is the prime reason.

Coping with the end-of-month syndrome is a major ongoing problem for most plants. A surge of product is encountered at the final operations that must be processed in the last week of the month if shipping goals are to be met. Even overtime may be sometimes insufficient to meet the peak load. A capacity shortfall is experienced at the end of the month which triggers requests for additional capacity. However, capacity plans may indicate that the capacity in final operations is several times the average workload. Even though these machines are often idle, particularly in the early part of each billing period, the organization is forced to invest in more machinery in order to make the monthly shipping targets. Large batch sizes move through the plant with long delays and discrete jumps. They almost always get to the final operations very close to or beyond the target shipping dates.

In a high inventory environment, the last operations are at peak load for an extended period of time and this peak load occurs at the worst possible time, the end of the billing period. In a low inventory environment, the load on the last operations is more uniformly spread and the idle time is even more uniformly distributed, even at the end of the month. This greatly reduces the investment required per unit of product and the return on investment is much higher. Even more importantly, the break-even point is lower, which allows much more flexiblity in pricing the products.

7.2 MEASURES OF STABILITY

All factors critical to the success of the enterprise should be met without chaos in internal operations. Month end fire drills clearly indicate instability in plant operations. Global measures of stability can provide senior management with an assessment of the impact of uncertainties, variabilities and poor flexibility on the profitability of plant operations. However, it must be noted that such measures can only indicate the existence of abnormalities. They are not intended for problem identification and problem solving like some of the measures developed in Chapters 4, 5 and 6. Measures to evaluate the stability of production operations are presented in the following sections.

7.2.1 Linearity of output

This is defined as the uniformity of end product shipments over a billing period. It can be computed as the variance (square of the standard deviation) of daily shipment quantities and/or dollar value of sales. The magnitude of this number will be proportional to the deviation of daily shipment figures from the mean. The linearity of output is a good measure of operations stability and a means to identify the existence of the end-of-month syndrome. A decrease in the variance should correlate with improvement in constraint utilization.

7.2.2 Final assembly workload variance

This is defined as the magnitude of statistical fluctuations in daily workload at the final stages of production. When the end-of-month syndrome prevails in a plant, equipment and other production resources in the final stages of production are poorly utilized at the beginning of the billing period and often work overtime towards the end to meet shipping targets. The fluctuations in workload can be measured as the variance (square of the standard deviation) in the daily average equipment utilization. A high variance is clearly an indication of instability.

7.2.3 Constraint utilization

Constraint utilization refers to the percentage of time the constrained resource is engaged in producing useful output. A constrained resource is one whose capacity is less than the demand imposed on it. The throughput of the plant is restricted by the capacity of its worst constraint. Constrained resources determine the effective capacity of the plant. The flow through the constraint must therefore be made equal to the demand from the market. A hour lost at a constraint has the same impact as a hour lost by the entire plant. Poor constraint utilization has two major financial impacts. One is the opportunity cost of lost profit and the other is poor leverage from the fixed operational expenses incurred by the firm to carry out its value adding and non value adding activities. Incidentally, these are the impacts of instability in manufacturing operations. With an improvement in the productivity of constrained resources, throughput improves and backlogs decline. When constraint utilization improves, the uniformity of end product shipments will most likely improve.

7.2.4 Overtime variance

Overtime in production operations is usually used to acquire the extra capacity badly needed to rush jobs and meet target shipping dates. Overtime throughout a billing period is rather uncommon and it only suggests that overtime is used as a tool to stretch the productive capacity of certain resources beyond recommended levels. When the end-of-month syndrome prevails, overtime would be resorted to primarily at the end of the month. The variance (square of the standard deviation) of daily overtime hours during a billing period, is another good measure of instability in manufacturing operations.

7.2.5 Operational expenses per unit of output

The utilization of constrained resources determines the output from the plant as a whole. Low utilization means low output. In most modern manufacturing plants, the total operational expenses are predominantly fixed in nature. When constraint utilization drops, the fixed operational expenses would be spread over fewer units of output. This will increase the operational expenses per unit of output. This measure would stay valid at least as long as demand exceeds the capacity of existing constraints. Operational expenses include all the money the organization spends in turning inventory into throughput. It includes the annualized cost of capital investments. The operational expenses per unit of output is therefore a good global measure of stability expressed in terms of its financial impacts. It would facilitate budgeting for and improving stability in plant operations.

In summary, measures of stability are intended to provide management with information on the ease with which the plant meets its throughput targets. They are also intended to provide global measures of the financial impacts of instability in the conduct of manufacturing operations. All efforts to identify and eliminate uncertainties and variabilities from manufacturing operations should ultimately result in a predictable and stable plant.

Chapter 8 presents a summary of this research, considerations for use of the measures developed, some general findings and finally, the conclusions drawn from this work and the scope for further research.

Chapter VIII

Summary, Conclusions and Recommendations

8.1 SUMMARY

A comprehensive set of indicators to measure total manufacturing performance was developed. The research recognized the fact that each organization is different in terms of its criteria for performance measurement. Different types of corporate missions, factors critical to their success and compatible manufacturing strategies were analyzed. It was recognized that performance measures should not only be product specific but also need to change as a product evolves through the different phases of its lifecycle.

The limitations of traditional performance measures and managerial incentive systems were analyzed and the need for strategic performance measures was discussed. Taking into consideration the shortcomings of traditional measures, the functional requirements for strategic performance measurement were developed. Maximization of profit was recognized as the goal of any manufacturing organization and that profit comes from providing customers with the desired levels of cost, quality and responsiveness. Operating expenses, throughput and inventory were acknowledged to be global measures of manufacturing productivity.

A framework for measuring total manufacturing performance was developed. It was characterized by four subsets of performance measures: measures of cost-effectiveness, quality, responsiveness and stability of internal operations. Within each subset, attempt was made to elaborate how each measure would reflect changes in throughput, operating expenses and/or inventory levels. The relevance of each measure to profitability and competitiveness was also discussed. Significant effort was made to relate potential impacts of uncertainty and variability in manufacturing operations, on the behavior of the measures developed.

Measures of cost-effectiveness dealt with the impact of operations related to material procurement and conversion on operational expenses. The importance of minimizing lifecycle costs was dealt with extensively. measures of quality were developed to evaluate the quality of design, the quality of conformance and end product performance. The relevance, uses and limitations of information on the cost of quality was discussed in detail. Measures based on quality costs were also developed. Measures of responsiveness were developed under five distinct heads:

cumulative lead time, due date performance, customer service performance, flexibility and new product innovation and introduction. The issue of flexibility was more extensively dealt with than the rest. The strategic importance of flexibility, different types of flexibility and ways to achieve and measure flexibility were discussed in detail.

Non-linearity of production output was purported to originate from uncertainties and variabilities in manufacturing operations. The end-of-month syndrome was introduced as the manifestation of instability in manufacturing operations. Measures were developed to assess the seriousness of the end-of-month syndrome and its impacts on plant profitability.

8.2 CONCLUSIONS

This research confirmed that performance measures should be tailored to the company's mission, its critical success factors, its manufacturing strategy, projects in progress to implement that strategy, products produced and the current phase of their individual lifecycles. Performance indicators could therefore vary across product lines in a multi-product company. Conflicts related to this should be expected as the criteria for their market success are different for the different products. The system of performance measurement should be comprehensive in its scope, in so far as the evaluation of adherence to customer expectations was concerned. At the same time, it should not lose sight of the primary goal - profit. Performance measures must be periodically reviewed for relevance to the measurement of progress in current projects, changing business needs and critical success factors. Irrelevant measures must be dropped and appropriate new measures must be added. To get the best utility of measures in use, the data collected should be extensively used for problem identification and problem solving as opposed to mere progress measurement.

8.3 RECOMMENDATIONS

A company faced with the need to develop a system for measuring total manufacturing performance should first review its niche and restate its corporate mission if need be. It must then critically examine the factors that seem critical to the success of its mission. Based on these factors and an unbiased assessment of its current state of affairs, it must then develop its manufacturing strategy to capitalize on its strengths and opportunities, to overcome its weaknesses and threats, and thereby maximize its profits. To effectively implement this strategy, a comprehensive set of measures that could reflect progress in the desired areas must be chosen. While doing so, significant care should be exercised to ensure that conflicts between measures do not exist. When conflicts exist, an improvement in one measure would lead to the deterioration of another. Targets set should be periodically reviewed to ensure ongoing improvement. It should be realized that a given set of performance measures, however comprehensive they may be, may not be valid forever. Markets change, critical success factors change and programs of continuous improvement may render some measures insignificant beyond a certain point. It is therefore necessary to recognize the changing information needs and suitably revise the performance measurement system.

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In the Spring of 1987, Nagesh joined the Manufacturing Systems Engineering program at Lehigh University. During his stay at Lehigh University, he also worked as a research assistant with the Institute for Robotics. He is currently finishing the program and will graduate in June of 1988. He will then join American Cimflex as a CIM systems engineer in their CIM systems division at Pittsburgh, Pennsylvania.