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EVALUATION OF THE ECONOMIC IMPACT OF OPERATIONAL TACTICS AT AN ELECTRONICS MANUFACTURER

Venus Pui-lai Chan

A Thesis
In
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of
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ABSTRACT

Evaluation of the Economic Impact of Operational Tactics at an Electronics Manufacturer

Venus Pui-lai Chan

Operational tactics of non-value added time, setup time and lot size reduction for reducing manufacturing cycle time at a large electronics manufacturer were evaluated with economic measures. Features of one of the assembly lines were modeled using actual production data. The simulation model developed covers all assembly operations of the line from board preparation to final system assembly and test.

Details of the assembly line modeled are presented. Parameters of the simulation model are described. Experimental design, performance measures, statistical analysis are discussed. The dollar value of both work-in-process (WIP) and finished goods (FG) inventory is used to evaluate the effectiveness of alternative tactics. Managerial implications and recommendations are presented.

Keywords: Cycle time, inventory levels, operational tactics, simulation, electronics.

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List of Abbreviations and Terms

AGV	Automatic Guide Vehicle.
ANOVA	Analysis of Variance, a statistical method.
APICS	American Production and Inventory Control Society.
ATO	Assemble-to-Order.
BOM	Bill of Material.
BPR	Business Process Reengineering.
CIM	Computer Integrated Manufacturing.
CONWIP	Constant Work-in-Process, one of the pull system.
ECN	Engineer Change Notice, same as ECO.
ECO	Engineer Change Order, same as ECN.
EOQ	Economic Order Quantity.
ERP	Enterprise Resource Planning.
ETO	Engineer-to-Order.
FCFS	One type of scheduling rule: first-come first-served.
FG	Finished Goods.
FMS	Flexible Manufacturing System.
JIT	Just-in-Time.
Kanban	Carriers with standard lot size.
MANOVA	Multivariate analyses of variance, statistical method.
MASS	Manufacturing Simulation System.
MPS	Master Production Schedule.
MRP	Material Requirements Planning.
MRP-II	Manufacturing Resource Planning.
MTBF	Mean Time Between Failures.
MTO	Make-to-Order.
MTS	Make-to-Stock.

NVA	Non-value Added.
NRC	National Research Council, headquarters in Ottawa.
PAL	Programming language used in PARADOX.
PARADOX	A database program by Borland, used for personal computers.
PCB	Printed Circuit Board.
POQ	Period Order Quantity, a lot-sizing technique.
ProModel	PROduction MODELer, a Windows based simulation software with animation capability.
R&D	Research and Development.
RM	Raw Material.
ROE	Return on Equity.
SAS	SAS System for data management, analysis and reporting. Generally known as a statistical application software.
TQM	Total Quality Management.
WIP	Work-in-process.
XCELL+	A simulation software for production systems.
ZI	Zero Inventory.

1. INTRODUCTION

1.1 *SCOPE OF RESEARCH*

Globalisation, as well as increased competition, complexity and uncertainty, are challenging North American firms to deploy new operations tactics. This research project evaluates the economic impact of some of the operations tactics that are currently employed by companies. Using an applied research approach, this study will focus on the main operations tactics that a large electronics manufacturer is planning to adopt, namely reduction of manufacturing cycle time. Three different tactics for manufacturing cycle time reduction are evaluated, namely the reduction of setup time, non-value added (NVA) time[1] and lot size.

The objective of this study is to evaluate the economic impact of the three different cycle time reduction tactics. Simulation modeling[2] is used in this respect. Recommendations are made to the manufacturer on the appropriate tactic(s) to be deployed.

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[1] Generally NVA time refers to production order preparation time, queue time, move/transportation time and put-away time. For the current model, NVA time only applies to queuing time, i.e. the time a job waits to be processed by a workstation.

[2] While the project is a joint venture among ABC, McGill University and NRC, the development team from NRC coded the program in ProModel.

The current study was carried out at the production facility of a large electronics manufacturer in Montreal, hereafter called ABC. This study was part of a simulation-based project, which the company conducted in collaboration with McGill University and the NRC. The following subsections provide a brief introduction to the company and its products.

1.2 *COMPANY BACKGROUND*

ABC is one of the leading global providers of electronic equipment and related services. Product demand is cyclical and ABC's products are increasingly treated as commodities. Delivery time commitment to customers is down to 1 to 3 weeks while manufacturing[3] cycle time remains at 4 to 7 weeks. The manufacturing mode is changing from make-to-order (MTO) to make-to-stock (MTS).

The Montreal Plant has set three major objectives for 1998: inventory reduction, cycle time reduction and customer service improvement. In order to achieve all of these seemingly conflicting objectives, various activities and projects are being undertaken. For example, extensive business process re-engineering(BPR) is being carried out to streamline operations and to reduce cycle time in all areas.

The company has adopted two main operations tactics: reducing the manufacturing cycle time and increasing the ratio of sales of MTS items to sales of MTO items. With a

---

[3] Montreal Plant of ABC does not manufacture any electronic component. The manufacturing department only carries out assembly work for boards and system building. In line with the terminology used in the literature, the word 'manufacture' is being used in this paper in place of 'assemble' to avoid confusion.

greater proportion of MTS items, cycle time becomes critical to ensure reasonable customer response time and service level. This research project will focus on the operations tactics of cycle time reduction and will evaluate its economic impact in terms of inventory levels and cycle time. Details of manufacturing operations at the Montreal plant will be presented in Section 3.1.

1.3 CHAPTER ORGANIZATION

Chapter 2 provides a review of the literature on characteristics and practices of the electronics industry, as well as strategies, tactics and performance measures typically used today in the industry. Description of the existing manufacturing system at ABC, as well as features, assumptions and validation of the simulation model will be presented in Chapter 3. Chapter 4 presents research methodology in terms of simulation issues, performance criteria, experimental factors and design. Simulation results, statistical analysis and managerial implications of findings are presented in Chapter 5. A summary of conclusions and the potential future directions for research are discussed in Chapter 6.

2. LITERATURE REVIEW

Wickham Skinner identifies five stages in the evolution of American manufacturing (see discussion in Moody, 1990). These five stages depict responses to changing technologies, evolving markets, proliferating products and intensifying competition in a flourishing nation. The year 1973 marked the end of the golden era of American manufacturing: a general slowdown of industrial growth that was worsened by the Japanese challenge in the 80's. By the end of the 80's, manufacturing was still a mystery and was looked down on by some in the financial, political and academic communities. Productivity and profits had just started to improve with the use of the Japanese Just-In-Time concepts (Moody, 1990).

Whereas the theme of the 60s was 'How to do more', it became 'How to do it cheaper' in the 70s, 'How to do it better' in the 80s and then 'How to do it quicker' in the 90s (Vesey, 1991). Back in the 1980's, the key competitive issue was on-time delivery, and quality was the order winner. Today quality has become an order qualifier while time and flexibility form the new competitive edge. The *1990 Manufacturing Futures Survey* (as cited in Lummus,

1995) states that product customization, product innovation, increased number of distribution channels and rapid product introduction will form the next competitive edge. According to the *1990 Manufacturing Futures Survey* (as cited in Vastag, Kasarda & Boone, 1994) the major sources of change will be: i) the global market, ii) higher customer demand for quality and speed, iii) changing characteristics of the workforce, and iv) environmental issues.

The following sections survey the literature on characteristics and practices of the electronics industry, as well as strategies, tactics and performance measures typically used today in the industry. In particular, Section 2.1 provides background information about the electronics industry. Section 2.2 describes operations strategies and the tactics of sales mix changes and order fulfillment time reduction. Section 2.3 discusses performance measures in manufacturing, particularly in the areas of inventory management and customer service.

2.1 THE ELECTRONICS INDUSTRY

The electronics industry comprises the whole supply chain from wafer fabricators to semiconductor manufacturers to end product providers of telecommunication equipment. We will discuss the supply problems that are created by upstream manufacturers, as well as comparing and contrasting the characteristics and problems of different stages of the industry.

With regards to supply problems, the semi-conductor manufacturers in particular have difficulty in matching production capacity to customer demand. Capacity has almost always been lower than demand (Berry & Naim, 1996). This indicates a supply problem for any downstream manufacturers in the electronics industry supply chain.

Capitalization is an important source of contrast in the electronics industry. The manufacturing processes of upstream companies are highly capital intensive and is one of the most complicated manufacturing processes in the world (Uzsoy, Lee & Martin-Vega, 1992). The order winner for these companies used to be product design, but has changed to cost and time of production in the last few years. Product life cycles are short and usually overlap.

The pace of product innovation hinders long term planning while capital intensities demand high throughput and equipment utilization (Duenyas, Fowler & Schruben, 1994). Production equipment is extremely sophisticated, demands extensive preventive maintenance and calibration, and is subject to unpredictable failures (Uzsoy et al., 1992).

Compared to manufacturing and fabrication operations, assembly and final test operations in the electronics industry require low investment and are labor-intensive. However, as these operations are closer to the customer they require good control of cycle times and WIP levels to provide good delivery performance. Computer Integrated Manufacturing (CIM) has been advocated to address these complex problems and performance pressures, but complete integration has not been achieved (Uzsoy et al., 1992).

Each stage of the electronics industry has a typical environment. Most major semiconductor manufacturers work in a make-to-stock (MTS) environment, producing standard products in high volumes with buffer inventories for fluctuation of demand and equipment downtime. The application-specific manufacturers need to work in make-to-order (MTO) mode and are under heavy pressure to achieve good order fulfillment time and delivery performance (Uzsoy et al., 1992). Certain end-product providers, e.g. telecommunication equipment suppliers, work in a make-to-order and/or assemble-to-order (ATO) environment. The MTO/ATO environments are subject to higher unpredictability of market requirements. Sometimes, delivery lead-time is shorter than the cumulative production lead-time. These problems are compounded by the high variety of product offerings. The characteristics and challenges of the different manufacturing environment, i.e., ETO/MTO/ATO/MTS, will be further discussed in Section 2.2.2.

Almost every semiconductor manufacturer uses a closed loop material requirements planning (MRP) logic or system for production planning. Some companies incorporate the logic in homegrown spreadsheets, while others use commercial MRP or Manufacturing Resource Planning (MRP-II) software. Most planning cycles last one or more weeks, and very few manufacturers have an automated process for regenerating an official plan in less than a week (Hung & Leachman, 1996). The use of MRP and long planning cycles create problems for the industry, but at the same time represent possible opportunities for cycle time improvement. This will be further discussed in detail in Section 2.2.2.

2.2 OPERATIONAL TACTICS

The terms 'strategies', 'tactics' and 'techniques' are not consistently distinguished in the literature. *'Strategy refers to competitive approaches toward winning a market niche ... for example, ... offering ... the newest idea. Tactics are the methods of supporting and executing the chosen strategy ...(for example) ...large expenditures for research and development and a very flexible and fast new product introduction capability.'* (Moody, 1990, p. 51). Techniques or methodologies such as JIT or FMS are used to execute tactics. It is of particular importance that manufacturing tactics be consistent with marketing tactics to help meet the order-winning criteria.

Over the last decade, much of the interest in Manufacturing has been concentrated on methodologies such as Total Quality Management (TQM), Just-In-time (JIT), MRP-II and Computer Integrated Manufacturing (CIM). These techniques received much attention in both academic and industry communities. While some companies report successes, there is also evidence of a high failure rate. This is partly due to the lack of a theoretical model to guide the formulation and implementation of Manufacturing Tactics (Marucheck, Pannesi & Anderson, 1990). It is widely assumed that there is a need to balance technological, organizational and human aspects of manufacturing (Berger, 1994). Besides aligning manufacturing tactics with corporate objectives and marketing tactics, human resources tactics should also be considered (Kinnie & Staughton, 1994).

The choice of standardization vs. customization is a marketing tactics. As illustrated in the five-step strategic planning process of Hewlett-Packard (discussed in Beckman, Boller, Hamilton & Monroe, 1990), product standardization is supported, at the macro level, by a strategic emphasis on responsiveness to customers and, at a micro or tactical level, by short order fulfillment time. Both product standardization and order fulfillment time reduction support the order-winning criteria of delivery speed and reliability.

The five-step strategic manufacturing planning process was develop from a combination of academic theory and practical experience. It was successfully applied by both HP and some of its customers. The process starts with segmenting the business according to customer needs and the cost structure required to meet them. Product/market characteristics are then identified: product variety, market volume, product standardization, growth of market and rate of product change. Then critical success factors, i.e., customer's preferences, are identified: price, quality, product/service availability and features. The primary success factor(s) helps define the company's overall objective or direction. Each functional department can then create strategies that would achieve one or more of the overall business objectives. The functional tactics developed by manufacturing may include some combination of cost, quality, flexibility/responsiveness, or innovation/technology. Structural issues such as number of facilities, degree of vertical integration and choice of process technology need to be examined to see if they are consistent with tactics. Having identified the strategic emphasis, manufacturing can then develop tactics to execute the tactics. These may include cost reduction programs, Total Quality Management (TQM), short cycle time or R&D/manufacturing linking. Proper control and management of the manufacturing process, resources and information are required to carry out tactics. Practices such as TQM, JIT or CIM represent tools or methods that can be employed as tactics by manufacturing. Proper performance measures and feedback loops should be implemented to monitor and continuously improve the strategic planning process.

The following sections will examine product standardization vs. customization, hereafter referred to as sales mix, (Section 2.2.1) as well as order fulfillment time (Section 2.2.2).

2.2.1 Sales Mix

The choice of sales mix, i.e., the level of standardization vs. customization of products, narrows the range of manufacturing environments that a firm can operate in. Generally manufacturing can be divided into Engineered-to-order (ETO), Make-to-Order (MTO), Assemble-to-Order (ATO) and Make-to-Stock (MTS). Companies operating in these different environments have very different characteristics.

Although the choice of manufacturing environment can be a tactical decision, it can also be influenced by the strategic decision to customize or standardize. Increased customization can lead manufacturing toward an ETO environment, just as increased standardization can lead toward an MTS environment. This is illustrated in a

Manufacturing Continuum in Figure 2-1 (Marucheck & McClelland, 1986).

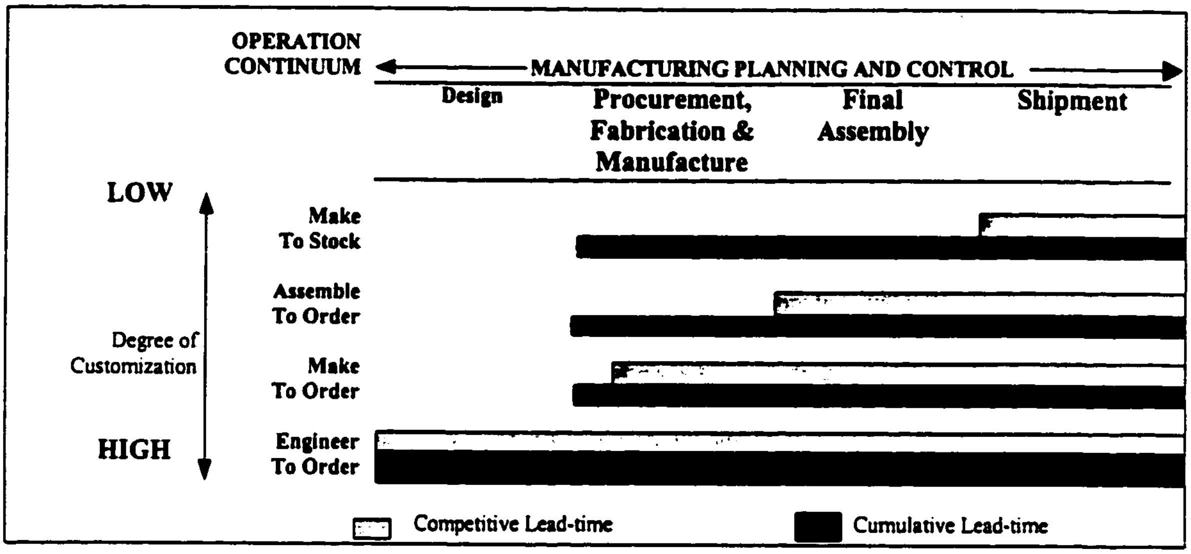

Figure 2-1 A Manufacturing Continuum

As indicated in Figure 2-1, MTS and ETO differ in the timing of customer orders, which reflects in the customer or competitive lead-time. When customers are willing to wait for their orders, production can be based on actual orders. When production lead time is longer than customer waiting time, as may be the case in MTS environments, production must begin with forecast demand (Vendemia, Patuwo & Hung, 1995).

The four manufacturing environments represent six possible decoupling points, each of which implies a different logistics structure, as presented in Figure 2-2 (Zijm, 1992). All planning activities prior to the decoupling point are forecast-driven while the remaining operations are customer-order-driven. For example, in MTS environments, shipments are made from inventory, which is decoupling point DP2. Quoted customer/competitive lead-time is only for picking and shipping and hence procurement and production activities are based on a forecast. Characteristics of the four different manufacturing environments, as they impact time-based competition, will be further discussed in the following section.

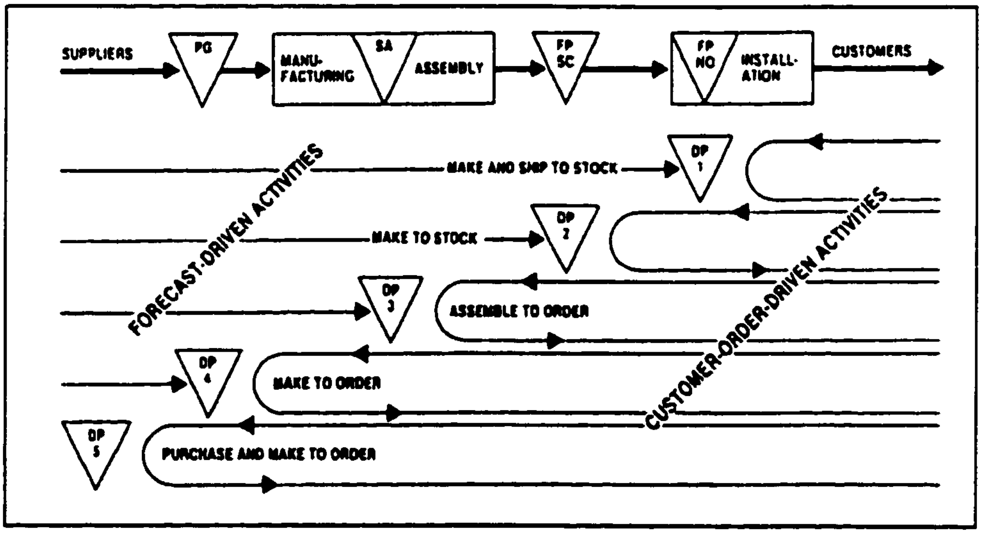

Figure 2-2 **Five Decoupling Point Positions Representing Five Logistic Structures**

2.2.2 Order Fulfillment Time

In most of the literature, order fulfillment time and production lead-time are not consistently distinguished. In this study, order fulfillment time is measured from the moment when a customer requests a quotation, and it includes order entry, design and process development, manufacturing to specification, shipment, and receipt of payment from the customer. As such, it includes production lead-time, which starts with work orders received in the shop and ends when finished goods are sent to store. The relation between these two times are illustrated in Figure 2-3.

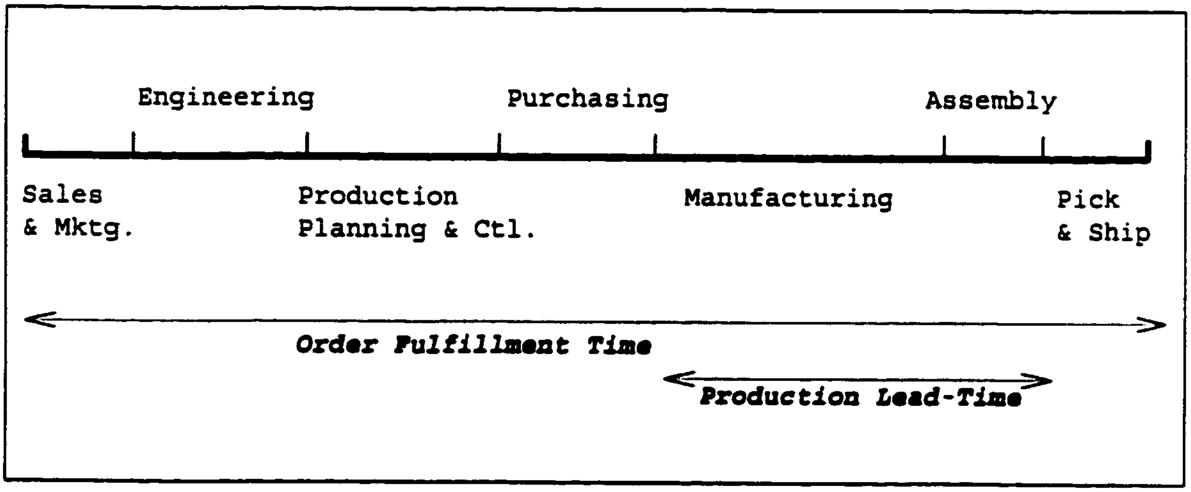

Figure 2-3 Order Fulfillment Time and Production Lead-Time

With the adoption of TQM and JIT, some manufacturers found that they still needed to improve cost, quality, delivery and flexibility. To meet these objectives, the Japanese started to practice order fulfillment time reduction in the mid-1980's and were soon followed by North Americans (Miltenburg & Sparling, 1996). It has since received tremendous attention from both academics and practitioners.

Some literature refers to order fulfillment time reduction as cycle time reduction or as time-based competition. Today time-based competition has become a powerful order-winner (Handfield & Pannesi, 1995). A survey of 212 American manufacturers reported an annual cycle time improvement of 12%, compared with a 10% improvement in Europe and one of less than 6% in Japan (Ehie & Stough, 1995).

For production in particular, long lead times raise costs by causing higher WIP inventory, increased uncertainty of demand, higher safety stocks, increased chances of schedule changes, greater difficulty in coordinating production, poorer performance on due dates, increased risk of deterioration/loss and reduced competitiveness (Karmarkar, 1987). Some of the symptoms of poor cycle time include poor quality, low throughput, falling sales, excess inventory, excess non-value added activities and poor delivery (Donovan, 1995). With cycle time reduction, productivity can be increased, and prices and risks can be reduced (Stalk & Hout, 1990).

Cycle time reduction is rooted in the JIT philosophy, which advocates the elimination of waste. Non-value-added activities are one type of waste, and can be classified into i) quality related activities, including inspection, rework and scrap, ii) inventory related activities, including materials handling, all indirect labor and cost of money, and iii) direct-labor-related activities measured in lost time due to parts shortages, tool unavailability, unbalanced operations, etc. (Funk, 1989). The relationship between lead-times and non-value-added activities can be subtle and controversial. There are cases where lead-time was reduced by adding either non-value-added activities or value-added activities. For example, a circuit board manufacturing plant decreased the number of moving carts, hence increased the 'waste' of material handling time, but production lead time was reduced by 30% due to decreased wait time and WIP (Hopp, Spearman & Woodruff, 1990). Another example is at the Pratt & Whitney's North Haven plant, where one 12-axis blade-grinder was replaced by eight 3-axis grinders, which increased processing time from 3 minutes to 75 minutes, but reduced production lead time by almost 97% due to decreased downtime and setup time (Womark & Jones, 1996).

Stalk and Hout (1990) first coined the term Value Delivery System to analyze the cycle time. An example of such a system is argued for a manufacturer of central office switching gear. This manufacturer's value delivery system involved eight steps. The assembly process, including premanufacturing and manufacturing, consumed only 10 percent of the total duration. The order fulfillment process was composed of four phases and 28 steps which had to be performed before the required parts could be assembled. Including possible loop-backs, when errors occurred or clarification was required, a typical order required almost 100 processing steps. This is a typical example of a manufacturing company that has approximately 90% non-value added activities in its operation (Ehie & Stough, 1995).

Another perspective on elements of business cycle is argued by Ehie and Stough (1995) and Heard (1990). The total business cycle is divided into four distinct, but related business subcycles: the book/bill cycle, the design/development cycle, the specification/source cycle, and the purchase/produce cycle. These business subcycles cover areas that include sales and marketing, design and process engineering, physical distribution, the factory, and the supplier.

The book/bill cycle is the time required to transform an order into a delivery of end products and invoicing. Although most of its activities are non-manufacturing, the book/bill cycle is one of the major competitive factors as it affects the customer's perception of the enterprise's responsiveness. Depending on product(s) and market(s), the book/bill cycle varies in length and complexity: it is much shorter in a grocery store than in an ETO enterprise.

The design/development cycle is the time required to design and develop a new product or modify and improve an existing one. The design/develop cycle can vary enormously in length and complexity. A long cycle can have a major negative impact such as lost market opportunities. This is demonstrated by the findings of the often quoted McKinsey & Company study that is presented in Table 2-1 below (as cited in Vesey, 1991, p. 25). Furthermore, design changes can be costly. For example, an average engineering change order (ECO) in the Electrical/Electronic industry takes 2 months with an average cost of $3,600 vs. 6 months and $12,000 for the aerospace industry (Vesey, 1991).

IF YOUR COMPANY IS LATE TO MARKET BY:	6 mo.	5 mo.	4 mo.	3 mo.	2 mo.	1 mo.
Your gross profit potential is reduced by:	-33%	-25%	-18%	-12%	-7%	-3%
Improve time-to-market by only 1 mo., profits improve	+11.9%	+9.3%	+7.3%	+5.7%	+4.3%	+3.1%
For revenues of $25 million, annual gross profits increases:	+$400K	+ $350K	+$300K	+$250K	+$200K	+150K
For revenues of $100 million, annual gross profit increases:	+$1600K	+$1400K	+$1200K	+$1000K	+$800K	+600K

Table 2-1 Cost of Arriving Late to Market

The specification/source cycle starts during or after the design/develop cycle. It includes the time required to develop and approve specifications of new materials by process engineering and to evaluate and qualify new suppliers by purchasers. Make or buy decisions must be made. Though not as critical as the design/development cycle, the specification/source cycle takes time, costs money and can harm or reduce the company's competitiveness.

The purchase/produce cycle lasts from when the raw material is ordered to when it becomes a part of a finished product.

This includes materials movement, production and inventory planning and control, and manufacturing process and quality inspection. The actual production time is a major element of the purchase/produce cycle. Production interacts with almost every other function of the company. The longer the production cycle, the greater the inventory, which leads to a higher carrying cost. The longer the production lead-time, the less responsive the company is to its customers' requirements.

In order to achieve the shortest cycle time and lowest cost, manufacturers must operate with superb efficiency within the four business subcycles. The degree of importance of each subcycle depends on the type of enterprise as previously defined: ETO, MTO, MTS and ATO. Sales & Marketing, Design and Process Engineering play a larger role in an ETO enterprise. Both customer involvement and engineering activities are increased substantially and the percentage of non-manufacturing workers is larger. Typically the design/develop cycle is much longer and costlier, and resulting designs are harder to produce. There is a tendency for these companies to employ concurrent engineering with cross-functional teams, and to bring in major suppliers during the design phase (Ehie & Stough, 1995; Marucheck & McClelland, 1986).

For an MTO enterprise, all four subcycles play critical roles. Almost all products are custom designed, the production process is non-repetitive, and there are very few interchangeable parts. Most purchased parts, sometimes also raw materials, are procured only after receipt of the customer order. Traditionally, each of the products is regarded as a small project with its own due date, and is organized and run by project management (Ehie & Stough, 1995; Fumero & Vercellis, 1994).

Unlike MTO, an ATO can hold an inventory of major components, subassemblies and materials till receipt of customer orders. The basic design is developed prior to the customer order, but allows customized or standard options at level 1 of the bill of materials. Engineering or product specifications in the customer order will determine the final assembly schedule. Unlike MTO firms, ATO firms can divide their production process into two stages with a buffer inventory in between. The first stage can be an MTS operation with a higher production volume that uses lot sizing and economies of scale. Then products can be placed in a buffer inventory to provide flexibility and buffer against uncertain demand. In the second stage, products are assembled and tested according to customer requirements. Sometimes expensive part(s) are installed at the second stage to decrease the value of the buffer inventory (Fumero & Vercellis, 1994; Marucheck & McClelland, 1986).

In MTS, production tends to be of high volume with dedicated production lines of repetitive processes. Customer orders are shipped from stock. Responsiveness and price are the key competitive strategies used in this market, so that purchasing, manufacturing and distribution are normally well developed for low cost production and efficient distribution. Typically, the other three subcycles are underdeveloped, with cost and quality improvements being overlooked (Ehie & Stough, 1995).

The relative importance of business subcycles in different enterprises can help to identify major opportunities for reducing cycle time. The Short-Cycle Management Principal illustrated in Figure 2-4 highlight such opportunities. Details of the Principal are described in Appendix 1.

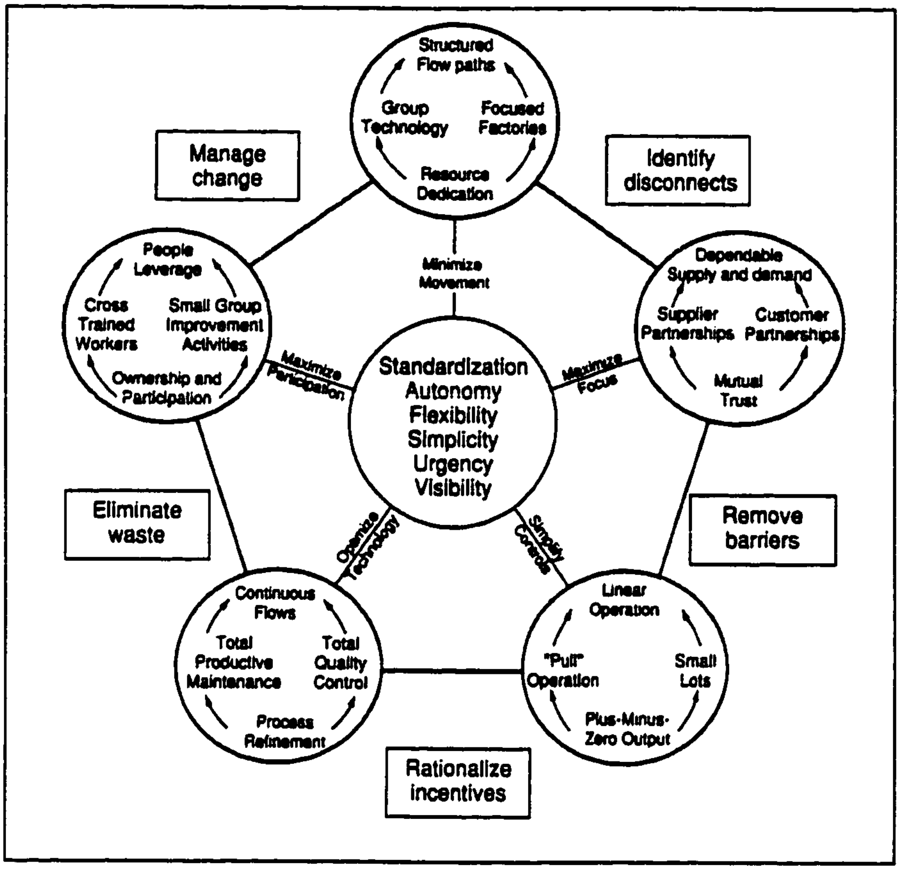

Figure 2-4 **Short-Cycle Management Principles and Action Steps**

While both the relative importance of business subcycles and the Short-Cycle Management Principal help guide cycle time reductions, there is no scientific theory of order fulfillment time reduction. Little is known about the impact of cycle time reductions on different subcycles, nor about the impact of individual subcycle reductions on the factory floor. However, a significant amount of research has been done on production lead-time. Production lead time, sometimes referred to as flow time, is the sum of the following parameters (Hopp, Spearman & Woodruff, 1990).

[illegible] time
processing time) + setup time + move time + queue time + wait-for-parts time + wait-to-move time (E2.1)

The relationship of production lead-time and other operational parameters has been extensively studied. Miltenburg (1993) studied the impact of JIT on cost, cycle time, inventory and quality, and found that the simple one card Kanban produces the same results as the classical two card Kanban. His conclusions are based on a mathematical treatment of the basic elements of a classical JIT system, although there is no evidence that his data were drawn from a real manufacturing system. His work could benefit from being tested in real time, real world conditions.

Another pull system, the Constant Work-In-Process (CONWIP), was found to produce higher throughput than Kanban when there is the same number of cards in the system (see discussion in Duenyas, 1994). In addition, the author has concluded, using his model of throughput and WIP in an assembly operation, that a bottleneck in assembly reduces throughput more than a comparable bottleneck in fabrication. Assuming that all machines have general processing time distributions, he used an approximation based on closed queuing networks to calculate an upper bound for throughput. The model is reported to predict throughput and WIP with great accuracy in a wide range of manufacturing conditions.

Hedge, Kekre and Kekre (1992) studied what they refer to as 'time drivers' - factors which are the key determinants of delays in a manufacturing environment. The main subject of this study is the potential detrimental effect of poor engineering change orders management on production cycle time. The authors also evaluated the interactions between different functional groups such as engineering, quality assurance and purchasing and the effects of response time when these interactions are strained. The setting of the study was a new shop floor control system of a Fortune 500 company. The study focused on the interface between design and manufacturing, specifically, engineering change order (ECO) requests generated while processing a population of 281 standard parts - a standard part being defined as one which had been processed at least once before in the shop. Analysis of data from job cards provided information on the planned cycle time versus the actual cycle time. The job cards also provided information on the product, process and environment, such as the number of operations, number of visits to bottleneck operations and raw material quality.

The main finding of the analyses of data from the shop travelers was that poor management of ECOs was causing excessive delays. It is argued that better management of the ECO process will reduce bottlenecks. For example, a typical order requiring engineering change spends 22 days longer in the shop. It is argued that this extra 22 days can be reduced to 11 days by better management of the ECO process, better control of raw material defects and better routing of jobs to bottleneck machines.

The main assumption of the aforementioned study is that congestion effects are the same for all the bottlenecks that are visited. This is what justifies assigning an equal capacity utilization to all work centers which was necessitated by a lack of data. However this assumption overlooks the fact that an extra visit to a work center with 95% utilization has a higher impact on cycle time than a visit to a machine operating at 90% of its capacity .

Krajewski, King, Ritzman and Wong (1987) developed and applied a composite Manufacturing Simulation System (MASS) to evaluate the merits of the Kanban system in comparison with more traditional US production/inventory systems. The MASS is a combination of three computer programs, namely a Bill of Material Generator, an Input Generator and a Discrete Event simulator. The discrete event simulator can accommodate 250 inventory items and 250 work stations and is capable of analyzing practically any manufacturing discrete lot environment. The MASS was validated by testing data from a real plant environment involving 13,000 inventory items, 800 workstations and 233 employees. Seventy-eight aggregate inventory items and work stations were defined and data were collected on bills of material, work station configurations, routings, lot size policies, processing time, etc. Four simulation experiments were performed in order to successfully validate the MASS program.

A panel of managers replied to a detailed questionnaire on the factors that are important for their respective manufacturing control systems. The factors were then grouped into the following clusters: customer influence, vendor influence, buffer mechanisms, product structure, facility design, process, inventory, and other factors. It was found that the factors of most importance for US manufacturing environments were lot sizes, set-up times, yield losses, work force flexibility, degree of product customization and product structure. A conclusion of this simulation study was that the Kanban system is not critical to improvement. It is only one approach within a general manufacturing philosophy designed to reduce inventory, improve productivity and service to customers.

Offset lead-time used in MRP or MRP-II is calculated by multiplying processing time and the number of units in a batch. This implies that lead-time is a function of batch size only. This fixed offset lead-time is machine independent and does not reflect process factors such as sequencing, work load and set-up time plan. This approach produces an unrealistic MPS and a highly distorted capacity planning function, as argued in Pandey & Hasin, 1996. The authors examined two process scenarios. First, a single-line production shop for a family of parts produced sequentially in batches, following identical operations and sequence. This is a dedicated production line processing only one batch at a time. In the second case, the manufacturing system has several lines, each dedicated to a family of parts. The following assumptions are made: a) production on the bottleneck machine cannot be moved to another machine; b) set-up time is very short; c) only one batch is processed over the planning period. The study concludes that manufacturing lead-time should be based upon shop routing and design rather than on standard Bills of Materials.

Tatsiopoulos and Kingsman (1983) view manufacturing lead times as a function of high level decisions within the firm and of the interaction between the marketing and production systems. They argue for closer integration of these two systems and point out that delays and backlogs are not necessarily the result of poor operations management. The authors suggest a production system with backlogs controlled by input/output and a heuristic algorithm for due date assignment and shop order release decisions. However, he authors also indicate that the system proposed is only suitable for small companies where communication between functional areas is easier. It is not clear how their approach would work in a larger organization.

Zijm and Buitenhek (1996) point out that lead times are directly related to machine utilization rates and recommend an approach which considers work-load-dependent planned lead times. The mean lead-time from rough queuing analysis is combined with aggregate scheduling procedure to calculate work-load-dependent planned lead times. Release and due dates determined by capacity planning are inputs to detailed shop floor scheduling. Product streams arriving and departing from workstations are assumed to follow the Poisson distribution. Further assumptions in the model are that: a) a batch of product is completed before moving to another processing operation; b) that no product is scrapped; c) lead times at different processing steps are independent.

Process plan selection is a production tactics studied by Seo and Egbelu (1996). With this tactic, the use of multiple static process plans in a dynamic batch production environment is possible. From multiple process plans, a suitable plan can be selected depending upon the part mix and required production volume for simultaneous processing in the shop. This flexible process approach requires assumptions about how materials handling systems deal with increased requirements. For the model presented, it is assumed that an Automatic Guide Vehicle (AGV) delivers one load at a time. This assumption underlies the mathematical model and affects approximations of travel time and of distances traveled to move parts.

Chakravorty and Atwater (1995) examine the relative merits and performance of the traditional line balancing approach and the more contemporary JIT. Using a 2x2x8 (32) factorial ANOVA with pair-wise comparisons, the authors studied relative cycle time performance of two production lines operating under line balancing and JIT approaches. Within the treatment of data, Mean Time Between Failures (MTBF) is assumed to follow an exponential distribution and the processing time was modeled as a lognormal distribution. The data analysis shows that the cycle time performance of JIT is superior to that of line balancing when system variability is low. It was also found that when inventory in the system is low, the balanced lines perform better than JIT lines. The reverse is true when inventory in the system is high.

A simulation model developed using XCELL+ by Spedding, Desouza and Tan (1996) was used to study the effects of product mix on a high volume assembly line. Since XCELL+ does not model conveyor operations, the authors developed what they claim is a realistic model of a conveyor system. Batches were assumed to be of fixed size and to be produced without a start up period. The first simulation experiment dealt with a condition of overlapping production. The second looked at overlapping production but with the order of product reversed and a final study ran the consecutive products with no overlap. Five different products were involved in the study in batch sizes from 1,000 to 7,000.

The results show that an improvement of up to 16% in line capacity can be obtained, depending on product mix. The order in which products are manufactured showed a significant effect on line capacity. Running the larger batch first had increased production rate. Grouping of similar product affects how work centers are utilized and contributes to achieving minimum idle time.

Purpura (1994) studied line pacing based on a scientific analysis and management of the line. The time required to process units to meet customer requirements is calculated and adjusted to allow for human factors and unplanned stoppages. Based on the physical dimensions (height, width and depth) of the product and the space needed by operators, the production line is visibly marked out by lines. The products travel within the space between the marked lines. This permits line workers a degree of predictability about when and where the next product will arrive. The author claims that these line pacing measures, along with proper operator training and communication measures, increased hourly capacity by 16%, reduced rework on the line by over 60% and reduced the cycle time by almost 14%. An 8% reduction in direct labor costs was also achieved. While the author does not state any assumptions, he seems to have assumed that the manufacturing system is not subject to machine and many other disturbances that often occur.

The management of lead times involves much more planning than is required to guide orders through the shop floor. The use of input/output control methods is recommended to control the overall order fulfillment time for ETO companies (Kingsman, Tatsiopoulos & Hendry, 1989). The process of managing order fulfillment must start as early as the customer order enquiry stage. The management objective must be to ensure that order backlogs and overall delivery lead times conform to acceptable standards.

A simulated JIT manufacturing system was developed to assess the effects of sequencing on productivity (Lummus, 1995). The simulation examined the effects of adding a second product to the line along with the associated set-up or processing time. A range of sequence and product mix combinations were investigated. The simulated production system consisted of three assembly lines with a total of nine workstations. Some workstations draw raw materials from stores while others combine sub-assemblies with purchased parts. The finished product then moves to a finished goods queue. The simulation assumed that work is completed before it can move to an adjoining workstation. Assembly times are assumed to follow the normal distribution. Production is Kanban driven and each workstation has only one processing machine. It is also assumed that no time is lost due to breakdown, that there are zero defects and bringing in a second product to the workstation incurs a significant increase in processing time.

The simulation results show that sequencing improves throughput in JIT environments and that an increase in set-up time has a bigger impact on throughput than a comparable increase in processing time. When added set-up time due to a second product exceeds certain limits, the workstation processing the second product controls the output of the line. However, if the added set-up time does not exceed 5% of the processing time of the standard product then there is no effect on performance. The author also concludes from the findings of the simulation study that simply allowing demand to trigger production improves performance more than a fixed schedule of production.

Zangwill (1987) applies a mathematical simulation based on a series of algorithms to model Economic Order Quantity (EOQ) and Zero Inventory (ZI). Although these concepts of EOQ and ZI are intuitively accepted as offering advantages in manufacturing systems management, the author claims that there is little mathematical evidence for this. The simulation results lead him to propose that these concepts may not always be applicable and may even produce misleading results. It is argued that in a non-stationary environment, set-up cost reduction may not reduce inventory cost or overall production cost. A case based on a mathematical model is made where investment in set-up reduction yields increasing marginal economic returns. It was pointed out that this finding is contrary to the economic theory of decreasing marginal returns from increasing investment.

Equations for calculating production lead-time using queuing theory are presented in the literature (for example, Lynes & Miltenburg, 1994). As production lead times are reduced, the number of potential stockouts increases. Furthermore, it is mathematically proven that production lead-time reduction will reduce costs in environments with stochastic demand (Vendemia et al., 1995). As demand forecasts shows greater variances as one goes further into the future, inventory variances at delivery time also increase. The variance, as well as the mean, of production lead time also impacts inventory. Based on the Little's Law, it is postulated that the average WIP and F/G stock increase linearly with the standard deviation of flow time for a given level of throughput and service (Hopp et al., 1990).

2.3 PERFORMANCE MEASURES

The fundamental use of performance measures is to change behavior and support execution of the company's strategic objectives. These measures help all employees focus on the same goal. To be effective, performance measures should be a part of the organizational design (Beckman et al., 1990). In most enterprises, financial indicators are used to measure performance with an emphasis on cost. Cost accounting was developed during the industrial revolution in order to understand product costs and to help establish selling prices. Over time, it also came to be used for inventory valuation, performance measurement and analysis. In the standard cost accounting system, overhead was allocated based on estimated direct labor, which was satisfactory in the past when direct labor was a major expense, overhead was relatively low and technology was relatively simple (Toomey, 1994; Schmenner, 1990). Today, even though direct labor cost is one fifth to one tenth of indirect costs, 75% of cost data is still related to direct costs (Meyer, 1993). Thus traditional cost data can be misleading, resulting in poor decisions if such decisions were based on this information alone. In recent years, many have advocated the use of activity-based accounting (see discussion in Toomey 1994) and throughput-time accounting (see discussion in Schmenner, 1990). Non-financial measures should also be part of performance measurement for factors such as customer service, productivity and quality.

Time-based enterprises focus on time more than on cost and often benchmark their operations against either the best practice or their leading competitor(s). The following table compares performance measure criteria of traditional and time-based enterprises (as cited in Stalk & Hout, 1990, p. 189).

Traditional Enterprise	Time-based Enterprise
Cost is the metric	Time is the metric
Look to financial results	Look first to physical results
Utilization-oriented measures	Throughput-oriented measures (Uptime X Yield Rate x # of Stations)
Individual or departmental	Team measures

Table 2-2 Performance Measurement Criteria Comparison

Time measures force analysis down to physical and activity levels. It also motivates managers to focus and find areas and ways to reduce lead-time. However, most results can only be temporarily observable and benefits cannot be systematically incorporated into common financial measures such as profits or contribution margins. Examples of performance measures used by six companies for controlling and monitoring lead time performance are presented in Table 2-3 (Lockamy, 1993).

Function	Measure
Product Design	Application engineering response time to customer requests
	Average engineering change notice (ECN) backlog
	Bill of Materials (BOM) accuracy
	ECN throughput rate
	Engineering hours per project
	# of days to process non-standard product requests
	# of ECNs completed
	% of new products or options introduced in past 2 years
Procurement	# of vendor delivery errors
	Part shortages due to vendors
	% of defect-free vendor deliveries
	% of on-time vendor deliveries
	Vendor lead time
Manufacturing	Average changeover time
	Internal delivery performance
	Manufacturing cycle time
	Master production schedule (MPS) deviations
	# of preventive maintenance jobs completed per shift
	Plant run time
	Scheduled versus unscheduled downtime percentages
	Scheduled versus unscheduled maintenance percentages
Distribution	Average number of days late
	On-time customer delivery percentage
	Shipment accuracy percentage
	Shipping schedule variances
	Stock service level percentage

Table 2-3 Performance Measures used for Individual Function

It is argued in Meyer (1993) that cycle time measurement system should be based on the following four principles: i) *clear and graphical information* that people can absorb quickly, ii) *timely* reports that can help detect and correct errors early and should be easily accessible, iii) *illuminate process drivers* by using the minimum number of elements required to control the enterprise, rather than comprehensive measures that cause people to lose sight of company strategy or operations, and 4) *easy-to-use*.

2.3.1 Inventory Measures

Inventory represents one of the major costs of capital and has long been used as a performance measure in enterprises. Today, inventory control remains a complex problem that is still not completely understood.

Very often, inventory is classified as raw material, work-in-progress and finished goods. Some ATO enterprises further break down WIP into WIP and semi-finished goods that are parts that are ready to be assembled. The most commonly used inventory measure is the inventory turnover (i.e. sales÷inventory). Inventory dollar value is also part of current assets in the return on equity (ROE) equation shown below. ROE and the company's growth rate are critical to the company's share price.

ROE [illegible] asset
turnover [illegible] Revenue÷Assets) × financial
leverage [illegible] (2.2)

American business school, operations research and industrial engineering departments have long been studying and optimizing inventory models. The first classical model of inventory control was the economic order quantity (EOQ) model which was first formulated by R. H. Wilson in 1934 (Chikan, 1990). Today, new books regularly appear on the subject of inventory control and papers on the subject are published routinely in scientific journals. A study done by Meredith and Mamoako-Gyampah (as cited in McLaughlin, Vastag & Whybark, 1994) reported that approximately 20% of the sample doctoral dissertations was on inventory control plus another 20% on scheduling and forecasting.

A study of 20 manufacturers (as cited in Greis, 1994) showed that they carried large quantities of inventories in a wide range of products and yet none of their managers used formal analytical techniques for inventory control. These examples suggest that most inventory models may not be used in industry. This may be partly due to the lack of realistic problem formulations in the models (Moon & Choi, 1994). It may also be because most of these models are not industry specific and most research on the models is done only for MTS environments (Kingsman, Worden, Hendry, Mercer & Wilson, 1993). The widely renowned techniques of MRP-II and JIT do not completely solve the problem of managing huge amounts of inventory with a large number of uncertainties and variables. We may conclude that the field of inventory control still has many research opportunities but requires a fresh approach (McLaughlin et al., 1994; Moon & Choi, 1994). New research might focus on attaining a much greater understanding of the environments in which inventory models are used. Only then would it be possible to develop models that managers will use. Researchers should also consider the trade-off between the complexity of inventory models and their effectiveness.

Inventory is the device that most manufacturing enterprises use as a buffer against variability and uncertainty in demand, supply, workforce and equipment. Inventory level is also a by-product of optimizing production runs and purchasing economic lot sizes. This is done to balance set-up and holding cost with the use of the EOQ/POQ formulas. However according to JIT principles, inventory is one of the operational wastes (Cook, 1996).

Inventory is visible as raw material, work-in-process and finished goods; and invisible as money spent well in advance of a given subcycle, for example, product development cost. Regardless of whether inventory is visible or invisible, it can be shown to decrease as production lead time decreases, according to the following two equations (Heard, 1990).

Average [illegible] in Process = Production Rate × Cycle Time (E2.3)

Average Dollars in Process = Average [illegible] per Process [illegible] / Average Cost [illegible] (E2.4)

As discussed in previous sections, both MTS and ATO enterprises are subject to higher unpredictability of market requirements than ETO and MTO enterprises. Hence there is a tendency to keep a larger safety stock in both MTS and ATO environments.

Numerous reports have stated that JIT helps to decrease inventory and increase service level, although some claimed that JIT merely displaces inventory to the supplier's facility (Duplaga, 1990; Vastag & Whybark, 1993). Based on a simulation study, Krajewski et al. (1987) reported that while the Japanese Kanban method is not a crucial factor, other factors embraced by the Japanese approach do help to reduce inventory. The most crucial ones are minimal lot sizes and reduced set-up times. Some other factors are increased yield rates, worker flexibility, increased product standardization and simplified product structure. The simulation study showed that inventory record accuracy as well as equipment and vendor reliability have little effect in reducing inventory.

The shop floor control theory and Little's Law (see discussion in Hopp et al., 1990) support the observation that as production lead time increases, work-in-process inventory increases (Karmarkar, 1987; Vastag & Whybark, 1993). Most researchers would agree that when raw material inventory increases, there is less chance of production line stoppages and hence a possible reduction of production lead-time. Likewise, with increased finished goods, there will be a better chance of servicing customers from stock, hence the lead-time for distribution may decrease and service level may increase.

There are quantitative models for determining the appropriate level of WIP inventory, among which is Conway, Maxwell, McClain and Thomas (1988). Under certain assumptions, mathematical models do exist for establishing the safety stock level that will achieve a desired service level, and for evaluating trade-off between service and costs (Greis, 1994).

2.3.2 Service Level Measures

As with inventory, service level is another commonly used measure in assessing performance. In this section, most commonly used service measures will be presented. While customer service may cover a wide spectrum, such as after sales service and maintenance contracts, we will use the APICS definition and concentrate mainly on the relation between inventory and service level. The tactical role of service level in relation to marketing tactics will be discussed, along with the problem of obtaining clear information for use in managing the service level.

Service level and inventory measures are closely related. The three most frequently used service measures in the past were: i) the α-service-level which is the probability of not being out of stock at any given time, ii) the β-service-level which is the fraction of demand which is not being lost or backordered per unit time, and iii) the γ-service-level which takes into account, not only frequency and amount of stockout, but how long the stockout lasts (Schneider, 1981).

Both TQM and JIT, which were introduced in North America in the 1980's, promote a customer-oriented philosophy. This is reflected in the new definition and calculations of service level. Service level is defined in the APICS dictionary as: '*A desired measure (usually expressed as a percentage) of satisfying demand through inventory or by the current production schedule in time to satisfy the customers' requested delivery dates and quantities.*' (Cox III, Blackstone & Spencer, 1995, p. 43).

A number of mathematical calculations of service level exist and different manufacturing environments use different formulas. For MTO, ATO and ETO environments, service level is the percentage of the time products are shipped on the customer's required or acknowledged date. For most MTS environments, service level is the percentage of the time products are shipped, from stock, upon receipt of the customer's order. Both measurements can be calculated based on complete or partial order shipments, and unit or dollar value. The six most common service measures are presented in the following table (Boylan & Johnston, 1994).

O_c = Proportion of orders filled completely

O_p = Proportion of orders filled (at least) partially

L_c = Proportion of order lines filled completely

L_p = Proportion of order lines filled (at least) partially

U = Proportion of units (quantity) filled from stock

V = Proportion of units ($) filled from stock

Table 2-4 Six Most Common Service Measures

Service measures may change over time, vary among divisions, or may need to be reconciled during centralization. In any of these three situations, a relationship between the old and new measures must be found in order to help set new targets. Boylan and Johnston (1994) presented mathematical equations for relating the six measures in Table 2-4 above.

As mentioned above in the APICS definition, customer service involves satisfying the customers' requirements. It does not take other aspects of service into account. The trade-off between customer service and its cost can be expressed mathematically and a sample curve is presented in Figure 2-5 below.

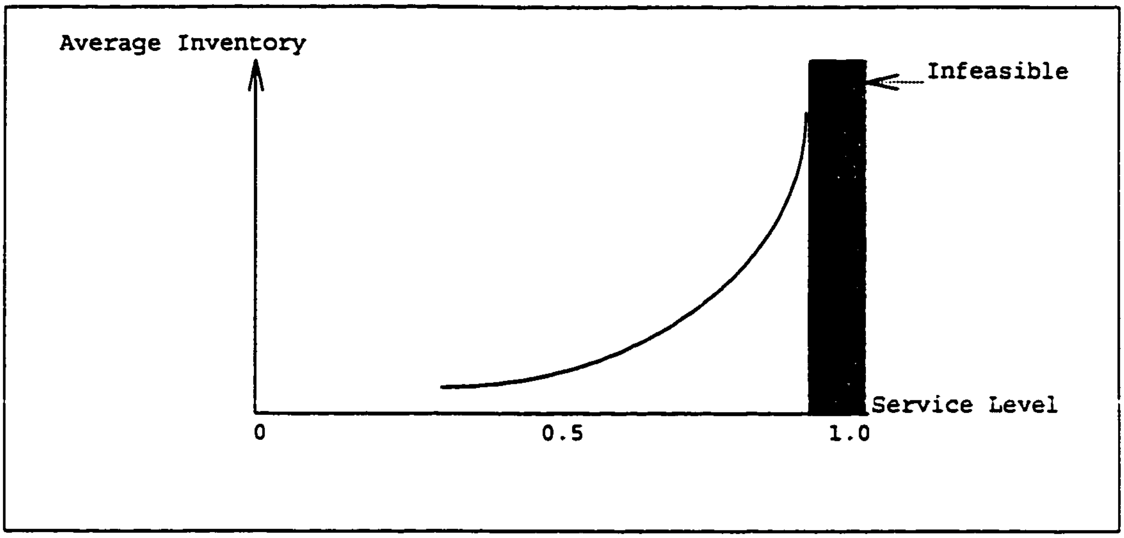

Figure 2-5 **Sample Service Level Curve**

In addition, the cost of service level can be indicated by the effectiveness of internal and external processes and management's skill in reconciling conflicting objectives. Greis (1994) developed a cost function of reliability curves for MTS environments.

Figure 2-5 presents a model, the associated equations of that are often quoted in standard Production and Operations Management textbooks. Although increased inventory used to be viewed as a necessity for improving service level, the Japanese have proven that a high service level can be achieved with lower inventory by using JIT.

Since service level decisions are considered to be tactical, they must be subordinated to the marketing tactics. For example, customer service level is one of the means available to improve market share. However, service level must be managed through a tradeoff of its cost against the benefit to the company. There is a trade-off between supplier and customer costs. The quantification of this trade-off provides an essential input to the development of the marketing tactics.

In managing the customer service level, a certain amount of ambiguity is inevitable. Market information is difficult to obtain and may be inexact. Internally, managers are tempted to restrict customer service level improvements to their own area of responsibility. Further refinements to marketing tactics involve the customer's buying pattern. Relatively infrequent purchases (once or twice per year) repeat buyers and longer-term partnership relations with customers will all require different approaches to the customer service level. The quantity and the quality of information, which is available to the supplier, increases as we move from incidental purchasing to repeat buying to partnership. With adequate information, the customer service level can be designed, delivered and subsequently measured for scientific improvement. In the case of partnership agreements, open sharing of information becomes possible.

2.4 SUMMARY

The American manufacturing sector has gone through many changes and the journey through successive improvement techniques has been a long one. Countless models are available for statistical inventory control, yet very little is known about managing complex manufacturing environments and much work remains to be done to achieve excellence in manufacturing planning and control.

In our efforts to find proper techniques or combinations of techniques for production and operations management, we should not forget to balance technology, organization and human factors. As most researchers recommended strong leadership in implementing different techniques, we can infer the need for better management of change or for alternative and superior change agents. In today's highly complex environment, there is a need for managers with a different and larger set of personal attributes (Hout, 1996).

The outstanding achievement of the Japanese in the 1980s showed us that '(the Japanese) without the benefit of formal training and experience with mathematical inventory models,' (Kaplan, 1983, p. 691) were able to re-invent the rules of competition. Maybe now is the time for Western managers to begin to think creatively.

Time-based competition is almost ten years old now and research (as cited in Hitomi, 1996; Vastag et al., 1994) indicates that the Japanese are working on increased flexibility and faster new product development. Globally, there is also an increasing concern about environmental issues and social responsibility, which managers must also take into consideration.

3. MANUFACTURING SYSTEM

The Mechanical Engineering Department of McGill University in Montreal, the Integrated Manufacturing Technologies Institute of NRC in Ottawa and ABC's Montreal plant are jointly developing a shop floor model for ABC's Montreal plant. The model will be used by McGill University as a teaching tool for its new course in Computer Integrated Manufacturing, by the NRC as a test bed for integrated solutions, and by ABC as a tool to study the impact of different operations tactics. The shop floor model is developed with the use of ProModel, a Windows based PROduction MODELer for manufacturing simulation with animation capability.

The simulation project consists of a series of distinct phases. Because the current study is part of the initial phase of the project, only Assembly Line 1 is being modeled. At a later phase, the current manufacturing model will serve as a generic line that can be modified to simulate lines 2 to 5 by incorporating data specific to these lines. The features of the generic line will also be used to model a planned sixth assembly line.

3.1 EXISTING SYSTEM

There are 27,000 part numbers at the ABC Montreal plant, for raw materials, semi-finished goods and FG. The company manufactures 3000 end items on 5 assembly lines in standard lot sizes of 7. Not all end items are manufactured on just one line, since some lines share manufacturing equipment. For example, some parts are put through the automated portion of Line 1 where there is excess capacity and then are finished on other assembly lines.

A typical production line involves a series of automatic component insertions onto printed circuit boards (PCB), followed by soldering and then a series of assemblies and tests. As some testing equipment is extremely expensive, some lines share testing facilities, e.g. In-Circuit testing. Line 1 has a typical arrangement with integrated testing facilities. The detailed processes of line 1 are presented in Figure 3-1.

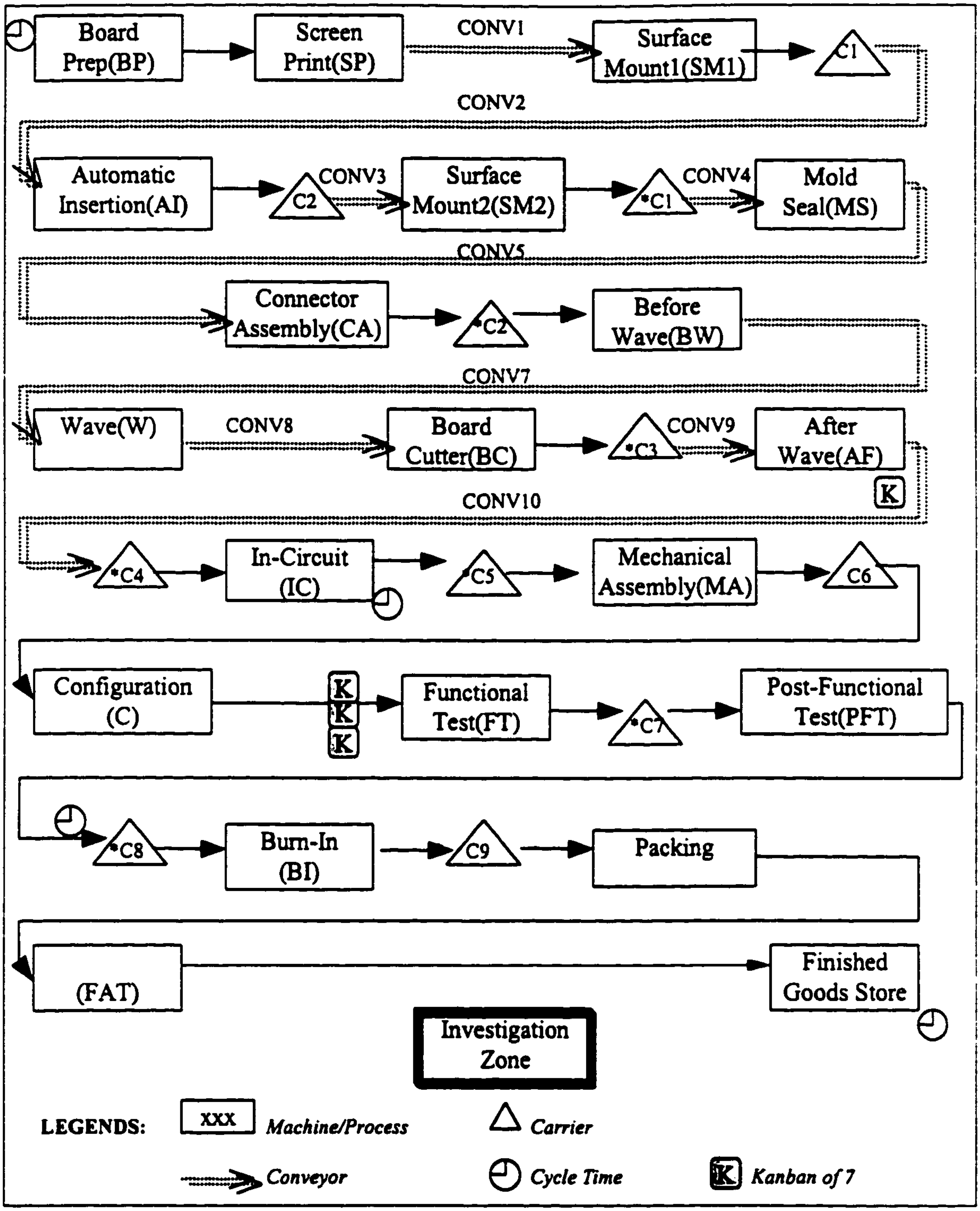

Figure 3-1 Detailed Processes of Line 1

As illustrated in Figure 3-1, the automated operations for component insertions includes Board Prep (BP), Screen Print

(SP), Surface Mount 1(SM1), Automatic Insertion (AI), Surface Mount 2(SM2), Mold Seal (MS) and Connector Assembly (CA). Soldering operations consist of Before Wave (BW), Wave (W)(soldering), Board Cutter (BC) and After-Wave (AW). Assembly and test operations includes In-Circuit Test (IC), Mechanical Assembly (MA), Configuration(C), Functional Test (FT), Post-Functional Test (PFT) and Burn-In (BI). BI, also called Environmental Test, is the most critical operation, as it is the bottleneck of the whole assembly line. Furthermore, the processing time at each of the nine ovens at BI is extremely long, ranging from seven to 11 hours each. Thus, the nine ovens start at different times to allow for flexibility in producing priority parts. For some customers, Functional Acceptance Test (FAT) is required on products after BI. The Investigation Zone is a rework area that is isolated from other processes.

Manufacturing at ABC follows both push and pull policies. Central Planning supplies manufacturing with a weekly production plan that is generated by Manufacturing Resource Planning (MRP-II). Production is started, based on the production plan, and blank boards are pushed from the start of the line to just before Functional Test. The boards are then pulled by actual customer orders from Configuration to the end of the assembly line.

Kanban carriers are used to allow accumulation of WIP in front of the machines. Following After-Wave, boards are grouped into Kanbans, in lots of 7, of the same family and kept intact till Post-Functional Test. Right before Functional Test there is a series of Kanban carriers. This is where most semi-finished goods are stored. When a customer order is received, parts are pulled from these Kanban carriers for completion of the product.

3.2 GENERAL FEATURES OF SIMULATION MODEL

Most real world production systems are quite complex, as in the case of the ABC Montreal plant. The complexity of the system precludes simple mathematical analysis. Simulation is the most widely applied technique for scientific analysis of complex systems and is used for this study. A simulation model was built in ProModel and used to test the behavior of ABC's production system under various operation tactics.

ProModel is a Windows based PROduction MODELer intended primarily for discrete manufacturing systems. It has many features to provide flexibility and convenience for modeling production facilities and related activities. For example, input data such as scheduling data, can be created in other Windows application(s) and read directly into ProModel. ProModel uses a Graphical User Interface (GUI) operating environment, which allows for animation of the system to appear on the screen during a simulation run. Simulation outputs on system performance, such as machine utilization, productivity and inventory levels are available and can be graphed. This modeling and simulation tool was used for all the simulation runs of the production facility. Output data from the simulations provided the basis for statistical and managerial analyses carried out for this study.

Due to time constraints in this initial phase of the project, it was decided to use Assembly Line 1 as the shop floor model in ProModel, since it is a typical line. Line 1 is modeled in detail as described in the previous section. Kanban carriers located between processes with the standard lot size of 7 were also modeled to allow for the accumulation of lots after each workstation. The flowchart representation of the simulation model appears in Figure 3-1. A graphical representation of the model used in ProModel is presented in Appendix 2.

As indicated by the graphical model in Appendix 2, the simulation model matches the series of operations shown in Figure 3-1. Some workstations that use multiple machines/operators can be identified in the graphical model. For example, there are 11 workbenches for the BW operation and nine ovens for the Environmental Test operation. Counters are added, some for program verification and others for tracking parts. For example, six counters are listed under Failed Boards to track the quantity of non-conforming boards for the six product groups. A discussion of the product groups is presented in subsection 3.2.1. Conveyors are added to include transport and associated traveling time of parts between workstations. Major components and operational characteristics of the simulation model will be described in the following subsections, 3.2.2 and 3.2.3 respectively. The 27,000 distinct parts at ABC are grouped into 36 categories, as described in the following subsection.

3.2.1 Product Grouping

Each individual part in ProModel needs to be modeled as an object with specific characteristics and processing times at each workstation. If all the current 27,000 distinct parts were modeled, the simulation program would be enormous with 27,000 distinct objects. Furthermore, program run time would be very long as each part would have to be tracked through the system during a simulation run. To reduce both the size and the run time of the simulation program, the number of parts considered had to be limited. After consultation with the management at ABC, it was decided at the beginning of the project that all raw materials (RM) were to be grouped into 24 categories, and that all finished goods (FG) items were to be grouped into 12 categories. These 36 categories represent the 27,000 distinct parts currently used at the ABC Montreal plant. Common parts that are used in several product categories, are put into the category where they are most frequently used. Details and mechanics on grouping of RM and FG are given in Appendix 3.

Of the different product categories, only PRODUCT A, PRODUCT B, PRODUCT C, PRODUCT D and PRODUCT E are qualified for the FG status on Line 1. The PRODUCT F and PRODUCT G categories are partially assembled on Line 1 and are included in the simulation from Board Preparation to Connector Assembly. This is done in order to represent the usage of the corresponding workstations by PRODUCT F AND PRODUCT G.

3.2.2 Major Components

The major components of the simulation model are as follows:

1. Products: The system produces 7 families of products. PRODUCT A, PRODUCT B, PRODUCT C, PRODUCT D, PRODUCT E are manufactured to completion. PRODUCT F and PRODUCT G are produced to a semi-finished state.
2. Workstations: The shop floor model comprises 19 workstations, of which 8 are multi-units. The workstation at Functional Test consists of 18 units.
3. Carriers: These represent Kanban carriers with a standard lot size of 7. Boards are grouped into lots of 7 after automated operations and kept together up to Post Functional Test.
4. Conveyors: These are modeled to represent the physical distance between workstations. Traveling speeds are modeled and traveling times are then calculated by the program.
5. Work in Process (WIP): Each station has its own processing capacity. Accumulation of inventory between workstations is made possible by the use of carriers.

6. Finished Goods (FG): Parts produced from the system are considered as throughput and referred to as FG. FG inventory in dollar terms is calculated from the throughput and used as a performance measure. The method of calculation is described in Section 4.2 and the equation for calculation is presented in E4.1.

3.2.3 Operational Characteristics

A description of the existing manufacturing system at the Montreal plant is presented in Section 3.1. Major operational characteristics and parameters of the existing system are modeled as follows:

1. Production is triggered by a predetermined requirement of the production plan on a fixed time schedule. Data is derived from historical production plans.
2. WIP is pulled in predetermined quantities in line with customer orders, every 12 hours. Customer order data are derived from historical sales figures.
3. Production is run on 3 shifts, 7 days a week with appropriate scheduled employee breaks.
4. Simulation is initialized with a number of parts already at various workstations to ensure that the nine ovens will start at different times, as in actual operations at ABC.
5. Each product family has its own route and a different processing time, and most product families follow the same sequence of workstations every time except for PRODUCT F and PRODUCT G. Process times are presented in Column C to Column I of Appendix 4.
6. The scheduling rule used is first-come-first-served (FCFS).

7. Setup is required at most workstations when a new product family is being processed. Each workstation is assigned its own setup time. Data is presented in Column B of Appendix 4.

8. Non-value added (NVA) time, i.e., queuing time, is modeled at 21 locations, exponentially distributed with mean values ranging from 72 minutes to 42 hours.

9. Breakdowns are modeled on machines SM1 and SM2 following normal distributions.

10. Defective parts occur at various workstations and are reworked at the Investigation Zone. Scrap rate is taken to be zero.

11. At ABC, some machines perform similar tasks in a serial manner one after the other. They are grouped together and modeled as single workstations in ProModel. SM1 in ProModel represents a group of four machines, AI represents a group of 3 machines and SM2 represents 2 machines. This grouping does not allow for collecting statistics on individual machines within a group, to rearrange individual machines physically, or replace/upgrade specific machine(s).

3.3 MAJOR ASSUMPTIONS

The following list shows the major assumptions that were made for the simulation program. These assumptions were discussed with ABC management and deemed by them to be reasonable assumptions.

1. Raw material is assumed to be unlimited. Receiving and incoming inspection times are assumed to be zero. Hence, the first workstation never runs short of material.

2. Raw materials are divided into 24 categories, and finished goods are divided into 12 categories with the following assumptions for each category:

    - All parts in a category are treated as a single entity in ProModel. Specific ABC parts cannot be traced within the model.
    - All parts in a category carry the same cost, based on a weighted average of standard costs.
    - All parts in WIP are valued at 50% of FG cost.
    - After Post Functional Testing, boards are considered as FG.

3. All boards in production are processed in the order of arrival at the machine, i.e., first-come-first-served.

4. New product introduction is not included in the models because it represents an insignificant portion of production. Hence, it is assumed that Line 1 is not used for testing or production of new products.

5. With the current growth in demand in the electronics sector, it is assumed that all goods produced can be sold.

6. As only Line 1 was modeled, other lines are assumed to have enough capacity to supply Line 1 with all the PRODUCT F and PRODUCT G boards it requires to operate without delays.

3.4 MODEL VERIFICATION AND VALIDATION

During the program development phase, trace statements which track the logical sequence of specific subroutine(s) were added to help debug and verify the program. Also added were debugging tools such as the trace function which follows events step by step during a simulation run to verify that the completed program performs as intended.

Extra variables and counters were added to verify the performance of the program. For example, Failed Boards counters were used to verify that the number and proportion of failed boards is appropriate. Information on cycle time is collected at three locations to ensure that the cycle time generated by the simulation model reflects the existing system.

Model validation was carried on throughout the entire project with the joint participation of ABC staff and the model development team. The animated simulation model was presented to the client several times during the model development phase. The final model was validated by comparing simulation output data to the actual throughput, cycle time and utilization rate of machines at ABC. The model was considered credible by ABC management.

4. RESEARCH METHODOLOGY

4.1 SIMULATION RELATED ISSUES

As with most simulation programs, it is necessary to decide on initial conditions for the simulation run(s), the length of transient period (if any), the length of simulation run(s), the use of random number streams and the number of independent simulation runs, i.e., replications.

Initial conditions for each simulation are such that certain workstations are filled with a predetermined number of parts to ensure that the 9 Environmental Testing Ovens will start at different times to reflect current operations. As the detailed breakdown of WIP quantity at each workstation at ABC is unknown, the remaining workstations in the model were arbitrarily chosen to have no jobs present at simulation time zero. When the simulation starts, not all workstations start simultaneously so average WIP quantity will be too low and not be representative of the actual conditions at ABC. This is also true for both cycle time and throughput, where cycle time is the average time required to manufacture boards and throughput is the number of boards that are completed in a certain time. As indicated in Figure 4-1 and Figure 4-2, both cycle time and throughput start with very low values. Cycle time and throughput slowly increase from simulation time zero to 250 hours when they begin to level out. If results, such as cycle time and throughput, were collected from the beginning of the run, the low start-up values would bias the overall average. A transient period, i.e., warm-up time, is therefore required to remove this initialization bias. A transient period allows the simulation to run for a predetermined time to reach steady state prior to collecting statistics. This is done to ensure that the arbitrary choice of initial conditions will no longer affect the results.

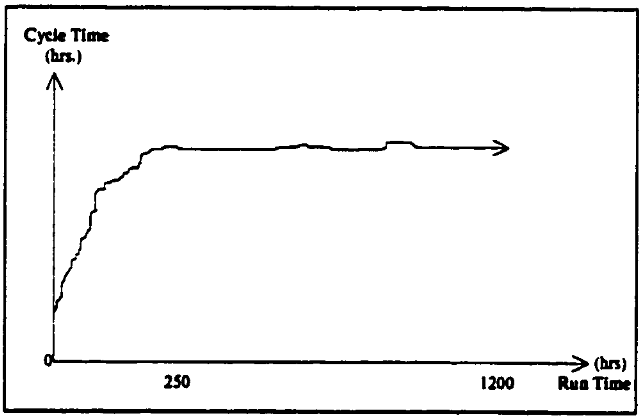

Figure 4-1 Simulation Run Time vs. Cycle time for PRODUCT A

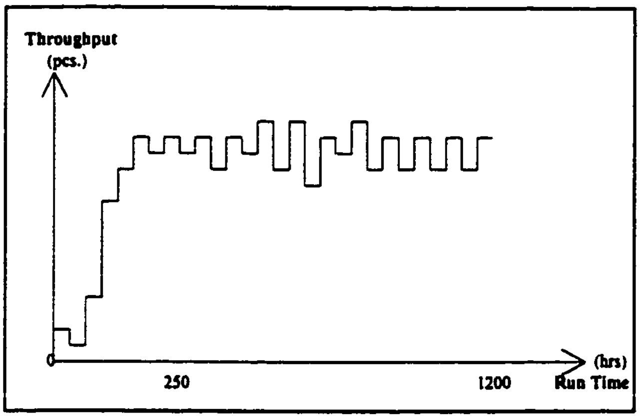

Figure 4-2 **Simulation Run Time vs. Throughput for PRODUCT A**

The length of transient period for the current model is determined by verifying the cycle time and throughput of all seven product categories. Sample graphs of cycle time and throughput for PRODUCT A are presented in Figure 4-1 and Figure 4-2, respectively. The graphs show that the system reaches a steady state at around 250 hours where cycle time levels out and throughput fluctuates within stable limits. Due to the requirement for daily reports on various data, the transient period is rounded up to 264 hours (exactly 11 days) before statistics are collected.

The transient period length was further tested by repeating simulation runs with twice the standard warm-up time. Simulation runs #1, #4 and #7 presented in Table 5-1 were rerun with 528 hours of warm-up time. The results are presented as reruns #1r, #4r and #7r in Appendix 5. The new cycle time and inventories generated by the reruns were within 5% of the first runs. Because of this small difference, a standard warm-up time of 264 hours was considered sufficient.

The shop floor model is a non-terminating simulation for which there is no specific event to indicate the completion of a simulation run and no obvious way to determine how long the simulation should run. Without a terminating event, it is necessary to use subjective judgment to determine the length of simulation required. It was decided that 28 days of production was sufficient to provide data for the current study. Hence, simulations were terminated when simulation time reached 936 hours, including the 264-hour transient period.

Most processing times, repair times and failure rates are derived from historical data. Average values were used as estimates of the mean. Machine downtimes have a normal distribution, and queuing times are exponentially distributed. When the actual form of a distribution is unknown, a statistical distribution was assumed. For example, at Before Wave 15% of boards were processed for 12 minutes and 85% of boards were processed for 5 minutes. ProModel uses random numbers to determine the sample value drawn from the distribution. The sequence of random numbers is determined by the initial seed value used by the random number generator in ProModel. Each random variable in the model is therefore assigned its own random number stream with different seed values. For example, machine SM1 uses stream #2 with a seed value of 2, while SM2 uses stream #3 with a seed value of 3. This helps to ensure that the same sequence of random numbers will be used for every run, hence producing the same result if the program is rerun for validation or development purposes. This would also ensure that any additional activities will not affect the sample values for the existing random variable.

Use of distributions and random numbers makes the current model stochastic; hence, simulation output data also exhibits randomness. Therefore, each experimental design must be replicated to increase its reliability. The outputs from all individual replications are used for statistical analysis. Multivariate analysis of variance (MANOVA) is used for statistical analysis. MANOVA requires that the number of samples in each cell, i.e. group, must be greater than the number of dependent variables (Hair, Anderson, Tatham & Black, 1995). It was determined that 10 replications of each simulation run would be sufficient to provide the required sample size.

As each random variable is assigned a different random number stream with no reset, the stream continues where it left off after each of the ten replications. This was done to ensure that each replication would use different sample values for distributions and would produce different simulation results from the preceding replication. Statistical counters for data collection are automatically reset to zero at the beginning of each replication. With the same initialization parameters, different random numbers and all statistical counters reset to zero, the replications are considered to be independent of each other and are therefore suitable for use in statistical analysis.

4.2 PERFORMANCE CRITERIA

Cycle time, average WIP dollar value and average FG dollar value are the performance measures that are used in statistical analysis of the findings to determine the effects of the three cycle time reduction tactics. The performance measures are chosen because they are direct measures of inventory reduction and cycle time reduction objectives that ABC has set for 1998. The objective of inventory reduction is measured with only WIP and FG inventory dollar values. RM is ignored in this study as RM is ordered based on the production plan. As there are no changes to the production plan, the investment in RM is relatively unchanged.

Cycle time is defined to be the average time required to manufacture a product category, from the start of production at the first workstation until it is completed. Board production is considered to start when the board reaches the first workstation, BP, and the simulation clock time at BP is recorded. Boards are considered completed after BI and the clock time is recorded again. Cycle time of an individual board is the difference between the two clock times. Cycle time of a product group is then calculated in a subroutine by averaging the cycle times of all boards finished in the product category. The cycle time of all FG categories is used as one of the performance measures for this study.

While ProModel reports WIP quantity at the end of simulation run(s), it does not report daily WIP nor the average daily WIP in dollar ($WIP) terms that is used as a performance measure for this study. The latter is calculated based on the average daily WIP quantity and is valued at 50% of the FG dollar value. WIP quantity is the difference between the number of boards started and the total throughput, i.e., number of boards that exited the system. To introduce greater precision into the study, values of daily board started and exited are written to an external file every 24 hours. The daily WIP quantity was calculated after simulation runs were completed with the use of a spread sheet program. Daily WIP quantity was then converted to dollar value based on the corresponding FG price. The average of all daily WIP dollar together with FG dollar was then used as a performance measure.

The average daily FG in dollars ($FG) also needs to be calculated. Average FG quantity is the average of the closing daily balances of FG inventory for 28 days. Daily FG is calculated as follows:

$$\text{ON-HAND INVENTORY} + \text{DAILY THROUGHPUT} - \text{DAILY SALES} \quad \text{(E4.1)}$$

Initial on-hand inventory is determined by the inventory policy of ABC, which allows for safety stock. For example, the average inventory for PRODUCT A is the total sales of three manufacturing cycles. The balance of FG inventory for a particular day becomes the on-hand inventory for the next day. FG dollar value is based on the weighted average dollar value of all the finished products that are grouped in the particular FG category. An example of the calculation of the weighted average dollar value of FG is presented in Appendix 3 Section A3.4.

While evaluating the potential savings for ABC, inventory carrying charge is taken to be 22.5%, which includes opportunity cost and inventory carrying cost. Then the total savings in inventory carrying cost is calculated as:

$$(\$WIP_2 - \$WIP_1) + (\$FG_2 - \$FG_1) \times 22.5\% \quad \text{(E4.2)}$$

where: $\$WIP_1$ and $\$FG_1$ are the values of the base model in simulation run #1 and $\$WIP_2$ and $\$FG_2$ are the corresponding values for each of the other 26 runs in turn.

The actual dollar savings can be reinvested in RM or kept as cash for other uses. To assess how much excess RM can be obtained from the dollar savings, the costing method for RM needs to be determined. Since many ABC parts are grouped into both FG and RM, RM cost cannot be calculated with the use of standard cost method. Instead the Dollar Board Equivalent is used. This expresses the total dollar amount of all RM included in a FG and is calculated as follows:

$$\Sigma\left(\frac{\text{average \# of RM parts}}{\text{\# of RM per board}} \times (\$RM \bullet \#RM \text{ per FG})\right) \qquad \text{(E4.3)}$$

where: average # of RM parts is the RM required for a stocking period, determined by requirements of FG from production plan and safety stock policy of RM category.

An example of the calculation of the Dollar Board Equivalent for one of the FG categories is presented in Appendix 6.

4.3 EXPERIMENTAL FACTORS AND DESIGN

As presented in Table 4-1 below, three cycle time reduction tactics are being evaluated, namely setup time, NVA time and lot size. These three tactics are among the most widely used cycle time reduction methods in the literature. The ABC management had also concurred as to the appropriateness of these tactics in the context of reducing cycle time at ABC.

				Performance Measures		
				y1	y2	y3
Input Factors:	**Levels**			Cycle Time (hr.)	WIP ($)	Finished Goods($)
x1 - Setup time	1.0	0.5	0.0			
x2 - NVA time	1.0	0.5	0.0			
x3 - Lot sizes	7	5	3			

Table 4-1 Factors and Performance Measures

The impact of setup time was tested at three levels: base (current) level (1.0), half of the base level (0.5) and zero setup time (0). As the company aims to reduce cycle time, setup time should be reduced to achieve this objective. The current setup times at different workstations form the base level of 1.0 or 100%. Ideally, it would be optimal to remove setup completely, i.e., 0%. This may be difficult but not impossible. One possible way to reduce setup almost to zero is by changing internal setup to external setup. In other words, rather than waiting till product A is finished to do the setup for product B on-line, setup for product B could be performed off-line while the machine is still working on product A. With the level of accuracy limited to 3 decimals in ProModel, setup times were set to 0.001 instead of 0.000(minutes) for 0%. Having set the two desired levels of 100% and 0%, the mid-point at 50% was chosen to be the third level for testing. For example, setup time at BP is tested at 0.54 minutes (100%), 0.27 minutes (50%) and 0.001 minutes (0%). Setup time at the base level for all workstations is presented in Column B of Appendix 4.

The impact of NVA time was also tested at 21 locations using three levels of 100%, 50% and 0%. For example, NVA time at Carrier 2 is tested at 116 minutes (100%), 58 minutes (50%) and 0.001 minutes (0%).

As several units of the same type of board are used for assembling a system unit, the minimum lot size tested was 3. Hence, the impact of lot size was tested at base (current) level (7), minimum level (3) and medium level (5). This study uses full factorial design for experimentation. With three factors, each having three levels, there were a total of 27 experimental cases. Each case is replicated 10 times for a total of 270 runs.

5. ANALYSIS OF FINDINGS

The experimental factors, i.e. independent variables, were setup time, NVA time and lot size. The response variables were cycle time, average WIP dollar value and average FG dollar value. A summary of results for the 27 experimental runs, each result being the average of ten replications, is presented in Table 5-1 below and discussed in the following section. Statistical results from SAS System, a statistical software application, are presented in Appendix 7 and discussed in Section 5.2.

	Var. 1 Setup	Var. 2 NVA Time	Var. 3 Lot Size	Cycle Time Wt. Avg (hrs.)	Average WIP ($)	Average F.G. ($)	Savings @Cost (@22.5%)
Run #1	100%	100%	7	181.0	$6,550,671	$29,826,057	0.00%
Run #2	100%	100%	5	178.2	$6,502,583	$29,459,225	0.26%
Run #3	100%	100%	3	175.3	$6,367,679	$29,051,879	0.59%
Run #4	100%	50%	7	112.6	$4,320,919	$19,080,025	8.03%
Run #5	100%	50%	5	111.1	$4,311,056	$18,823,563	8.19%
Run #6	100%	50%	3	109.2	$4,215,180	$18,549,705	8.42%
Run #7	100%	0%	7	25.1	$821,701	$5,178,458	18.79%
Run #8	100%	0%	5	24.7	$822,419	$5,118,687	18.83%
Run #9	100%	0%	3	22.2	$733,101	$4,670,307	19.16%
Run #10	50%	100%	7	177.0	$6,436,543	$29,729,845	0.13%
Run #11	50%	100%	5	175.7	$6,466,952	$29,154,321	0.47%
Run #12	50%	100%	3	172.8	$6,342,740	$28,799,171	0.76%
Run #13	50%	50%	7	108.2	$4,161,154	$18,685,595	8.37%
Run #14	50%	50%	5	107.8	$4,186,089	$18,576,007	8.42%
Run #15	50%	50%	3	105.7	$4,111,944	$18,245,134	8.67%
Run #16	50%	0%	7	23.0	$722,971	$4,833,657	19.06%
Run #17	50%	0%	5	23.0	$747,660	$4,866,769	19.03%
Run #18	50%	0%	3	20.8	$663,455	$4,463,746	19.33%
Run #19	0%	100%	7	174.4	$6,377,029	$29,248,211	0.46%
Run #20	0%	100%	5	171.2	$6,301,854	$28,654,250	0.88%
Run #21	0%	100%	3	168.6	$6,193,883	$28,251,515	1.19%
Run #22	0%	50%	7	107.9	$4,147,827	$18,631,115	8.41%
Run #23	0%	50%	5	106.4	$4,151,597	$18,346,714	8.58%
Run #24	0%	50%	3	103.4	$4,017,726	$17,878,519	8.96%
Run #25	0%	0%	7	22.0	$680,591	$4,717,160	19.16%
Run #26	0%	0%	5	21.6	$687,489	$4,613,217	19.22%
Run #27	0%	0%	3	20.0	$625,636	$4,360,551	19.42%

Table 5-1 Simulation Results of 27 Experiments

5.1 SIMULATION RESULTS

When setup was reduced from the current level of 100% to 50% and 0%, as per runs #1, #10, #19 in Table 5-1, cycle time and inventory were reduced by only 2% on each level as demonstrated in Figure 5-1 below. In spite of the attention to setup reduction in the early 80s, setup has a small impact on the operations of ABC. This is due to the low setup times currently existing in the company, ranging from 0% to 7% of available processing time. Available processing time is three shifts totaling 24 hours less time for scheduled employee breaks. As cycle time was reduced, WIP was also reduced from $6.6 millions to $6.4 millions. Average FG inventory is based on the total sales of three manufacturing cycles. As cycle time decreased, average FG inventory decreased from $29.8 millions to $29.2 millions.

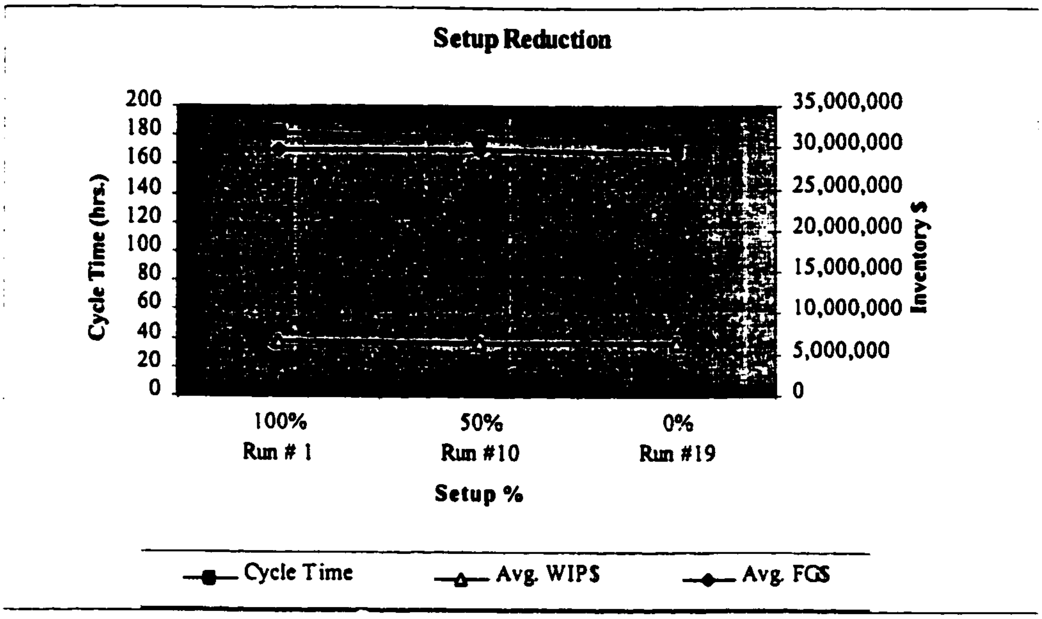

Figure 5-1 Setup Reduction

Runs #1, #4 and #7 (Table 5-1) compare the performance measures when NVA times are reduced from 100% to 50% and 0%. Cycle times were reduced by 38% and 86%, respectively and inventory levels were reduced by 36% and 84%, respectively, as shown in Figure 5-2. These drastic effects can be explained by the long queuing times that currently exist at ABC. Actual total processing time for an average board is only about three hours. Hence, when the NVA times are reduced, the cycle time decreases drastically.

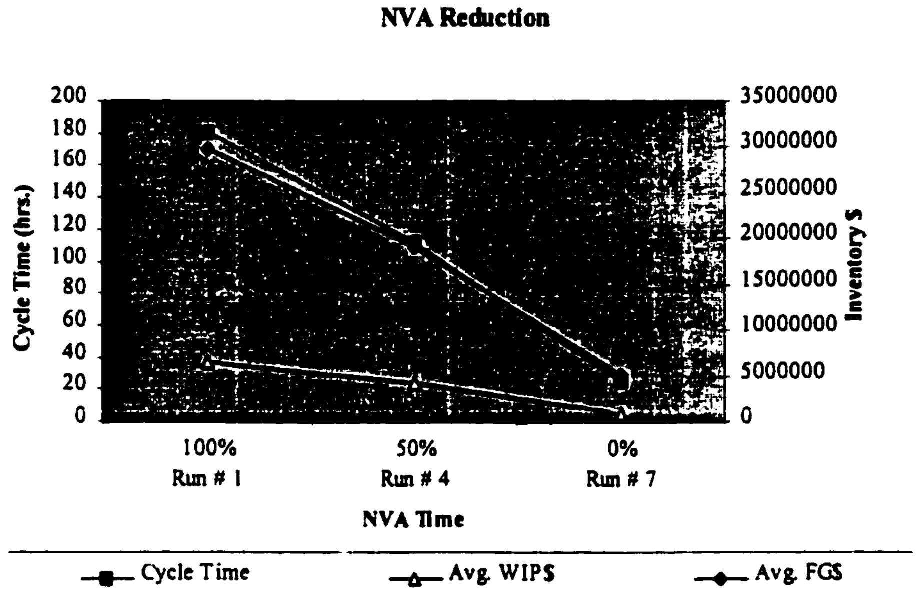

Figure 5-2 NVA Reduction

When lot sizes are reduced from 7 to 5 to 3, cycle time and inventories are reduced by less than 3%, as seen in Figure 5-3. (Refer to runs #1, #2 and #3 in Table 5-1.) When lot sizes are reduced, the number of batches increases, which increases the total setup time. As setup time is relatively small at ABC, as shown in Appendix 4, the increase in total setup time is also small. When lot sizes are reduced, the time required to accumulate the whole lot prior to moving to the next workstation is also reduced. This offsets the increased total setup time due to smaller lot size. Overall, there is a slight reduction in both cycle time and inventory levels.

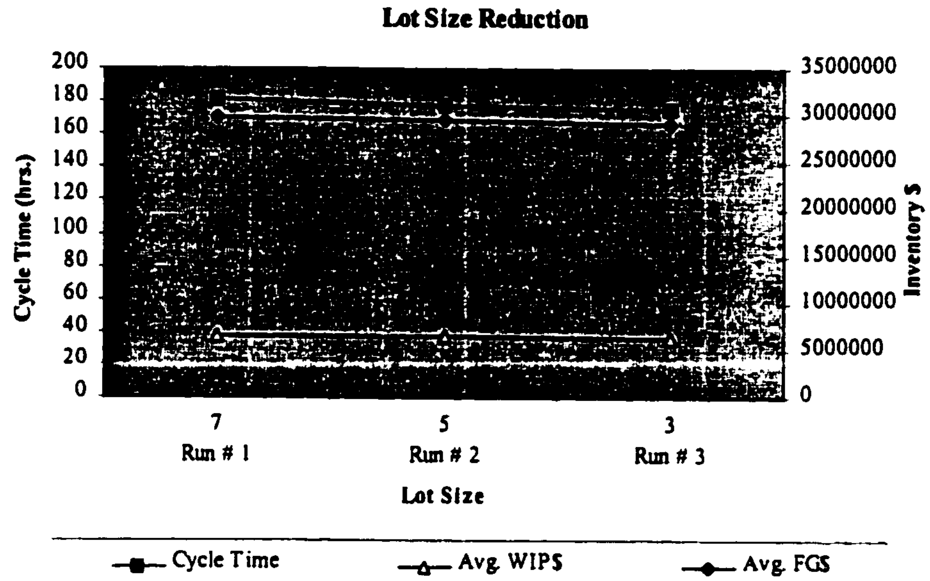

Figure 5-3 Lot Size Reduction

An additional 20 simulation runs, for a total of 27 runs, were done to test the effects when individual factors are reduced simultaneously. The results are presented in both Table 5-1 and graphically in Figure 5-4. The optimum scenario occurs at run #27 when setup is at 0%, NVA time at 0% with a lot size of 3, resulting in potential cost savings of up to 19.42%. Overall, NVA time has the most significant effect on performance measures. Reducing NVA time alone at run #7 produces cost savings of 18.79%.

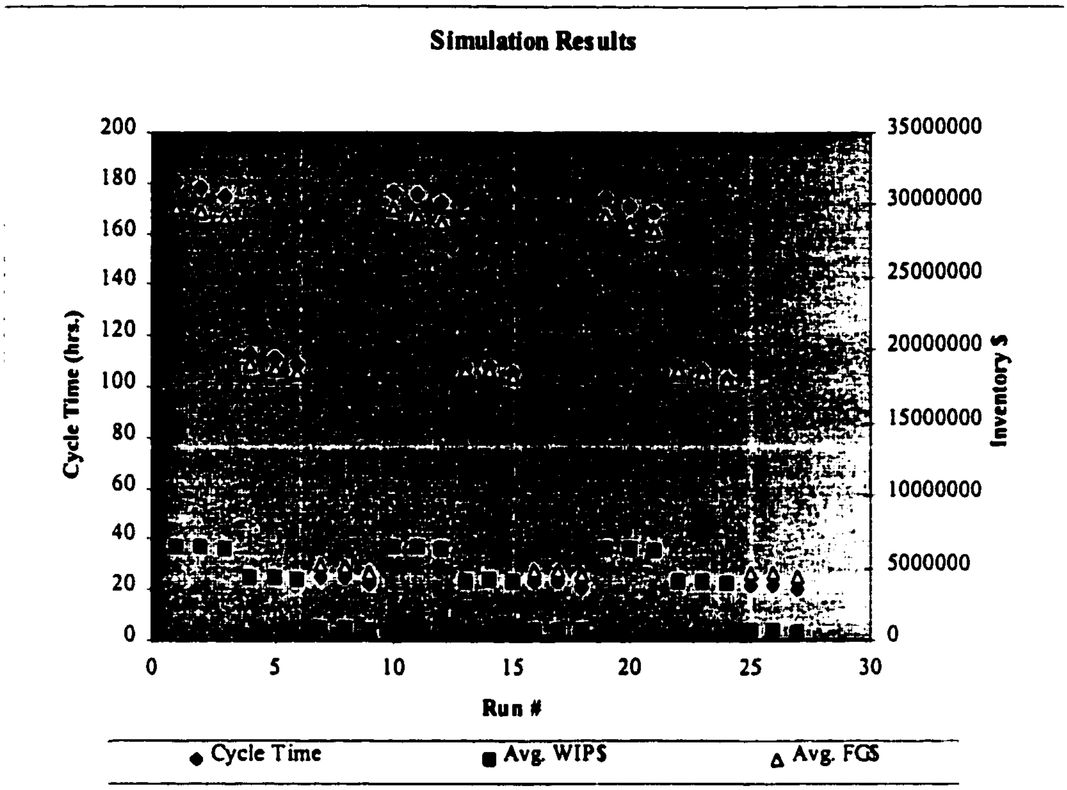

Figure 5-4 Simulation Results

In order to further study the impact of the most influential factor of NVA time in detail, the NVA times were further evaluated by stepwise reductions of 10% increments from 100% down to 0%, with lot sizes of 7 (runs #30-40) and 3 (runs #50-60). Results are presented in tabular form in Appendix 5 and graphically in Figures 5-5 and 5-6 below. It was observed that while throughput is relative unchanged, reductions in cycle time and savings are relatively linear when reduction in NVA times vary between 40-100%. However, when reductions are between 0% and 30%, the relations are non-linear: throughput increased slightly and cycle time declined more rapidly. As NVA time decreases, so does dwell time in the queues.

The reduction of waiting time in queues was modeled by reducing waiting times in queues all along the process by the same fraction or percentage. The non-linearity in cycle time reduction can be explained as follows. As queue dwell time is reduced (100%-40%), the overall slack in the system is reduced with a reduction in cycle time, but there is no reduction in processing time or increase in throughput. As queue dwell time is further reduced (30% - 0%), the reduction speeds up overall processing by eliminating queues. The limiting factor is the lot size. It can be seen by comparing Figures 5-5 and 5-6 that with a smaller lot size, the end point (0%) cycle time is lower. In the 30% to 0% NVA range, as NVA times are reduced, boards are being moved through production faster. As most workstations have excess capacity, faster moving boards increase both machine utilization and throughput.

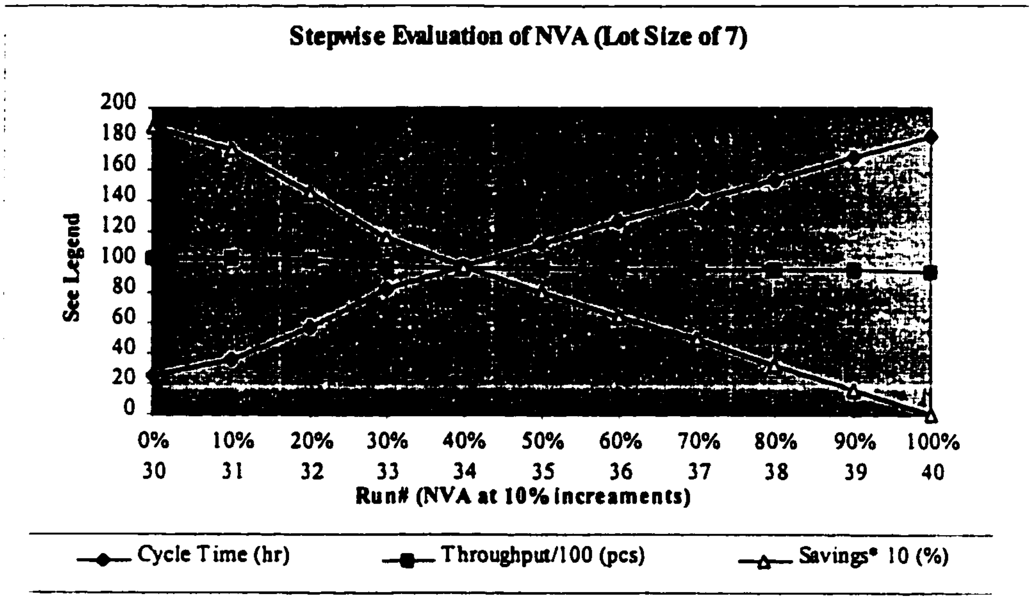

Figure 5-5 Stepwise Evaluation of NVA (Lot Size of 7)

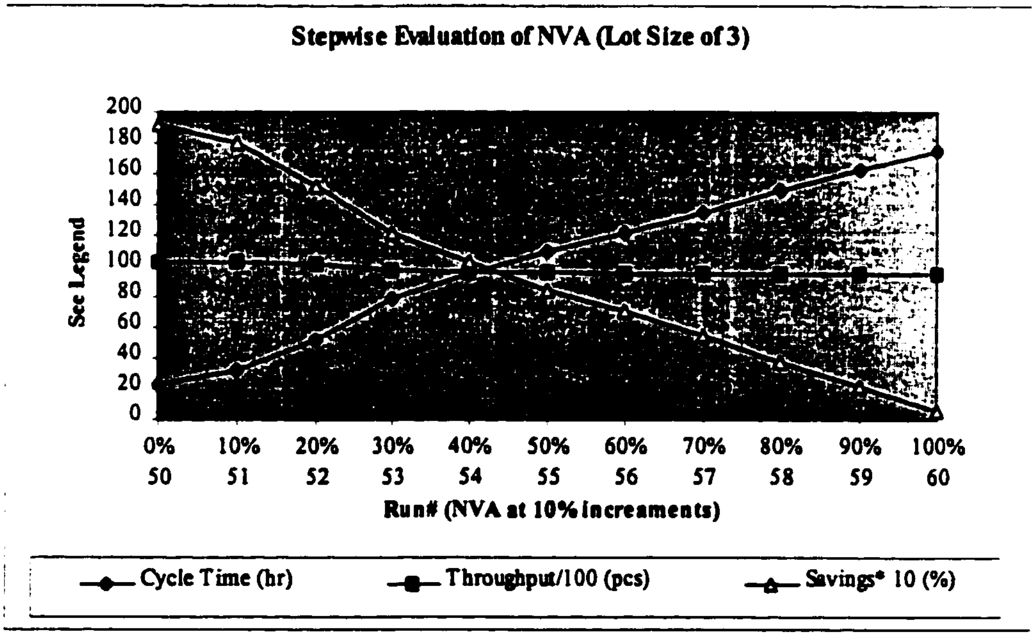

Figure 5-6 Stepwise Evaluation of NVA (Lot Size of 3)

5.2 STATISTICAL ANALYSIS

As the three dependent variables need to be examined simultaneously, multivariate analyses of variance (MANOVA) techniques were applied to obtained data. The effects of individual independent variables were examined by the overall test of significance on all of the dependent response variables. MANOVA based results are presented on pages A7-5 to A7-11 in Appendix 7. Individual factors, i.e. independent variables, are then examined with the use of analysis of variance (ANOVA) to determine the effect of independent variables on dependent variables. Details of SAS analysis are presented on pages A7-1 to A7-4 in Appendix 7. Canonical correlation is performed to analyze the relationship between the two sets of variables and is presented on pages A7-14 to A7-19 in Appendix 7. Linear combinations from each set of variables were developed to obtain the canonical coefficients/weights. A summary of significance of individual variables is presented in Table 5-2 below.

Hotelling's T^2 test indicates that effects of all three factors on the performance measures are significant at a confidence level of 95%. (Refer to pages A7-6 to A7-8 in Appendix 7.) There is no three-way interaction among the three independent variables (pp. A7-10 to A7-11). The two-way interaction among NVA time and Setup (pp. A7-7 and A7-8), and NVA time and Lot Size (pp. A7-9 and A7-10) were found to be significant. As indicated by the canonical coefficients on page A7-17, NVA time (0.9982) impacts the dependent variables of cycle time and inventory levels much more than Setup (0.0321) and Lot Size (0.0306). Thus, the effects of any independent variable when combined with NVA time would exhibit significance.

	Dependent Variables		
Independent Variables	**Cycle Time**	**WIP**	**FG**
x1 - Setup time	S	S	S
x2 - NVA time	S	S	S
x3 - Lot size	S	S	S
x1, x2	S	NS	NS
x1, x3	NS	NS	NS
x2, x3	NS	NS	NS
x1, x2, x3	NS	NS	NS
* S = Significant NS= Not Significant			

Table 5-2 Summary Table of Statistical Significance

There are two-way interactions among all three dependent variables as indicated on page A7-5. Data transformation was applied to the raw data of both the dependent and independent variables. Raw data were normalized. All values changed to z-values, to remove any distortions due to units of measurement, i.e., percentage of setup/NVA time versus hours in cycle time versus dollars of inventory value. However, results indicate that this does not further improve the relationship (correlation) among variables.

The combined effects of NVA and Setup on Cycle Time were found to be significant. Both variables affected cycle time in the same direction; hence, ANOVA shows significance as indicated on page A7-2.

The correlation between performance measures and cycle time reduction tactics ranges between low and high. Correlations between Setup and Lot Size and performance measures are extremely low, ranging from 0.01 to 0.03. However, there is a very high correlation between NVA and all performance measures at 0.99. There are large within-set correlations among the performance measures at 0.99. There is no within-set correlation among the cycle time reduction tactics. The three correlation tables are presented on page A7-14.

The first canonical correlation is 0.9991(p. A7-15), which is larger than any of the between-set correlations. The probability level for the null hypothesis that all the canonical correlations are 0 in the population is only at 0.0001. Hence, firm conclusions about the findings of the study can be drawn from a statistical point of view. The Canonical R-Square is at 0.9983, which is highly significant (p. A7-18).

The first canonical variable for the performance measures is the weighted sum of all individual measures since all the coefficients (0.9968, 0.9910, and 0.9965) have the same sign (p. A7-17). The first canonical variable for the tactic variables shows the same sign, with the highest weight on NVA (0.9982)(p. A7-17). This implies that there is no suppresser variable among the variables studied.

The proportions of variance that can be explained are 0.9895 (p. A7-18) for performance measures and 0.3328 (p. A7-19) for tactics. The square multiple correlation as shown on page A7-19, indicates that the first canonical variable of the performance measures has predictive power for NVA time (0.9964), but almost none for Setup (0.0010) nor Lot Size (0.0009). The first canonical variable for tactics is a near perfect predictor of Cycle Time (0.9936), WIP (0.9821) and FG (0.9930).

5.3 MANAGERIAL IMPLICATIONS

The statistical analysis discussed in Section 5.2 confirms the simulation findings in Section 5.1. All three factors are found to be significant, with NVA time having the most impact on all three performance measures. In the best case where NVA time is reduced to 0%, setup time is reduced to 0% and lot size is changed to 3, an annual saving of 7.1 million dollars is achievable. This is for an average inventory of 60 million dollars. This saving is based on lower inventory carrying cost and opportunity cost, and only applies to products considered on Line 1 of the 5 production lines at ABC. Besides the potential cost savings in inventory investment, other savings in storage space for WIP on the shop floor and material handling cost also become possible with the reduction in WIP. Furthermore, cycle time was reduced from 181 hours to 20 hours in the best case scenario. This will reduce customer response time, representing an improved customer service.

Reduction of lot size could be implemented at an extremely low cost. It would involve changing the size of Kanban carriers, increasing the number of carriers and implementing lot size changes in the Enterprise Resource Planning (ERP) system. No other changes would be required on the production floor. Although it is unrealistic to reduce NVA time to zero, substantial reduction is possible at ABC nevertheless. NVA time reduction would require setting up a special project group to study ways to reduce it. This would require some investment and a certain amount of time, but with the potential cost savings, the project could be easily justified. Reduction of setup time could be problematic for ABC as it involves a very significant financial investment to further upgrade existing machinery and equipment. For example, an additional oven would cost around 2 million dollars.

With the increased throughput, more jobs are started, and hence, there is an increase in usage of raw materials. However, as raw materials are purchased based on the fixed production plan, all additional raw materials are already in storage and do not require further expenditure, since the production plan at ABC is usually overstated. However, with the increased throughput and the cost savings from cycle time reduction, management may consider increasing the safety stock of raw material to buffer against uncertainty of customer demand. With the use of board equivalents method (See Section 4.3 and equation E4.2.), the cost of raw material for the month is calculated at 24 million dollars. The potential cost savings of 7.1 million dollars are sufficient to increase raw material inventory by up to 30%. Such an increase will certainly offset any decrease of customer service due to possible shortages of raw materials.

6. CONCLUSION

We have evaluated the economic impact of three cycle time reduction tactics. It was found that reduction of NVA time is far more effective than reduction of setup time and lot size at ABC.

Over the last two decades, much literature has dealt with the elimination of setup and NVA activity, and the reduction of lot size to improve performance of manufacturing companies. Modeling and analytical aspects have also been well studied. The findings of this study are in agreement with most studies in showing that reduction of NVA time will improve both cycle time and inventory, by over 80% in this case. However, while most of the literature reported positive impacts, the present study showed that setup and lot size reduction have insignificant impact at ABC on selected performance criteria. This may be explained by the development and adaptation of new manufacturing technologies, such as Flexible Manufacturing Systems (FMS) and robotics, which enables modern manufacturing facilities to operate efficiently with minimal setup. The current study demonstrates that, in the case of ABC, deployment of such technologies do not achieve significant improvements in cycle time or inventory when setup and lot size reduction tactics are employed. This may also indicate that a saturation point may have been reached at ABC with respect to setup time and lot size with the existing advanced technologies used. Most recent literature (Handfield & Pannesi, 1995; Miltenburg & Sparling, 1996) now focuses on time based competition, which seeks to reduce the total time in the supply chain, and suggests that shop floor delays are no longer a major factor in lead-time reduction. This justifies the investigation of total lead-time for ABC, which is planned for the later phase of the project.

The simulation results show that ABC should not invest in setup reduction as it would require costly machinery upgrades and would provide a rather small 2% improvement in cycle time and inventory. On the other hand, although reducing lot sizes would only provide a 3% improvement, ABC's management should consider this tactic as it requires very little investment. Finally, it is recommended that ABC should work on reduction of NVA time to both reduce cost and streamline production, as it provides a possible 80% improvement in cycle time and inventory.

It was outside the scope of this research to study the impact of setup, NVA time and lot size on customer service level and RM level. As customer service improvement is one of the main objectives of ABC, this should be an interesting area for ABC to look at subsequently.

Two other simulation models have been developed for other aspects of the company. An Order Fulfillment simulation model was built and will be integrated with the current shop floor model to investigate the impact of other factor(s) on the organization as a whole. Simulations of machine breakdown and repairs have also been conducted. These models can be integrated into the existing model to study the combined effect, if any, of all these factors and to find the optimum operation plan for ABC.

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APPENDIX 1

Short-Cycle Management Principal

This is a conceptual model for cycle time improvement which strives for improvements in 3 dimensions simultaneously - cost, quality and responsiveness. This model has five prerequisites, five guidelines, six improvement themes and five improvement tactics. (Heard 1990a)

The five prerequisites for non-production activities are structured flow paths, people leverage, continuous flows, linear operation and dependable supply and demand. Enterprises should have *structured flow paths* that are dedicated and repeatable. Travel time and distance should be eliminated; delays and confusion should be avoided. *People leverage* aims at integrating individual and enterprise goals. Responsibility for cost and quality should be shared by individuals. Work processes should be visible so that workers can learn, question and improve the processes. Continuous flow should be established to increase reliability and predictability, and all disruptions should be eliminated. *Linear operation* should be well synchronized with small batch sizes and daily goals. Partnerships should be developed among workers to establish dependable supply and demand within operations.

The five improvement guidelines set the criteria for evaluating and improving an organization. They are minimize movement, maximize focus, simplify controls, maximize participation and optimize technology. Internal and existing resources should be deployed rather than acquiring glamorous new technology that does not meet the company's needs.

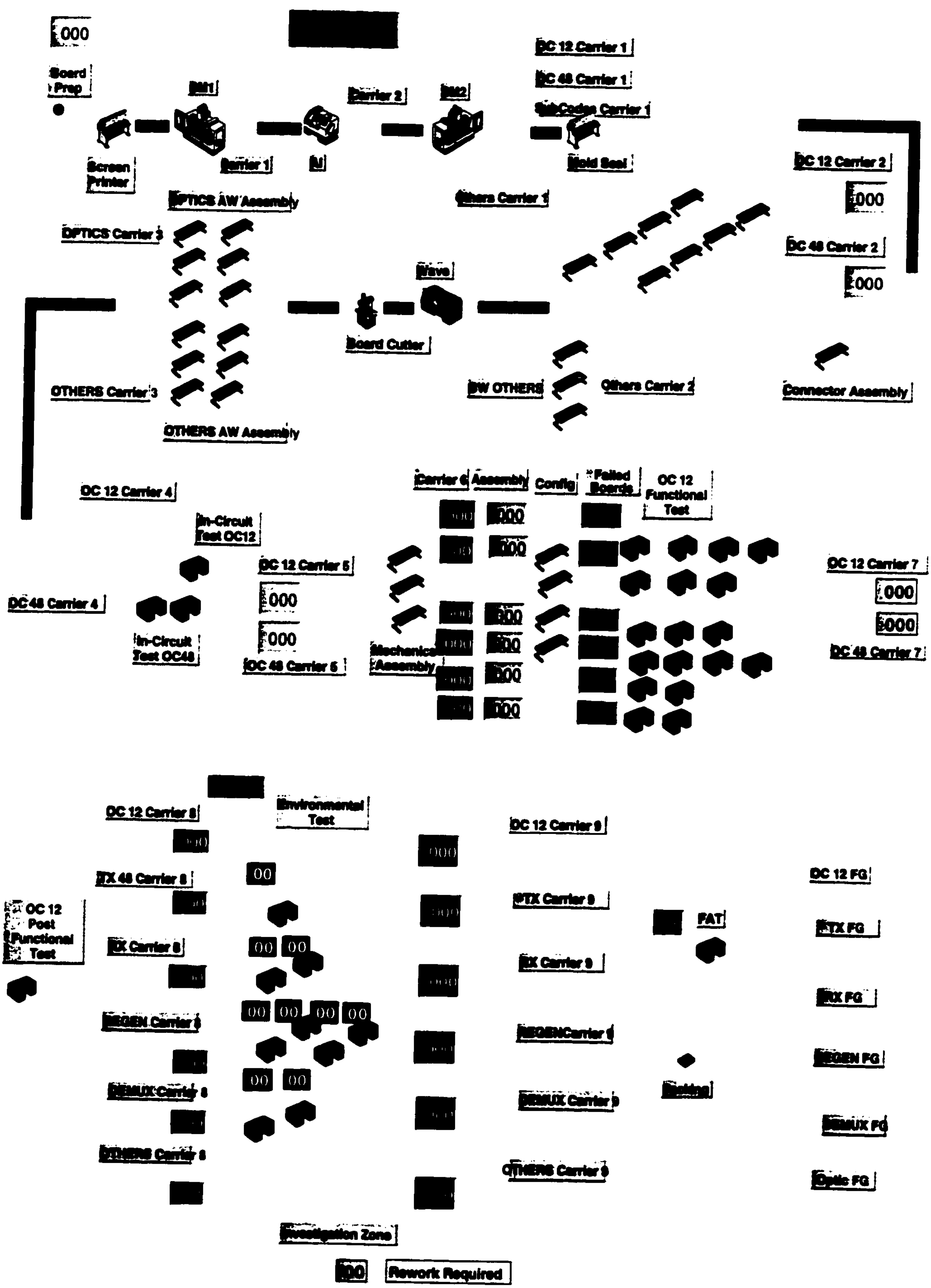
The six improvement themes help to emphasize the importance of non-production activities. They are standardization, autonomy, flexibility, simplicity, urgency and visibility. Everything should be *standardized* as far as possible to achieve simplicity and homogeneity. *Autonomous* work teams with proper resources should be established. *Flexibility* increases responsiveness to change, e.g., in customer requirements and work loads. When seeking better and faster approaches, whether systems or processes, we should not forget that the simplest way may be the easiest and most reliable. Enterprises should also try to create a sense of *urgency* in all personnel. Finally, all processes should be visible, both in manufacturing and white collar work, to help prevent and solve problems.

The five improvement tactics are to identify disconnects, remove barriers, rationalize incentives, eliminate waste and manage change. Identify disconnects: points where departments fail to exchange important information about a common task. Disconnects often occur between white collar and manufacturing personnel. Related to disconnects is the problem of hand-offs: the refusal to take responsibility for a task or a problem, which is dumped elsewhere in the same or in another subcycle. *Remove barriers* in operations, such as policy problems, territorial or priority conflicts, procedural questions, resource needs and authority issues. *Rationalize incentives* to use performance measures that are related to the overall enterprise objectives. *Eliminate waste*, visible or invisible, in both white collar and manufacturing areas. *Manage change* with proper planning, organizing and control.

Appendix 2

Graphical Model of Line 1
in ProModel

ABC Montreal Plant Manufacturing Model



Appendix 3

Grouping of RM and FG

In order to simplify product structure, average quantity of raw materials (RM) required for each finished good (FG) was based on the 1997 annual sales of ABC. RM and FG classification was carried out with ABC personnel in both the Planning and Manufacturing departments. FG parts are grouped by ABC part numbers, while RM parts are grouped by ABC internal account numbers.

Simplification of product structure was done with Turbo C++, PAL in PARADOX, PARADOX database and spreadsheet programs. A number of small programs were written in Borland Turbo C++ for data conversion. A material requirement planning (MRP) program written in PAL in PARADOX was used to process the data. Output from the MRP-program is then further processed by a spreadsheet program.

A3.1 Input Data

The Item Master file and the Bill of Material file were obtained from ABC. In order to reduce data handling errors, Turbo C++ programs were written to convert files for direct import into PARADOX databases. For this project, RM and FG categories were added to the Item Master file. This forms two additional levels in product structures which were added to the Bill of Material (BOM) file. Hence, a Super Bill was created with each FG group being a pseudo assembly with actual ABC boards as components and with a RM being assigned as a child component to each lowest level ABC part. An example is shown in Figure A3-1 below.

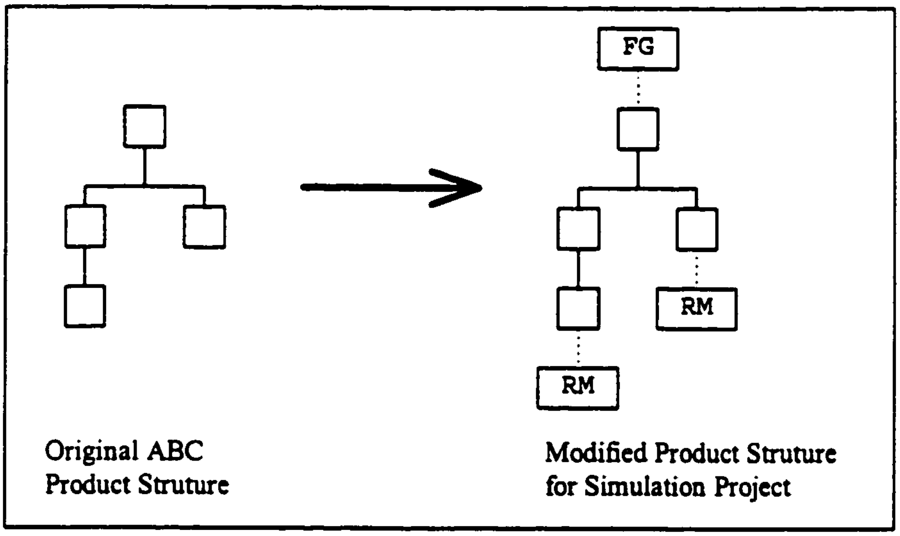


Figure A3-1 Modifying Product Structure

A3.2 Data Processing

Weekly sales data from August 1996 to July 1997 was provided by ABC to the project team. All sales items for the year were inputted into the MRP-program. The MRP-program generated all the RM components required for producing the FG parts that were sold during the year, based on product structures in the BOM file.

As RM groups were made of phantom parts of all purchased raw materials in the BOM file, the semi-finished components requirements could be ignored and the RM requirements could be sorted out for further processing.

A3.3 Output Data

The MRP-program generates the RM requirements for each original source requirement, i.e. the sales item. With the part number of the sales item, the corresponding FG group was located in the BOM file. All components requirements were then sorted by FG group and RM group. The weighted average of RM usage per FG group was calculated with a spreadsheet program. The weighted average cost of RM and FG were also calculated at the same time. With the product grouping, there are over 100 parts grouped into one FG category and up to 1000 parts grouped into one RM category. A simplified example, shown in Section A3.4 below, for calculations of weighted average usage and costs is presented with the use of a simplified product structure presented in Figure A3-2.

A3.4 Simplified Example for Calculations

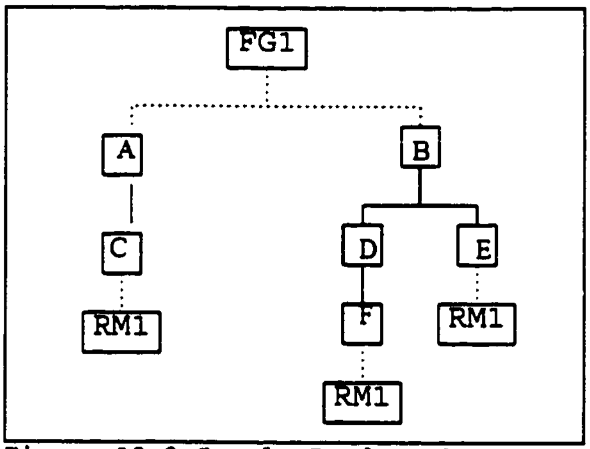


Figure A3-2 Sample Product Structure

Assuming:

1. Quantity per level is one piece,
2. Annual demand for A is 100 pieces,
3. Annual demand for B is 200 pieces, and
4. RM1 is not used for any other FG category.

	A	B	C	D	E	F	G	H	I	J
					FG			RM		
Row #	FG	Parent	Child	RM	Qty	Unit $	Total $	Qty	Unit $	Total $
1	FG1	A	C	RM1	100	$100	$10,000	100	$1	$100
2	FG1	B	F	RM1	200	$200	$40,000	200	$2	$400
3	FG1	B	E	RM1	200	$200	$40,000	200	$3	$600
Total					300*		$50,000*	500		$1,100

* *FG Qty and FG Total $ on row #2 and row #3 are duplicated.*

Hence:

1. Weight average usage of RM1 for FG1 is:
   *500 / 300 = **1.66** (pieces)* ***(Columns H/E)***

2. Weight average cost of FG1 is:
   *$50,000 / 300 = **$166.66*** ***(Columns G/E)***

3. Weight average cost of RM1 is:
   *$1,100 / 500 = **$2.2*** ***(Columns J/H)***

Appendix 4

Process and Set-up Times

	A	B	C	D	E	F	G	H	I
	Workstations	Setup	Process Time						
		All Products	Pdt A	Pdt B	Pdt C	Pdt D	Pdt E	Pdt F	Pdt. G
		(min.)	(min.)	(min.)	(min.)	(min.)	(min.)	(min.)	(min.)
1	Board Prep.	0.50	0.67	0.67	0.67	0.67	0.67	0.67	0.3
2	Screen Print	10	1.06	1.06	1.06	1.06	1.06	0	0.08
3	SMI	3	1.067	2.667	1.663	1.567	1.319	2	0.35
4	Auto. Insert.	0.561	0.133	0.133	0.633	0.18	0.44	3	0.12
5	SM2	0.957	2.527	0	0.688	0	0	0	0.62
6	Mold Seal	0	1	1	0	1	1		0
7	Connector	0	1	1	1	1	1		0
8	Before Wave	0	11/5	9.8	7	6.4	5.29/22	12/5.5/9	
			15%/85%	100%	100%	100%	20%/80%	50%/16% /34%	
9	Wave	0.258	1	1	1	1	1	1	1
10	Board Cutter	0	0	0	0	0	0	0	0
11	After Wave	0	9/13	19.5	17.6	12.5	10/20	3/0/5	
			85%/15%	100%	100%	100%	20%/80%	50%/16% /34%	
12	In Circuit	0.356	3.8	3.7	3.3	1.6	3.4	2.1	
13	Mech. Assy.	0	7.9/11	6	11	3	5/3	3/4/0	
			20%/80%	100%	100%	100%	20%/80%	50%/16% /34%	
14	Config.	0	5/8.4	9.5	8.5	6.2			
			85%/15%	100%	100%	100%			
15	Functional	5.4	31/46	31	40	22	18	9/0	
			75%/25%	100%	100%	100%	100%	50%/50%	
16	Post Funct.	0	2.7	2.7	2.7	2.7	2.7	2.7/0	2.7
			100%	100%	100%	100%	100%	50%/50%	
17	Oven 1	60	11 hr.	11 hr.	11 hr.	11 hr.	11 hr.		
	Oven 2	60	11 hr.	11 hr.	11 hr.	11 hr.	11 hr.		
	Oven 3	60	11 hr.	11 hr.	11 hr.	11 hr.	11 hr.		
	Oven 4	60	7 hr.	7 hr.	7 hr.	7 hr.	7 hr.		
	Oven 5	60	7 hr.	7 hr.	7 hr.	7 hr.	7 hr.		
	Oven 6	60	7 hr.	7 hr.	7 hr.	7 hr.	7 hr.		
	Oven 7	60	7 hr.	7 hr.	7 hr.	7 hr.	7 hr.		
	Oven 8	60	7 hr.	7 hr.	7 hr.	7 hr.	7 hr.		
	Oven 9	60	7 hr.	7 hr.	7 hr.	7 hr.	7 hr.		
18	Repair Time	0	60	60	60	60	60	60	60

Appendix 5

Detailed Evaluation of NVA Time

	Var. #1 Setup	Var. #2 NVA Time	Var. #3 Lot Size	Cycle Time Wt. Avg (hrs.)	Average WIP ($)	Average F.G. ($)	Savings @Cost (@22.5%)
Orun#1r				191.4	$7,425,229	$31,956,637	
Orun#4r				121.1	$5,037,369	$20,737,201	
Rerun#7r				25.5	$840,860	$5,216,229	
Run # 30	100%	0%	7	25.1	$821,701	$5,178,458	18.79%
Run # 31	100%	10%	7	36.2	$1,178,616	$7,190,900	17.32%
Run # 32	100%	20%	7	57.5	$2,025,087	$10,759,335	14.59%
Run # 33	100%	30%	7	82.2	$3,137,873	$14,393,099	11.66%
Run # 34	100%	40%	7	98.0	$3,750,751	$16,789,969	9.80%
Run # 35	100%	50%	7	112.6	$4,320,919	$19,080,025	8.03%
Run # 36	100%	60%	7	126.8	$4,799,857	$21,254,029	6.38%
Run # 37	100%	70%	7	140.4	$5,253,808	$23,251,356	4.87%
Run # 38	100%	80%	7	153.7	$5,654,113	$25,466,341	3.25%
Run # 39	100%	90%	7	167.7	$6,098,822	$27,714,260	1.59%
Run # 40	100%	100%	7	181.0	$6,550,671	$29,826,057	0.00%
Run # 50	100%	0%	3	22.2	$733,101	$4,670,307	19.16%
Run # 51	100%	10%	3	31.6	$1,036,407	$6,333,832	17.94%
Run # 52	100%	20%	3	52.6	$1,857,811	$9,864,358	15.25%
Run # 53	100%	30%	3	78.1	$3,030,499	$13,763,999	12.11%
Run # 54	100%	40%	3	94.4	$3,698,360	$16,104,492	10.25%
Run # 55	100%	50%	3	109.2	$4,215,180	$18,549,705	8.42%
Run # 56	100%	60%	3	121.3	$4,629,382	$20,429,408	7.00%
Run # 57	100%	70%	3	134.5	$5,055,735	$22,411,086	5.51%
Run # 58	100%	80%	3	149.5	$5,542,900	$24,716,611	3.78%
Run # 59	100%	90%	3	162.3	$5,939,140	$26,932,786	2.17%
Run # 60	100%	100%	3	175.3	$6,367,679	$29,051,879	0.59%

Appendix 6

Dollar Board Equivalent for FG1

A	B	D	E	F	G	H	I
RM TYPE	$Board Eq	#RM/FG	Avg $RM	Safety Stk	Lot Size	Daily Usage	=(E4*D4)
	($)	(pcs)	($)	(wks)	(wks)	(pcs)	
BAC A		0.00	$1,053.92	0	1	0	0.00
BAC B		0.00	$194.18	0	1	0	0.00
BAC C		0.00	$109.06	0	1	0	0.00
INT A	31,290	1.10	$12.90	1.5	2	138.6	14.19
INT B	25,820	0.79	$9.26	2.5	3	99.54	7.32
INT C	88,655	4.87	$2.58	4	8	613.62	12.56
LAS A	2,264,706	0.62	$1,656.58	2	1	78.12	1027.08
LAS B	85,092	0.13	$296.85	2	1	16.38	38.59
LAS C		0.00	$291.05	2	1	0	0.00
MEC A	17,374	0.13	$101.02	1	1	16.38	13.13
MEC B	173,330	10.33	$4.76	3	2	1301.58	49.13
MEC C	180,846	40.20	$0.51	4	12	5065.2	20.50
OEM A	6,864	0.01	$389.11	1.5	1	1.26	3.89
OEM B		0.00	$347.79	3	2	0	0.00
OEM C	52,753	0.04	$135.93	7	8	5.04	5.44
PCB A	54,799	0.32	$77.66	1.5	2	40.32	24.85
PCB B	67,101	0.66	$28.82	2.5	3	83.16	19.02
PCB C	7,681	0.10	$10.89	4	8	12.6	1.09
RAW A		0.00	$6.92	1	1	0	0.00
RAW B		0.00	$21.21	3	2	0	0.00
RAW C	15,289	1.20	$1.44	4	12	151.2	1.73
SEM A	589,181	13.35	$25.02	1.5	1	1682.1	334.00
SEM B	337,437	137.20	$0.70	3	2	17287.2	95.65
SEM C	551,277	410.12	$0.14	7	8	51675.12	56.82
Total	4,549,494						

Equations:

B50=H1*(F1+(G1*0.5))*7*E1

H1=D1* Average Daily FG production

Dollar Board Equivalent for FG1 is the total of column B, i.e. **$4,549,494**.

Appendix 7

Statistical Results

```
ECONOMIC IMPACT OF OPERATIONAL STRATEGY              14:52 Saturday, April 4, 1998   1

     Analysis of Variance Procedure
        Class Level Information

       Class     Levels    Values

       SETUP          3    0 1 0.5

       NVA            3    0 1 0.5

       LOT_SIZE       3    3 5 7

Number of observations in data set = 270
```

```
                         ECONOMIC IMPACT OF OPERATIONAL STRATEGY          14:52 Saturday, April 4, 1998   2

                              Analysis of Variance Procedure

Dependent Variable: CYCLE_HR

Source                  DF          Sum of Squares          Mean Square      F Value          Pr > F

Model                   26        1052292.51851852       40472.78917379      7919.97          0.0001

Error                  243           1241.78300000           5.11021811

Corrected Total        269        1053534.30151852

                  R-Square                    C.V.             Root MSE                  CYCLE_HR Mean

                  0.998821                2.220261           2.26057915                   101.81592593


Source                  DF                Anova SS          Mean Square      F Value          Pr > F

SETUP                    2           1089.99674074         544.99837037       106.65          0.0001
NVA                      2        1050339.52496296      525169.76248148     99999.99          0.0001
SETUP*NVA                4            143.18548148          35.79637037         7.00          0.0001
LOT_SIZE                 2            625.35829630         312.67914815        61.19          0.0001
SETUP*LOT_SIZE           4             15.02814815           3.75703704         0.74          0.5687
NVA*LOT_SIZE             4             67.93259259          16.98314815         3.32          0.0113
SETUP*NVA*LOT_SIZE       8             11.49229630           1.43653704         0.28          0.9717
```

```
                              ECONOMIC IMPACT OF OPERATIONAL STRATEGY          14:52 Saturday, April 4, 1998   3

                                 Analysis of Variance Procedure

Dependent Variable: WIP

Source                  DF          Sum of Squares          Mean Square         F Value          Pr > F

Model                   26     1472252063102357.00000   56625079350090.60000    5181.49          0.0001

Error                  243        2655584102228.00000     10928329638.79830

Corrected Total        269     1474907647204585.00000

                  R-Square                    C.V.             Root MSE                         WIP Mean

                  0.998199                2.776224      104538.65141085                 3765498.10629630


Source                  DF                Anova SS          Mean Square         F Value          Pr > F

SETUP                    2        1191105879780.00000     595552939890.00000      54.50          0.0001
NVA                      2     1470217070041297.00000  735108535020648.00000   67266.32          0.0001
SETUP*NVA                4          84425162086.00000      21106290521.50000       1.93          0.1058
LOT_SIZE                 2         637793384675.00000     318896692337.50000      29.18          0.0001
SETUP*LOT_SIZE           4          37036726947.50000       9259181736.87500       0.85          0.4964
NVA*LOT_SIZE             4          58388071208.00000      14597017802.00000       1.34          0.2573
SETUP*NVA*LOT_SIZE       8          26243836363.50000       3280479545.43750       0.30          0.9654
```

```
                          ECONOMIC IMPACT OF OPERATIONAL STRATEGY          14:52 Saturday, April 4, 1998   4

                                Analysis of Variance Procedure

Dependent Variable: FG

Source                  DF          Sum of Squares             Mean Square       F Value         Pr > F

Model                   26   26919003839092240.0000   1035346301503548.0000       8204.48          0.0001

Error                  243      30664867928368.0000      126192872133.2010

Corrected Total        269   26949668707020608.0000

                  R-Square                    C.V.                Root MSE                      FG Mean

                  0.998862                2.032876         355236.36093903            17474570.44444440


Source                  DF                Anova SS             Mean Square       F Value         Pr > F

SETUP                    2      14216932365616.0000      7108466182808.0000         56.33          0.0001
NVA                      2   26882556152034128.0000  13441278076017064.0000      99999.99          0.0001
SETUP*NVA                4       1228261171152.0000       307065292788.0000          2.43          0.0481
LOT_SIZE                 2      17989512944208.0000      8994756472104.0000         71.28          0.0001
SETUP*LOT_SIZE           4        158047017360.0000        39511754340.0000          0.31          0.8691
NVA*LOT_SIZE             4       2367276201712.0000       591819050428.0000          4.69          0.0012
SETUP*NVA*LOT_SIZE       8        487657358064.0000        60957169758.0000          0.48          0.8677



                                   E = Error SS&CP Matrix

                                 CYCLE_HR             WIP              FG

                  CYCLE_HR       1241.783    48869433.069    -69832249.06
                  WIP        48869433.069    2.6555841E12    -4.104796E12
                  FG         -69832249.06    -4.104796E12    3.0664868E13
```

```
          ECONOMIC IMPACT OF OPERATIONAL STRATEGY            14:52 Saturday, April 4, 1998   5

               Analysis of Variance Procedure
             Multivariate Analysis of Variance

Partial Correlation Coefficients from the Error SS&CP Matrix / Prob > |r|

          DF = 243    CYCLE_HR        WIP         FG

          CYCLE_HR    1.000000   0.851010  -0.357860
                        0.0001     0.0001     0.0001

          WIP         0.851010   1.000000  -0.454874
                        0.0001     0.0001     0.0001

          FG         -0.357860  -0.454874   1.000000
                        0.0001     0.0001     0.0001
```

```
                    Analysis of Variance Procedure
                   Multivariate Analysis of Variance

                    H = Anova SS&CP Matrix for SETUP

                     CYCLE_HR              WIP               FG
     CYCLE_HR      1089.9967407      36010419.25     123556515.56
     WIP             36010419.25     1.1911059E12     4.0992955E12
     FG             123556515.56     4.0992955E12     1.4216932E13


        Characteristic Roots and Vectors of: E Inverse * H, where
        H = Anova SS&CP Matrix for SETUP   E = Error SS&CP Matrix

 Characteristic   Percent              Characteristic Vector  V'EV=1
      Root
                                        CYCLE_HR          WIP            FG
   2.06402516      99.60              0.02369717   0.00000008    0.00000015
   0.00832200       0.40             -0.04502592   0.00000094    0.00000012
   0.00000000       0.00             -0.01850948   0.00000078   -0.00000006


Manova Test Criteria and F Approximations for the Hypothesis of no Overall SETUP Effect
        H = Anova SS&CP Matrix for SETUP   E = Error SS&CP Matrix

                         S=2    M=0    N=119.5

  Statistic                     Value          F     Num DF    Den DF  Pr > F
  Wilks' Lambda            0.32367446    60.8689          6       482  0.0001
  Pillai's Trace           0.68188524    41.7304          6       484  0.0001
  Hotelling-Lawley Trace   2.07234716    82.8939          6       480  0.0001
  Roy's Greatest Root      2.06402516   166.4980          3       242  0.0001

        NOTE: F Statistic for Roy's Greatest Root is an upper bound.
              NOTE: F Statistic for Wilks' Lambda is exact.


                    H = Anova SS&CP Matrix for NVA

                     CYCLE_HR              WIP               FG
     CYCLE_HR     1050339.525      39236239110     168033345700
```

```
WIP           39236239110      1.4702171E15       6.278629E15
FG           168033345700       6.278629E15      2.6882556E16
```

```
                       Analysis of Variance Procedure
                     Multivariate Analysis of Variance

         Characteristic Roots and Vectors of: E Inverse * H, where
          H = Anova SS&CP Matrix for NVA   E = Error SS&CP Matrix

  Characteristic   Percent            Characteristic Vector  V'EV=1
       Root
                                   CYCLE_HR           WIP            FG
      2810.15691     99.77         0.01478904    0.00000026    0.00000017
         6.60896      0.23        -0.04963324    0.00000120    0.00000003
         0.00000      0.00        -0.01578971   -0.00000004    0.00000011


Manova Test Criteria and F Approximations for the Hypothesis of no Overall NVA Effect
          H = Anova SS&CP Matrix for NVA   E = Error SS&CP Matrix

                         S=2    M=0    N=119.5

  Statistic                    Value          F       Num DF    Den DF  Pr > F
  Wilks' Lambda             0.0000468    11668.7          6       482  0.0001
  Pillai's Trace            1.8682203     1143.6          6       484  0.0001
  Hotelling-Lawley Trace 2816.7658769   112670.6          6       480  0.0001
  Roy's Greatest Root    2810.1569127   226686.0          3       242  0.0001
        NOTE: F Statistic for Roy's Greatest Root is an upper bound.
               NOTE: F Statistic for Wilks' Lambda is exact.


                   H = Anova SS&CP Matrix for SETUP*NVA

                      CYCLE_HR            WIP              FG
        CYCLE_HR   143.18548148     2833135.5805     11780871.171
        WIP        2833135.5805      84425162086     277848117480
        FG         11780871.171     277848117480     1.2282612E12


         Characteristic Roots and Vectors of: E Inverse * H, where
        H = Anova SS&CP Matrix for SETUP*NVA   E = Error SS&CP Matrix

  Characteristic   Percent            Characteristic Vector  V'EV=1
       Root
```

```
                                        CYCLE_HR          WIP            FG
0.25668418      82.20                  0.04387028   -0.00000050    0.00000010
0.05303237      16.98                 -0.03138566    0.00000109    0.00000014
0.00255146       0.82                  0.00467208    0.00000025   -0.00000011
```

```
                         Analysis of Variance Procedure
                        Multivariate Analysis of Variance

Manova Test Criteria and F Approximations for the Hypothesis of no Overall SETUP*NVA Effect
               H = Anova SS&CP Matrix for SETUP*NVA   E = Error SS&CP Matrix
                              S=3    M=0    N=119.5

    Statistic                     Value         F      Num DF    Den DF  Pr > F
    Wilks' Lambda              0.75374676    5.9947        12  637.9176  0.0001
    Pillai's Trace             0.25716166    5.6958        12       729  0.0001
    Hotelling-Lawley Trace     0.31226801    6.2367        12       719  0.0001
    Roy's Greatest Root        0.25668418   15.5936         4       243  0.0001
        NOTE: F Statistic for Roy's Greatest Root is an upper bound.


                    H = Anova SS&CP Matrix for LOT_SIZE

                       CYCLE_HR              WIP               FG
        CYCLE_HR    625.3582963     19019424.343     105801869.76
        WIP        19019424.343     637793384675     3.1450164E12
        FG         105801869.76     3.1450164E12     1.7989513E13

             Characteristic Roots and Vectors of: E Inverse * H, where
            H = Anova SS&CP Matrix for LOT_SIZE    E = Error SS&CP Matrix

   Characteristic   Percent               Characteristic Vector  V'EV=1
        Root
                                         CYCLE_HR          WIP            FG
      1.69902189     95.45             0.02216325   0.00000007    0.00000017
      0.08092260      4.55            -0.04379324   0.00000122    0.00000004
      0.00000000      0.00             0.02285677  -0.00000014   -0.00000011


Manova Test Criteria and F Approximations for the Hypothesis of no Overall LOT_SIZE Effect
               H = Anova SS&CP Matrix for LOT_SIZE   E = Error SS&CP Matrix
                              S=2    M=0    N=119.5

    Statistic                     Value         F      Num DF    Den DF  Pr > F
    Wilks' Lambda              0.34276699   56.8800         6       482  0.0001
    Pillai's Trace             0.70435979   43.8535         6       484  0.0001
```

```
Hotelling-Lawley Trace      1.77994450    71.1978         6       480  0.0001
Roy's Greatest Root         1.69902189   137.0544         3       242  0.0001
        NOTE: F Statistic for Roy's Greatest Root is an upper bound.
               NOTE: F Statistic for Wilks' Lambda is exact.
```

```
                        Analysis of Variance Procedure
                      Multivariate Analysis of Variance

                 H = Anova SS&CP Matrix for SETUP*LOT_SIZE

                       CYCLE_HR              WIP               FG
        CYCLE_HR    15.028148146     727532.70627      1076906.101
        WIP         727532.70627      37036726948      46970133702
        FG           1076906.101      46970133702     158047017360


              Characteristic Roots and Vectors of: E Inverse * H, where
        H = Anova SS&CP Matrix for SETUP*LOT_SIZE   E = Error SS&CP Matrix

    Characteristic   Percent            Characteristic Vector  V'EV=1
         Root
                                     CYCLE_HR          WIP            FG
       0.02819841     87.97        0.00419273   0.00000056    0.00000015
       0.00282858      8.82       -0.03630188   0.00000089   -0.00000009
       0.00102792      3.21       -0.03995102   0.00000062    0.00000011


Manova Test Criteria and F Approximations for the Hypothesis of no Overall SETUP*LOT_SIZE Effect
        H = Anova SS&CP Matrix for SETUP*LOT_SIZE   E = Error SS&CP Matrix

                           S=3    M=0    N=119.5

    Statistic                      Value          F     Num DF    Den DF  Pr > F
    Wilks' Lambda             0.96883580     0.6400         12  637.9176  0.8086
    Pillai's Trace            0.03127253     0.6399         12       729  0.8088
    Hotelling-Lawley Trace    0.03205491     0.6402         12       719  0.8085
    Roy's Greatest Root       0.02819841     1.7131          4       243  0.1477

          NOTE: F Statistic for Roy's Greatest Root is an upper bound.


                 H = Anova SS&CP Matrix for NVA*LOT_SIZE

                       CYCLE_HR              WIP               FG

        CYCLE_HR    67.932592592     1870074.8587     12436257.267
```

```
WIP            1870074.8587        58388071208      326508044832
FG             12436257.267       326508044832      2.3672762E12
```

```
                         Analysis of Variance Procedure
                        Multivariate Analysis of Variance

                Characteristic Roots and Vectors of: E Inverse * H, where
           H = Anova SS&CP Matrix for NVA*LOT_SIZE   E = Error SS&CP Matrix

  Characteristic   Percent               Characteristic Vector  V'EV=1
       Root
                                        CYCLE_HR           WIP             FG
     0.20267857      95.63            0.02416300    -0.00000001     0.00000017
     0.00859719       4.06           -0.04066503     0.00000121     0.00000004
     0.00066341       0.31            0.02634377    -0.00000022    -0.00000011


Manova Test Criteria and F Approximations for the Hypothesis of no Overall NVA*LOT_SIZE Effect
           H = Anova SS&CP Matrix for NVA*LOT_SIZE   E = Error SS&CP Matrix
                                S=3    M=0    N=119.5

   Statistic                    Value          F       Num DF    Den DF  Pr > F
   Wilks' Lambda              0.82384338     4.0395        12  637.9176  0.0001
   Pillai's Trace             0.17770951     3.8252        12       729  0.0001
   Hotelling-Lawley Trace     0.21193916     4.2329        12       719  0.0001
   Roy's Greatest Root        0.20267857    12.3127         4       243  0.0001

           NOTE: F Statistic for Roy's Greatest Root is an upper bound.


                H = Anova SS&CP Matrix for SETUP*NVA*LOT_SIZE

                        CYCLE_HR             WIP               FG
           CYCLE_HR   11.492296297     492184.84396     1126337.7711
           WIP        492184.84396      26243836364      24876884054
           FG         1126337.7711      24876884054     487657358064


                Characteristic Roots and Vectors of: E Inverse * H, where
         H = Anova SS&CP Matrix for SETUP*NVA*LOT_SIZE   E = Error SS&CP Matrix

  Characteristic   Percent               Characteristic Vector  V'EV=1
       Root
                                        CYCLE_HR           WIP             FG
```

```
0.03039329     73.28          0.01160297     0.00000029     0.00000018
0.00811688     19.57         -0.02994816     0.00000100    -0.00000003
0.00296617      7.15         -0.04358863     0.00000065     0.00000009
```

```
                    ECONOMIC IMPACT OF OPERATIONAL STRATEGY           14:52 Saturday, April 4, 1998  11

                         Analysis of Variance Procedure
                        Multivariate Analysis of Variance

Manova Test Criteria and F Approximations for the Hypothesis of no Overall SETUP*NVA*LOT_SIZE Effect
            H = Anova SS&CP Matrix for SETUP*NVA*LOT_SIZE   E = Error SS&CP Matrix

                              S=3    M=2    N=119.5

            Statistic                     Value          F      Num DF    Den DF  Pr > F

            Wilks' Lambda            0.95984213     0.4149        24  699.5745  0.9944
            Pillai's Trace           0.04050571     0.4157        24       729  0.9943
            Hotelling-Lawley Trace   0.04147634     0.4142        24       719  0.9945
            Roy's Greatest Root      0.03039329     0.9232         8       243  0.4978

                NOTE: F Statistic for Roy's Greatest Root is an upper bound.
```

```
                                        ECONOMIC IMPACT OF OPERATIONAL STRATEGY           14:52 Saturday, April 4, 1998  12

                                              Analysis of Variance Procedure
                                            Multivariate Analysis of Variance

Dependent Variable: CYCLE_HR

Source                      DF                   Anova SS                 Mean Square        F Value           Pr > F

SETUP                        2           1089.99674074               544.99837037            106.65            0.0001
NVA                          2        1050339.52496296            525169.76248148          99999.99            0.0001
SETUP*NVA                    4            143.18548148                35.79637037              7.00            0.0001
LOT_SIZE                     2            625.35829630               312.67914815             61.19            0.0001
SETUP*LOT_SIZE               4             15.02814815                 3.75703704              0.74            0.5687
NVA*LOT_SIZE                 4             67.93259259                16.98314815              3.32            0.0113
SETUP*NVA*LOT_SIZE           8             11.49229630                 1.43653704              0.28            0.9717

Error                      243           1241.78300000                 5.11021811

Dependent Variable: WIP

Source                      DF                   Anova SS                 Mean Square        F Value           Pr > F

SETUP                        2       1191105879780.000000          595552939890.000000         54.50            0.0001
NVA                          2    1470217070041297.000000       735108535020648.000000      67266.32            0.0001
SETUP*NVA                    4         84425162086.000000           21106290521.500000          1.93            0.1058
LOT_SIZE                     2        637793384675.000000          318896692337.500000         29.18            0.0001
SETUP*LOT_SIZE               4         37036726947.500000            9259181736.875000          0.85            0.4964
NVA*LOT_SIZE                 4         58388071208.000000           14597017802.000000          1.34            0.2573
SETUP*NVA*LOT_SIZE           8         26243836363.500000            3280479545.437500          0.30            0.9654

Error                      243       2655584102228.000000           10928329638.798300

Dependent Variable: FG

Source                      DF                   Anova SS                 Mean Square        F Value           Pr > F

SETUP                        2       14216932365616.00000          7108466182808.00000         56.33            0.0001
NVA                          2    26882556152034128.00000      13441278076017064.00000      99999.99            0.0001
SETUP*NVA                    4        1228261171152.00000           307065292788.00000          2.43            0.0481
LOT_SIZE                     2       17989512944208.00000          8994756472104.00000         71.28            0.0001
SETUP*LOT_SIZE               4         158047017360.00000            39511754340.00000          0.31            0.8691
NVA*LOT_SIZE                 4        2367276201712.00000           591819050428.00000          4.69            0.0012
SETUP*NVA*LOT_SIZE           8         487657358064.00000            60957169758.00000          0.48            0.8677
```

```
Error                    243       30664867928368.00000         126192872133.20100
```

```
                        ECONOMIC IMPACT OF OPERATIONAL STRATEGY              14:52 Saturday, April 4, 1998  13

                             Means and Standard Deviations

  3 Performance Measures
  3 Cycle Time Reduction Tactic
270 Observations

                       Variable              Mean           Std Dev

                       CYCLE_HR        101.815926         62.581822
                       WIP                3765498           2341565
                       FG                17474570          10009228
                       SETUP             0.500000          0.409006
                       NVA               0.500000          0.409006
                       LOT_SIZE          5.000000          1.636026
```

```
             Correlations Among the Original Variables

            Correlations Among the Performance Measures

                   CYCLE_HR            WIP              FG

CYCLE_HR             1.0000         0.9981          0.9983
WIP                  0.9981         1.0000          0.9965
FG                   0.9983         0.9965          1.0000


         Correlations Among the Cycle Time Reduction Tactic

                      SETUP            NVA        LOT_SIZE

SETUP                1.0000         0.0000          0.0000
NVA                  0.0000         1.0000          0.0000
LOT_SIZE             0.0000         0.0000          1.0000


Correlations Between the Performance Measures and the Cycle Time Reduction Tactic

                      SETUP            NVA        LOT_SIZE

CYCLE_HR             0.0320         0.9960          0.0240
WIP                  0.0284         0.9905          0.0184
FG                   0.0230         0.9959          0.0257
```

```
                            ECONOMIC IMPACT OF OPERATIONAL STRATEGY          14:52 Saturday, April 4, 1998  15

                                  Canonical Correlation Analysis

                                                                             Eigenvalues of INV(E)*H
                     Adjusted       Approx        Squared                       = CanRsq/(1-CanRsq)
       Canonical     Canonical      Standard      Canonical
       Correlation   Correlation    Error         Correlation    Eigenvalue   Difference   Proportion   Cumulative

   1    0.999161      0.999151      0.000102      0.998322       595.0926     595.0639      0.9999       0.9999
   2    0.166982       .            0.059271      0.027883         0.0287       0.0197      0.0000       1.0000
   3    0.094155       .            0.060431      0.008865         0.0089        .          0.0000       1.0000

                               Test of H0: The canonical correlations in the
                                 current row and all that follow are zero

                          Likelihood
                            Ratio       Approx F      Num DF      Den DF      Pr > F

                      1   0.00161636    930.2594           9    642.6572      0.0001
                      2   0.96349909      2.4865           4         530      0.0426
                      3   0.99113486      2.3792           1         266      0.1241


                         Multivariate Statistics and F Approximations

                                    S=3    M=-0.5    N=131

              Statistic                      Value           F      Num DF    Den DF   Pr > F

              Wilks' Lambda             0.00161636      930.26           9  642.6572   0.0001
              Pillai's Trace            1.03507051       46.71           9       798   0.0001
              Hotelling-Lawley Trace  595.13019711    17368.99           9       788   0.0001
              Roy's Greatest Root     595.09256996    52764.87           3       266   0.0001

                  NOTE: F Statistic for Roy's Greatest Root is an upper bound.
```

```
                  Canonical Correlation Analysis

   Raw Canonical Coefficients for the Performance Measures

                   IMPACT1           IMPACT2           IMPACT3

CYCLE_HR      0.0264447868      -0.351307064      0.1453904673
WIP           -4.554222E-7      2.4925769E-6      -6.545138E-6
FG            4.0738126E-8      1.6172854E-6      6.1342373E-7


Raw Canonical Coefficients for the Cycle Time Reduction Tactic

                   TACTIC1           TACTIC2           TACTIC3

SETUP         0.0785696942      -2.442877594      -0.062877982
NVA           2.4425419782      0.0804322402      -0.072781296
LOT_SIZE      0.0186970343      -0.015119301      0.6107642252


 Standardized Canonical Coefficients for the Performance Measures

                       IMPACT1       IMPACT2       IMPACT3

      CYCLE_HR          1.6550      -21.9854        9.0988
      WIP              -1.0664        5.8365      -15.3259
      FG                0.4078       16.1878        6.1399


Standardized Canonical Coefficients for the Cycle Time Reduction Tactic

                       TACTIC1       TACTIC2       TACTIC3

      SETUP             0.0321       -0.9992       -0.0257
      NVA               0.9990        0.0329       -0.0298
      LOT_SIZE          0.0306       -0.0247        0.9992
```

```
                              Canonical Structure

        Correlations Between the Performance Measures and Their Canonical Variables

                              IMPACT1       IMPACT2       IMPACT3

              CYCLE_HR         0.9976        0.0010       -0.0690
              WIP              0.9918        0.0227       -0.1256
              FG               0.9973        0.0550       -0.0484


      Correlations Between the Cycle Time Reduction Tactic and Their Canonical Variables

                              TACTIC1       TACTIC2       TACTIC3

              SETUP            0.0321       -0.9992       -0.0257
              NVA              0.9990        0.0329       -0.0298
              LOT_SIZE         0.0306       -0.0247        0.9992


Correlations Between the Performance Measures and the Canonical Variables of the Cycle Time Reduction Tactic

                              TACTIC1       TACTIC2       TACTIC3

              CYCLE_HR         0.9968        0.0002       -0.0065
              WIP              0.9910        0.0038       -0.0118
              FG               0.9965        0.0092       -0.0046


Correlations Between the Cycle Time Reduction Tactic and the Canonical Variables of the Performance Measures

                              IMPACT1       IMPACT2       IMPACT3

              SETUP            0.0321       -0.1668       -0.0024
              NVA              0.9982        0.0055       -0.0028
              LOT_SIZE         0.0306       -0.0041        0.0941
```

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                  ECONOMIC IMPACT OF OPERATIONAL STRATEGY          14:52 Saturday, April 4, 1998  18

                       Canonical Redundancy Analysis

                  Raw Variance of the Performance Measures
                                Explained by
                    Their Own                           The Opposite
                 Canonical Variables                 Canonical Variables

                          Cumulative    Canonical                  Cumulative
            Proportion    Proportion    R-Squared    Proportion    Proportion

        1       0.9941        0.9941       0.9983        0.9924        0.9924
        2       0.0029        0.9970       0.0279        0.0001        0.9925
        3       0.0030        1.0000       0.0089        0.0000        0.9925


               Raw Variance of the Cycle Time Reduction Tactic
                                Explained by
                    Their Own                           The Opposite
                 Canonical Variables                 Canonical Variables

                          Cumulative    Canonical                  Cumulative
            Proportion    Proportion    R-Squared    Proportion    Proportion

        1       0.0563        0.0563       0.9983        0.0562        0.0562
        2       0.0561        0.1124       0.0279        0.0016        0.0578
        3       0.8876        1.0000       0.0089        0.0079        0.0657


              Standardized Variance of the Performance Measures
                                Explained by
                    Their Own                           The Opposite
                 Canonical Variables                 Canonical Variables

                          Cumulative    Canonical                  Cumulative
            Proportion    Proportion    R-Squared    Proportion    Proportion

        1       0.9912        0.9912       0.9983        0.9895        0.9895
        2       0.0012        0.9924       0.0279        0.0000        0.9896
        3       0.0076        1.0000       0.0089        0.0001        0.9896
```

```
                 Canonical Redundancy Analysis

     Standardized Variance of the Cycle Time Reduction Tactic
                         Explained by
           Their Own                           The Opposite
       Canonical Variables                 Canonical Variables

                  Cumulative   Canonical                Cumulative
      Proportion  Proportion   R-Squared   Proportion   Proportion

 1      0.3333      0.3333      0.9983       0.3328       0.3328
 2      0.3333      0.6667      0.0279       0.0093       0.3421
 3      0.3333      1.0000      0.0089       0.0030       0.3450

Squared Multiple Correlations Between the Performance Measures and the
   First 'M' Canonical Variables of the Cycle Time Reduction Tactic

         M                  1           2           3

         CYCLE_HR      0.9936      0.9936      0.9936
         WIP           0.9821      0.9821      0.9822
         FG            0.9930      0.9930      0.9931

Squared Multiple Correlations Between the Cycle Time Reduction Tactic
  and the First 'M' Canonical Variables of the Performance Measures

         M                  1           2           3

         SETUP         0.0010      0.0289      0.0289
         NVA           0.9964      0.9964      0.9964
         LOT_SIZE      0.0009      0.0010      0.0098
```