A SYSTEM DYNAMICS APPROACH TO STUDYING MANUFACTURING STRATEGY

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

BY

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ABSTRACT

Many firms take actions which affect their competitive position without fully understanding the complexities of relationships and linkages among decision areas of manufacturing strategy. A lack of knowledge or explanation of relationships among widely disparate and dispersed elements of production in a firm has been cited as one of the key reasons why manufacturing has slipped to being a millstone rather than a source of competitive advantage. The standard techniques utilized in Operations Research today are almost incomprehensible to the typical manufacturing manager. Manufacturing managers need a process to help them effectively integrate their actions in manufacturing meaning that they must be able to understand the relationships among the decision areas of manufacturing strategy from a holistic approach rather than a piecemeal or micro-functional point of view.

The research in this dissertation uses Systems Dynamics to conceptualize a systems dynamic model which can be simulated for the purposes of better understanding what constitutes manufacturing strategy, and why certain decision choices mesh more successfully and lead to a superior competitive position. In addition, this work identifies maintenance as a key decision area that has not been previously linked to manufacturing strategy.

The simulations conducted for this dissertation indicated that manufacturing as a system can behave in unexpected ways. In addition to confirming that maintenance indeed does influence manufacturing strategy. This shows that it is not enough to assume one knows how the system will respond; it is necessary to think carefully about how the strategies one sets influence other parts of the system.

The author hopes that the concept of a systematic holistic approach to studying manufacturing strategy will help managers in industry to understand the complex nature of operations management and that operations management can become a competitive weapon if decision areas are effectively linked. In addition, the results of adopting a systematic holistic approach validates the fact that if one does not believe that a system can behave in unexpected ways, one will not be on guard and think carefully about the ramifications of one's strategic and policy decisions. This was one of the main reasons for this dissertation.

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I am indebted to all the people in industry from senior manufacturing managers to front line supervisors , who took time off their busy schedule to be interviewed. Without their input, the dissertation could not have been accomplished. They are an important source for theoreticians to explore and test theories for new practices in management.

Last, and most of all, I must thank my wife Majda Ficko and my son Demitri for their unending patience, understanding and support under unfair conditions. Without their support and understanding, this dissertation could not have been accomplished.

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CHAPTER 1

INTRODUCTION

The research in this dissertation attempts by using system dynamics to gain insight into manufacturing strategy. Manufacturing strategy concerns itself with integrating operations management decisions and linking them with the firm's business strategy to attain a competitive position. System Dynamics is a rigorous method for qualitative description, exploration and analysis of complex systems in terms of their processes, information, organisational boundaries and strategies, which facilitates quantitative simulation modelling and analysis for the design of system structure and control (Wolstenholme 1990). The objective of the proposed research is to conceptualize a systems dynamics model which can be simulated for the purposes of better understanding what constitutes manufacturing strategy, and why certain decision choices mesh more successfully and lead to a superior competitive position. This dissertation focuses on understanding relationships among some operation management decisions which constitute the content of manufacturing strategy. This research focuses specifically on the content of manufacturing strategy and excludes issues relating to the process of planning strategy which, although is equally important, but is left as an area of future research.

1.1 RESEARCH OVERVIEW

The purpose of this research is threefold. First, issues and questions that need to be answered to bridge the gap in the knowledge base are identified, based on a review of the current literature. Second, a qualitative analysis is conducted whereby a system dynamics model representing some of the operations management decisions commonly part of manufacturing strategy is conceptualized. Maintenance is introduced as one key decision area of operations management. Third, a quantitative analysis on one sector of the manufacturing strategy model is conducted for the purposes of illustrating how a systems dynamic approach can offer a means to visualize how a system in its entirety works. The analysis demonstrates that by better understanding relationships among and within a system, policies can be evaluated in a more concrete and decisive manner, which leads to better decision making.

The first chapter initially presents an overview of the research problem, the methodology used, and expected contributions. The next section defines manufacturing strategy, as viewed in this research. The motivation for this research is discussed in the third section. The fourth section presents an overview of the research methodology. The fifth section discusses the research problems addressed in the dissertation. The sixth section summarizes the contributions of this research.

A review of the current literature on manufacturing strategy is presented in the second chapter. The third chapter introduces the concepts of Systems Dynamics modelling. A qualitative analysis of our conceptualizing of the manufacturing strategy model is described in chapter four. The fifth chapter describes the systems flow diagrams for the maintenance sector of the manufacturing strategy model, along with the associated equations for the flow diagrams. The sixth chapter examines various scenarios within the maintenance sector of the manufacturing strategy model. Lastly, the seventh chapter summarizes the research contributions and the direction for future research.

1.2 MANUFACTURING STRATEGY DEFINITION

Recent competitive pressures have triggered an increased attention on manufacturing management and its role in creating sources of competitive advantage. This increased attention has led to a broader, strategic view of manufacturing and its potential to help firms compete successfully. Managers, strategists and research scholars are promoting manufacturing strategy as a formal framework for thinking strategically. This broader view has thrust manufacturing strategy or operations management strategy to the forefront of management approaches believed to have answers for the competitive ills of the firm. The popularity of manufacturing strategy as a management concept has also led to diverse views and definitions of manufacturing strategy.

In this research, manufacturing strategy is defined as a pattern of decisions designed to (a) link operations management decisions to the firm's business strategy, (b) link operations management decisions with each other so that they do not counteract each other, and (c) link the operations management decisions with the other functional strategies or decisions. Figure 1 shows the various linkages that constitute operations or manufacturing strategy. The term link and linkages imply relationships among decisions. Two other terms, integrate and mesh, are used interchangeability with link in this thesis.

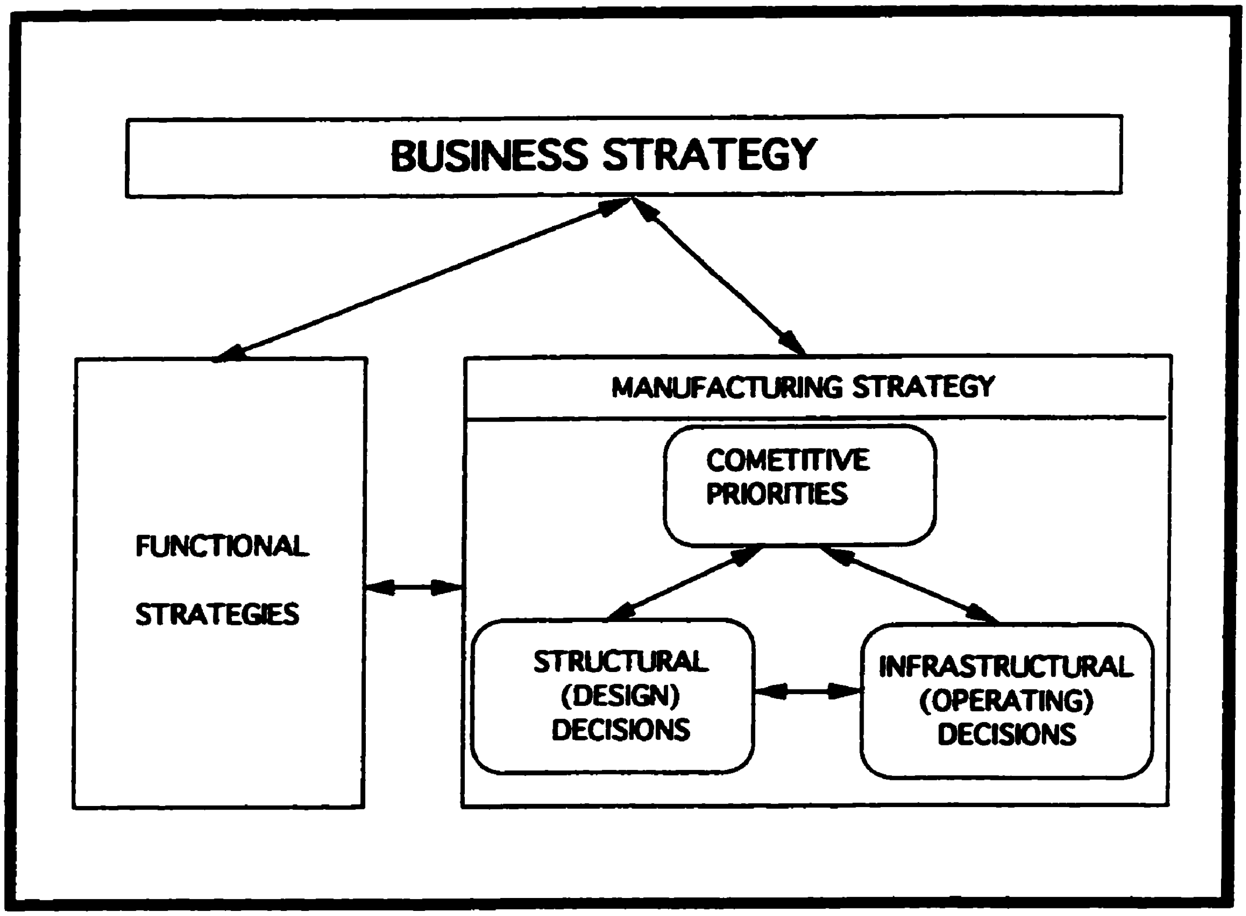

Figure 1. Linkages

Manufacturing strategy can be intended or realized. Intended strategy is that which management desires to implement. Realized strategy is that which currently directs the firm's direction and actions. Intended strategy is typically expressed by formal statements regarding planned actions. Realized strategy is reflected by the decisions and choices currently implemented in the plant.

This research focuses its attention on realized strategy for two reasons. First, realized strategy exists in every organization, irrespective of whether it is formally planned or not. In other words, an organization may not formally plan a strategy, but it still has a strategy which is reflected by the decisions and choices made in the organization. Swamidass (1986) reports in his survey that very few companies express manufacturing strategy formally. Second, the final outcome and performance of a plant depends on the decisions implemented rather than on decisions or choices that are planned for implementation.

1.3 RESEARCH PROBLEM MOTIVATION

The pressures to understand and gain greater insights into managing manufacturing strategically comes from two sources: practice and academe. The pressures on managers to make manufacturing respond to competitive needs of the business motivates research scholars to develop a better understanding of operations and its relationship to business strategies.

1.3.1 Growing Pressure On Manufacturing Managers

The pressures on managers, strategists and economists to improve the competitiveness of the manufacturing sector is enormous, not only in the U.S.A. and other industrialized nations but also in developing countries. A healthy manufacturing or industrial sector is essential for the survival and growth of national economies (Manufacturing Studies Board Report 1986; Cohen and Zysman 1987). Without a strong manufacturing sector, a nation loses its ability to produce and market products competitively against foreign competitors. Trade deficits are one sign of a manufacturing sector that is not competitive in the global economy. Trade deficits add to a nation's debt. As a nation's debt increases, it has to set aside increasing proportions of its gross national product for paying interest on the debt. This reduces the gross national product available per person. Gross Nation Product (GNP) per person is a measure of the standard of living.

The trade deficits and the slow economic growth, particularly in the U.S.A., indicate that an expanding service economy may not be enough to sustain a healthy economy. In fact, the manufacturing economy is critical to the survival of a service economy. Cohen and Zysman (1987) in their book eloquently argue why manufacturing matters. They argue that half of the service jobs are directly related to manufacturing. Many of the service jobs essentially perform functions or activities to support production and manufacturing activity. If manufacturing vanishes, then service jobs related to manufacturing also vanish. Therefore, a healthy manufacturing sector is critical for a healthy service economy.

The governments in many countries are intervening to artificially buffer their manufacturing or industrial sector against the increased global competition (Vernon 1986). The governmental effort to make manufacturing competitive, both in U.S.A. and in other industrialized countries such as Japan and France, also reflects the importance of manufacturing to the national economy. A healthy manufacturing sector seems essential to sustain and improve the standard of living of its citizens. Thus managers, strategists, policy makers and research scholars must shoulder the responsibility of making manufacturing more productive and competitive, to keep the national economics healthy and the standard of living for its citizens high.

Today's business environment is much more complex than ever before. Economic, technological, government regulations and social demands have made the business environment more hostile and competitive. Technological advances have made national economics more interdependent than ever. The rapid development of new technology and its equally rapid diffusion across companies nationally and internationally continues to intensify competition. The decline in the growth of the world economy is resulting in surplus capacity in almost every industry (Wall Street Journal March 9, 1987), which further increases the already intense global competition (Manufacturing Studies Board Report 1986).

Markets are also becoming more fragmented (Manufacturing Studies Board Report 1986). Customer needs are no longer homogeneous as they were perhaps a decade or two ago. The fragmentation of the markets and the slower demand growth has led to an increase in product diversity and a decline in the volume per product. For example, in the food industry the number of product lines increased 21% in the last four years without any increase in the overall demand (Metz et al 1986). As a result the average market share per product line declined, considerably reducing the volume per product line. Volume reductions change the cost structures and alternatives that a company can use. Thus, there are ever greater demands on manufacturing to respond to customer's needs.

Two conclusions are apparent. First, competition in the industrial sector continues to increase, and second, a competitive and productive industrial sector is essential for the long-term prosperity of a national economy.

1.3.2 The Need For More Research

The management of manufacturing requires actions that emphasize the firm's business strategy to make it more competitive. Two different approaches are being adopted by American manufacturers to improve their competitiveness: productivity improvement and an integrative approach (Skinner 1986). In a bid to regain competitiveness quickly, many American firms are emphasizing productivity improvement through cost reduction and waste elimination. Skinner (1986) reports that this productivity approach to manufacturing is not enough since companies cannot cut costs deeply enough to restore competitive vitality.

There are other firms such as General Electric, Chrysler, Outboard Marine, and Allen-Bradley that are adopting the integrative approach. The recent successes in the plants owned by these U.S. companies (Wall Street Journal, Sept. 6, 1986) and Japanese companies (Wheelwright 1981) are an evidence of how an integrated approach can lead to competitive success. The integrative approach subscribes to the argument that manufacturing decisions must mesh with each other and with the firm's business strategy. The effectiveness of an integrative approach in some of the examples cited above is one reason for conducting research on how to integrate actions in manufacturing. If theories are made available, then manufacturing firms may be better able to achieve superior performances more consistently.

A lack of knowledge or explanation of relationships among widely disparate and dispersed elements of production in a firm has been cited as one of the key reasons why manufacturing slipped to being a millstone rather than a source of competitive advantage (Skinner 1978; Hill 1985; DeMeyer and Ferdows 1986).

The current literature pays very little attention to the actual content of operations management strategy. Lack of research in this area makes it difficult to ascertain how manufacturing strategy ties in with business strategy, takes advantage of operations talent and resources, and interacts with the environment. What objectives should operations pursue? What are the policies for quality, capacity, workforce, etc? What is the relationship between objectives and policies? How does operations help the business compete? These are only some of the questions we find hard to answer without a sound working knowledge of the interrelationships among operation management decisions (Anderson et al. 1989).

Up until the early nineties the majority of the research in manufacturing strategy focused on a single content area such as quality (Garvin 1986) or facilities (Schmenner 1983). Little research has been aimed at understanding the relationships that exist among content areas or how decisions in one content area affect decisions in other areas (Leong et al. 1990).

Research scholars must bear blame for this lack of knowledge base. More knowledge about integrating actions in manufacturing is needed. Such information will help managers transform manufacturing from a millstone to a source of competitive advantage. In essence there is a need to develop an extensive knowledge base to guide systematic planning and implementation of manufacturing strategy to bring manufacturing to the level of other function's as being a source of competitive advantage.

Developing an extensive knowledge base about the integration of actions in manufacturing means understanding the relationships among operations management decisions. Porter (1980) suggests that firms are better able to develop sustainable competitive positions if the decisions mesh with each other. The soundness of Porter's argument re-emphasizes the importance for studying relationships within manufacturing strategy. Noori (1990) suggests that more and more, competitive advantage will go to the companies that seek strategic breakpoints through the integration of decisions in every area of manufacturing.

The benefits of developing an extensive knowledge base in manufacturing strategy extend beyond the boundaries of the operations management discipline. The success of business strategy depends to a large extent on its successful implementation. Business strategies are implemented through functional strategies; the more effective the manufacturing and other functional strategies: the more successful the implementation of the business strategy. The progress of the implementation aspect of the field of strategic management depends to a large extent on the advancement in functional strategies. Therefore, research in functional strategies, such as manufacturing strategy, is important.

In summary, this research is driven by the importance of manufacturing to national economies, the rapidly changing competitive environment that mandates an integrated approach to managing manufacturing, and finally, by the present lack of a knowledge base dealing with strategic relationships in operations.

1.4 RESEARCH METHOD OVERVIEW

Until recently, the majority of research on manufacturing strategy, such as that by Abernathy (1975, 1976) and Skinner (1969, 1974), has mainly relied on case studies. Recently, there have been some empirical studies

(Schmenner 1982, Miller et al. 1983, 1984, 1985, 1986; Hayes and Clark 1985; Roth et al. 1987; DeMeyer et al. 1987) that have statistically analyzed data collected from many organizations. There also have been some studies that have employed analytical (Cohen and Lee 1984) analysis to gain insight into the linkages in manufacturing.

A significant weakness of the above mentioned research is that most of the research tends to be deep rather than broad in scope. In other words, most content studies found in the literature focus on a single content area and give little attention to interactions with other content areas. (Leong et al. 1990). Therefore, one may suggest that the majority of research to date is being conducted from a disjunctive point of view rather than of a holistic one.

This research examines manufacturing strategy from a systems thinking perspective which focuses on problem solving and analysis of complex real world systems by methodological means, where the emphasis is on promoting holistic understanding rather than piecemeal solutions.

According to Marquardt (1994) systems thinking, particularly systems dynaimcs, can be a very powerful tool to facilitate organizational learning. Systems dynamics recognizes that organizations are like giant networks of interconnected nodes. Changes, planned or unplanned, in one part of the organization can affect other parts of the organization with suprising, often negative consequences.

The use of the systems dynamics approach permits relatively easy modelling of the somewhat imprecise relationships between the parameters and processes of interest (Chen et al. 1995).

Senge (1994) describes systems thinking as a "discipline for seeing wholes, a framework for seeing interrelationships rather than linear cause-effect chains, for seeing patterns of change rather than snapshots".

This research draws on the systems dynamics methodology developed orginally at MIT (Forrester 1961, 1969; Roberts 1978) to first, conceptualize a qualitative model that can offer a means to better understand relationships among the decision areas of process, quality, workforce management, materials management and maintenance (which in this research is being introduced as a decision area) in manufacturing strategy. Secondly, a quantitative analysis is conducted to provide insights on the effects of the proposed variables for the decision area of maintenance within manufacturing.

Qualitative system dynamics is based on creating cause and effect diagrams (causal loop or influence diagrams) which create a forum for translating our individual's thoughts, perceptions and assumptions about a system into usable ideas which can be communicated to others. The intent is to increase the understanding of each individual and, by sharing their thoughts to make them aware of the system as a whole, and of the interrelationships of the various parts within the system. Essential to understanding systems is being aware of the process and information structure of the system and is referred to the information feedback structure of the system. Fundamental to system dynamics is the concept of feedback structures which are deemed to be a direct determinant of the system's behavior over time.

Once created, the casual diagrams can be used to qualitatively explore alternative structure and strategies, both within the system and its environment, which might benefit the system. Although comprehensive simulation is not advocated by the method at this stage, it is possible from a study of the feedback loop structure of the diagrams, to estimate their likely general direction of behavior (e.g: growth or decline). Further by using some of the experiences from the results of quantitative simulation modelling in other systems it is possible to apply guidelines for the redesign of system structures and strategies to improve system behavior.

The next step to qualitative system dynamics is quantitative computer simulation modelling using specialized software. It involves dereiving the shape of relationships between all variables within the diagrams, calibration of parameters and the construction of the simulation equations. Although numbers are attached to variables during quantitative simulation modelling, it should be stressed that the method is not aimed at accurate prediction or solutions. It is more concerned with the shape of change over time. Accurate prediction on the basis of past performance assumes that the structure and strategies of the future will not be too dissimilar from the past. If the purpose of the model is to redesign structure and strategies, prediction needs, by definition, to be less accurate. Emphasis is on the process of modelling as a means of improving understanding; the idea being that such understanding will change perceptions and add to the ability of decision makers to react better to future problems (Wolstenholme 1990).

The power of quantitative system dynamics has been significantly enhanced in recent years by the development of the desk-top computer and associated software. The creation of computer simulations of dynamic models has always been a significant factor in improving systemic understanding. This is because there is a severe limit in the cognitive ability of the human brain to process multi-variate problems without such help. Never before has computer power been so readily accessible and the potential this creates for experimental learning through questioning is enormous (De Geus 1988).

Why use simulation to analyze manufacturing strategy? First, many practical problems cannot be solved with optimizing methods. The relationship between the variables may be nonlinear and very complex. In addition, there may simply be too many variables and/or constraints to handle with current optimizing approaches. A simulation model may be the only way to estimate the operating characteristics and analyze the problem.

Second, simulation models can be used to conduct experiments without disrupting real systems. Experimenting with a real system can be very costly. It would be unreasonable to go through the expense of purchasing and installing a new flexible manufacturing system without first estimating its benefits in detail from an operating perspective. A simulation model can be used to conduct experiments for a fraction of the cost of installing such a system. Also, the model could be used to evaluate different configurations or processing decision rules. To try any of these methods while attempting to maintain a production schedule would be virtually impossible.

Third, simulation models can be used to obtain operating characteristic estimates in much less time than required to gather the same operating data from a real system. This feature of simulation is called time compression. For example, a simulation model of the manufacturing operations of a plant can generate five years worth of statistics regarding the cycle time of products, effects of a labor strike, production systems, layoffs and effects of quality on on-time deliveries, in a matter of minutes on a computer. Alternative strategies and policies could be analyzed and decisions made easily.

1.5 RESEARCH PROBLEM OVERVIEW

Two problems are studied in this thesis. The first problem is the conceptualization of a qualitative model to represent some of the operations management decision areas of manufacturing strategy with maintenance being introduced as new specific key decision area. The current literature on manufacturing strategy describes eight key decision areas of manufacturing strategy - capacity, workforce management, quality, process, materials management, production planning, new product development and technology (Hayes and Wheelwright 1984, Fine and Hax 1985). Nowhere in the current literature has the author to the best of his knowledge found any mention of maintenance as a key strategic decision area of manufacturing strategy. The decision areas selected for the present research are quality, workforce, process, materials and maintenance. Within each decision area are factors or key variables that can significantly influence the behavior of the decision areas. In order for the model to be representative of the decision areas, it is imperative that appropriate variables are selected.

In developing the model, two distinct avenues were pursued in the process of selecting variables for the decision areas under examination. Variables for the decision areas of process, quality, materials management, and workforce management were deductively derived from the author's existing knowledge base. Interviews were then conducted with manufacturers in industry ranging from senior manufacturing managers to front line manufacturing supervisors to validate the selection of the key variables. The influence diagrams as described in this dissertation have evolved as a result of numerous discussions with individuals that have had direct involvement in developing manufacturing strategy in industry. Since there seems to have been little, if any, published effort to date to relate maintenance to manufacturing strategy, the variables identified for this decision area in the model are of an exploratory nature by the author as a result of his own experiences and insights gained from being directly involved in the process of developing maintenance strategies within two very large manufacturing organizations in North America. The author's experiences with the maintenance departments of these two large manufacturing organizations were utilized to propose and verify the variables for the maintenance sector of the model.

The second problem addressed in this thesis is a quantitative analysis of one sector of the manufacturing strategy model (the maintenance decision area), conducted for the purposes of illustrating how a systems dynamic approach can offer a means for people to visualize how a system in its entirety operates. The analysis demonstrates that by better understanding relationships among systems and within a system, policies can be evaluated in a more concrete and decisive manner, thus leading to better decision making. The variables studied within the maintenance decision area are percentages completed for both preventive maintenance and maintenance requests, the level of the production machine operator's involvement with maintenance, the operating condition of the production equipment and production equipment capacity to produce product.

According to the Executive Summary of the 1987 North American Manufacturing Futures Survey, competitive priorities based on quality, and delivery time will be the theme of the nineties. Delivery time denotes the elapsed time between receiving a customer's order and filling it. Speed of delivery is viewed as a means of achieving superior service quality (Wheelwrigh 1978; Hayes and Schemmer 1978). Krajewski and Ritzman (1987) consider fast delivery as an independent basis for gaining competitive advantage.

A key measure of the delivery time is the cycle time for a product. Cycle time is defined as the time required to manufacture one part or product unit. Cycle time has been selected as the measure to examine relationships among and within the decision areas of process, quality, material management, workforce management and maintenance.

1.6 RESEARCH CONTRIBUTIONS

This thesis hypothesizes that the use of a systems dynamics model will create an indepth understanding of a manufacturing system, not evident in routine everyday operations, and that this heightened understanding can be used to have more meaningful insights which would lead to more effective policy and decision making.

If this hypothesis is correct, it is expected that in utilizing the model, managers will be asked to come up with data they do not typically collect and to view the system in ways they have never before done. As a result one would expect that utilizing the model will generate substantial discussions about what the key points of the system and the key parameters really are.

In addition, it is proposed that, in its role in exacting an understanding of the most important aspects of the system and their interactions, the modeling tool can be used as a communication device for visualizing and better discussing how the organization operates. The above expectations will be tested on one sector of the model, the maintenance decision area.

In summary, the contributions of this research from an academic standpoint lies in two areas. First in the development of a new perspective on understanding manufacturing strategy, and second, in the introduction of maintenance as another strategic operations management decision area within manufacturing. A quantitative analysis of the maintenance decision area demonstrates the main theme of this research (i.e. creating a better understanding of a system which leads to more effective decision making), and its applicability within industry

1.7 CONCLUSION

This chapter briefly describes the main thrust of this thesis. Manufacturing strategy is to be examined utilizing a systems dynamics approach. This chapter identifies the need for more research on the relationships among and within decision areas of manufacturing strategy from a holistic point of view. Hence, the research problems were established around using system dynamics to model some of the operations management decision areas of manufacturing strategy.

An overview of the research methodology was provided. This study identifies the key variables of the selected decision areas of manufacturing strategy. A qualitative model will be conceptualized and a quantitative simulation analysis conducted on one sector of the model to demonstrate that by better understanding relationships among and within a system, policies can be evaluated in a more concrete and decisive manner which leads to better decisions.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews the current knowledge base on manufacturing strategy. The purpose is to classify and categorize past research with the intent of identifying issues and areas that represent gaps in our knowledge. The objective is not to describe and summarize the current knowledge base, but to use it as a framework to guide future research. This review uses ideas from the strategy management literature to classify past research on manufacturing strategy.

The next section briefly introduces and defines some concepts that are used to categorize manufacturing strategy research. The review here organizes the literature in terms of the key elements of managing manufacturing strategy - planning, control and process. The second, third and fourth sections present a discussion on the three components of planning strategy - decisions, linkages and segmentation. The fifth section reviews the literature on the control of strategy, and the sixth section deals with the process of planning and controlling strategy. Finally the last section discusses some directions for future research.

2.1 INTRODUCTION

This section describes some concepts for classifying the literature on manufacturing strategy. The concepts and terms borrowed from strategy management literature are first discussed. The role of "Operations" (i.e. the Operations Department or Function of an enterprise) in managing organizational strategies is also briefly discussed in the first subsection; the purpose is to show how manufacturing strategy fits into the broader picture of managing organizations strategically. A paradigm proposed to describe the content and process of managing manufacturing strategy is also presented here. The paradigm is used as basis for developing a taxonomy to organize and classify the manufacturing strategy literature. The taxonomy presented in the third subsection summarizes the dimensions according to which the literature is reviewed.

2.1.1 Strategy Management

This section first defines strategy, and then describes the different levels at which strategy is managed. Two planning paradigms proposed in the strategy management literature are also briefly reviewed.

2.1.1.1 Strategy Definition

Strategy, derived from the Greek word strategos meaning "art of the general" was introduced into the management literature in the 1960's. Research scholars labeled the "pattern of objectives, purposes, or goals and major plans and policies for achieving these goals . . ." as strategy (Andrews, Learned, Christensen and Guth 1965). Schendel and Hoffer (1978) offer a composite definition of strategy built around four components: (1) scope, defined in terms of product/market and geographic territories, (2) resource deployments and distinctive competencies, (3) competitive advantage, and (4) synergy.

2.1.1.2 Strategy Levels

Strategy researchers (Ansoff 1967; Ackoff 1970; Schendel and Hoffer 1978; Hax et al. 1985) concur on three organizational levels at which strategy is typically planned: corporate, business and functional. Table 1 describes the purpose and role of strategy at each level. Manufacturing strategy is one functional strategy. Marketing, human resources, research and development (R & D), and financial/control are other functional strategies through which the business strategy is articulated.

Strategy Level	Purpose
Corporate	Defines what businesses to be in and how resources are to be acquired and allocated among different businesses
Business	Defines how to compete for each business
Functional	Defines how to develop sources of competitive advantage within a particular function of a business

Table 1. Strategy levels

Functional strategies are the medium through which the corporate and business strategy is implemented. The successful implementation of higher level strategies depends on functional strategies. As researchers start to emphasize strategy implementation, functional strategies such as manufacturing strategy are becoming areas of interest.

2.1.1.3 Strategy Management Paradigms

Many approaches and frameworks have been proposed for managing strategy. Most of the approaches find their roots in two basic paradigms: rational and incremental. These two paradigms are regarded as being at the two ends of a continuum of strategy planning approaches. Figure 2 defines the two paradigms at the extreme ends of the continuum.

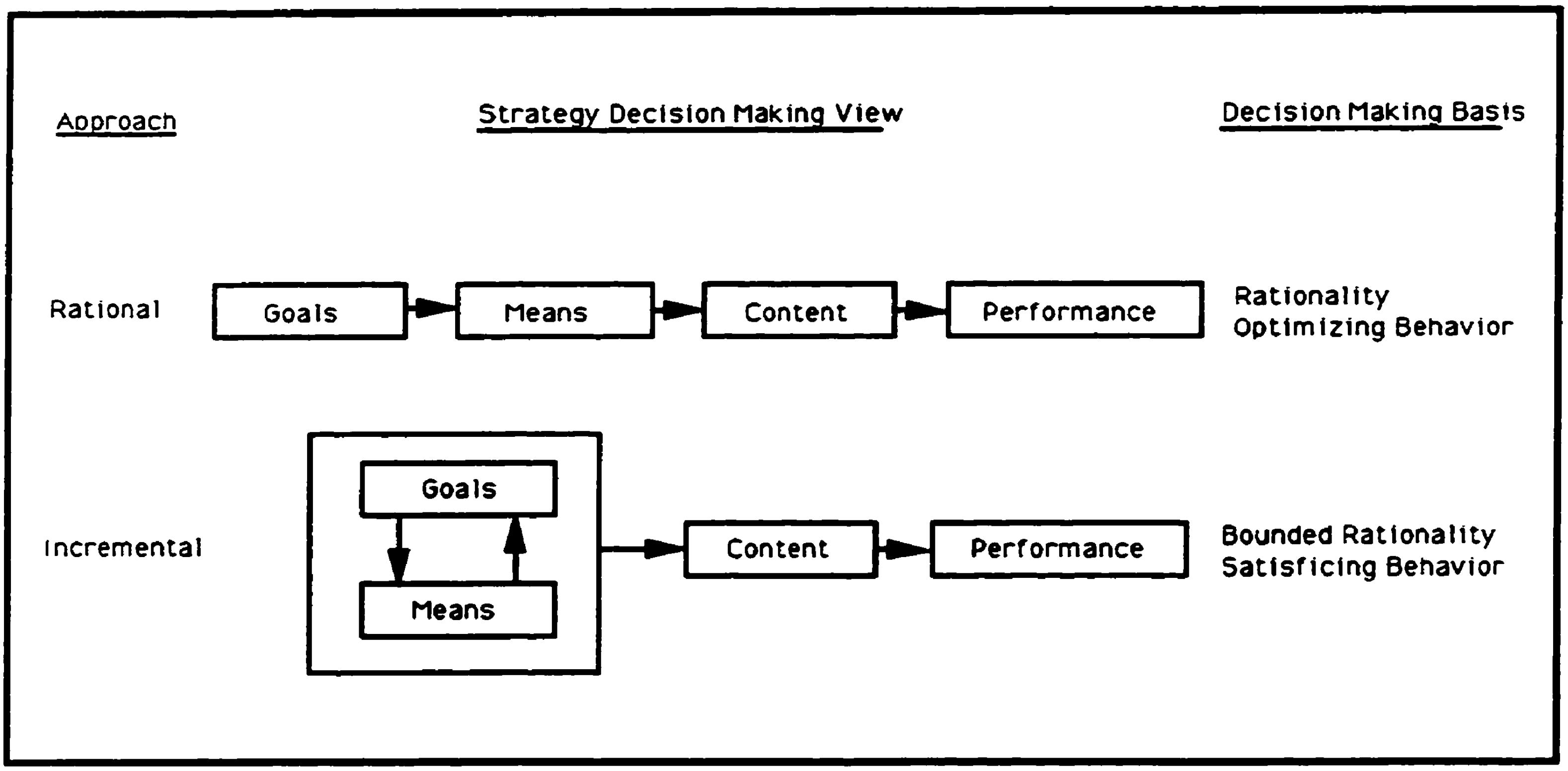

Figure 2. Approaches for managing strategy

The rational paradigm (described in Bourgeois 1980) for strategy planning involves four steps. Decision makers (after carefully analyzing environmental conditions and organizational capabilities) first define goals and objectives. Second, they generate a comprehensive list of policy alternatives (means) and evaluate the probabilities associated with the consequences in terms of satisfying corporate objectives. An alternative is then chosen and the actions to implement the alternative are defined (these constitute the content of the strategy). The action when taken affects performance (hopefully resulting in superior performance). The first two steps involve strategy formulation and the third step involves the strategy implementation. The rational approach assumes that some rationale and logic drive the decision-making process. One can argue that the premise behind the rationality assumption is the belief that there exist "universal laws", which when applied leads to superior performance. The rational paradigm essentially views functional strategy as a derivative of business and corporate strategy.

The incremental paradigm, on the other hand, suggest that goals and means are both mutually adjusted until the policy makers arrive at alternatives that offer an "acceptable" (versus optimal) solution. The goals are not necessarily fixed or well defined prior to consideration of alternatives. The goals and means are adjusted to what is feasible and politically acceptable to all the decision makers. Some researchers (Cyert and March 1963; Cohen, March and Olsen 1972) advocate the incremental approach over the rational approach; cognitive limits on human rationality to process knowledge, along with inertia against change, drive human beings to make marginal changes. The researchers argue that the incremental approach reflects the natural cognitive process of human beings. The incremental approach implies a bigger role for functional strategies than implied by the rational approach. The incremental approach suggests that functional managers negotiate a role that fits the capabilities and strengths of the functional area. The functional managers can modify the corporate goal and strategy in the incremental approach, whereas in the rational approach the corporate goals determine the role the functions must play in achieving the goal.

2.1.2 Manufacturing Strategy Definitions

Manufacturing strategy as a concept has existed in some form for many years. The principal idea behind the concept - to deploy manufacturing resources to efficiently produce goods that consumers value - is very simple. The example of the Ford Motor Company, mass producing inexpensive cars, exemplifies the notion as early as the beginning of the twentieth century. Although the idea behind manufacturing strategy is not new, manufacturing strategy as a research area has only received scholarly attention since the 1960's.

Manufacturing strategy as a scholarly topic originated in business courses taught at the Harvard Business School in 1950's. Researchers have written on the topic in scholarly journals since the 1960's. Thurston (1960) introduced the notion of integration, a key idea underlying manufacturing strategy. He argued that integrating product design, process design and material with each other and other functional areas is key to superior performance. Skinner (1969) suggested the idea that it is not enough for manufacturing to be efficient. He emphasized the need to make manufacturing an ally in the competitive struggle. He argued that manufacturing must work in synergy with other functional areas in accomplishing the business objectives. Skinner with his article in 1969 laid the foundation for the manufacturing strategy concept. Since then a number of books and articles have been written on the subject.

Most researchers subscribe to Skinner's (1960) view of manufacturing strategy. Even though there is general consensus on the purpose of manufacturing energy, differences on its definition, formulation and implementation have started to emerge. The next subsection presents two definitions of manufacturing strategy. Following that, a paradigm on manufacturing strategy management is presented.

2.1.2.1 Two Definitions

Two alternate views on manufacturing strategy are emerging. The first view considers strategy to be reflected by a pattern of decisions in operations (Skinner 1969; Wheelwright 1978, 1984; Hayes and Wheelwright 1984). This view concurs with Hoffer and Schendel's (1975) definition of strategy which is well accepted by strategy management scholars and professionals. Wheelwright (1984) contends that it is "the pattern of decisions that constitutes manufacturing strategy". The pattern of decision means how decisions relate to one another over time. Manufacturing strategy is embodied in decisions and choices, rather than in formal statements and documents.

The second view (Schroeder et al. 1989; Anderson et al. 1987) focuses on planned strategy. This view defines manufacturing strategy as formal statements regarding mission, objectives, manufacturing policy and distinctive competence. This definition focuses on the choices of alternatives and not so much on how those choices are applied. The distinctions made between mission, objectives and distinctive competence in the definition are somewhat ambiguous. All three seem to refer to the same thing - elements or dimensions that are considered important for achieving advantage over the competitors. The second definition emphasizes strategy formulation and does not offer the breadth offered by the first view.

The two definitions view strategy differently. The differences in the two definitions can be explained in terms of Mintzberg's (1978) classification of patterns in strategy formulation (Figure 3). Strategies that are formally formulated and planned are defined as intended. The intended strategy may be realized or unrealized. Mintzberg (1978) defines a "pattern in a stream of important decisions" not planned by management as emergent strategies. The "pattern of decision" view seems to focus on realized strategy; but does not rule out the notion of intended strategy. The "formal statement" definition, on the other hand, views strategy in terms of intended strategy only. The first view is more realistic since every organization has a strategy, whether intended or not. Moreover, the first view is more flexible, since it allows either a holistic or disjunctive view of strategy.

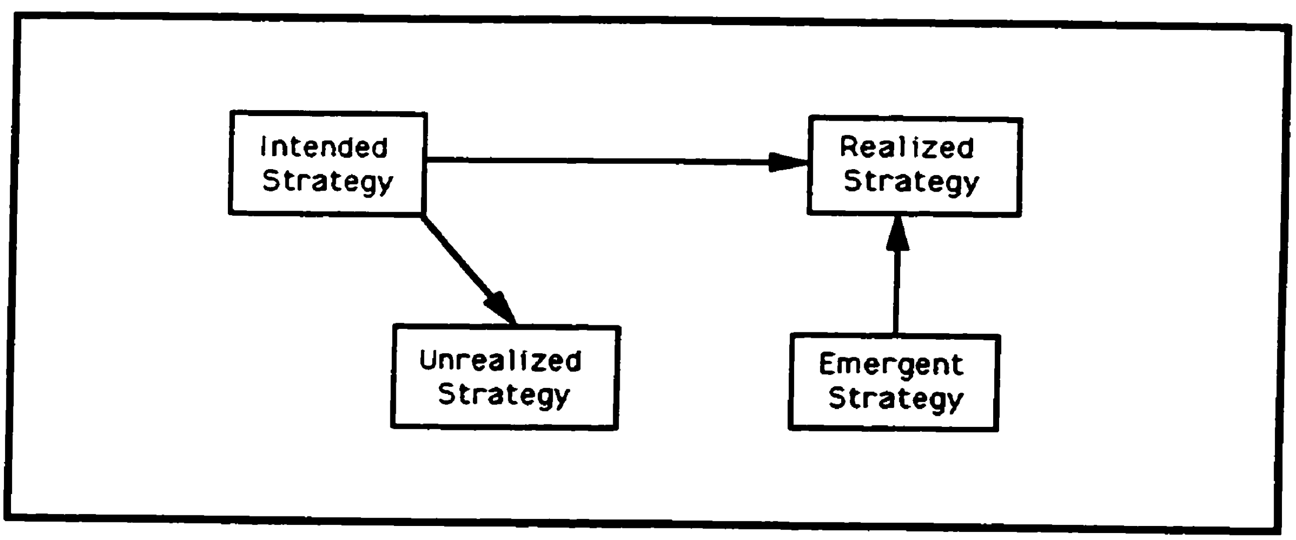

Figure 3. Strategy types
(Adapted from Mintzberg (1978))

The holistic view of strategy considers the total picture by looking at interactions and relationships between all strategic variables (Snow and Hambrick 1980; Ginsberg 1984). The holistic view assumes that there exists an internal integrative logic that links strategic variables and decisions. The disjunctive view examines relationships and interactions among a few variables.

The distinction between the two views and the type of strategy operationalized is important. Research scholars in strategy management (Mintzberg 1978; Snow and Hambrick 1980; Ginsberg 1984; Ginsberg and Venkatraman 1985) suggest that researchers must be explicit about the type of strategy being analyzed. Intended strategies require a different set of measures and operationalizations than do realized strategies.

2.1.2.2 A Paradigm

I now present a framework summarizes manufacturing strategy (Figure 4). The paradigm defines the components of manufacturing strategy and the dimensions associated with managing it. The paradigm schematically represents the process of managing manufacturing strategy. The paradigm is a synthesis of ideas suggested by several researchers in the literature.

Manufacturing strategy is seen to consist of (a) competitive priorities that define the mission or goals in operations, (b) strategic variables which comprise decisions in operations that have strategic significance, and (c) control variables for evaluating performance and controlling strategy implementation.

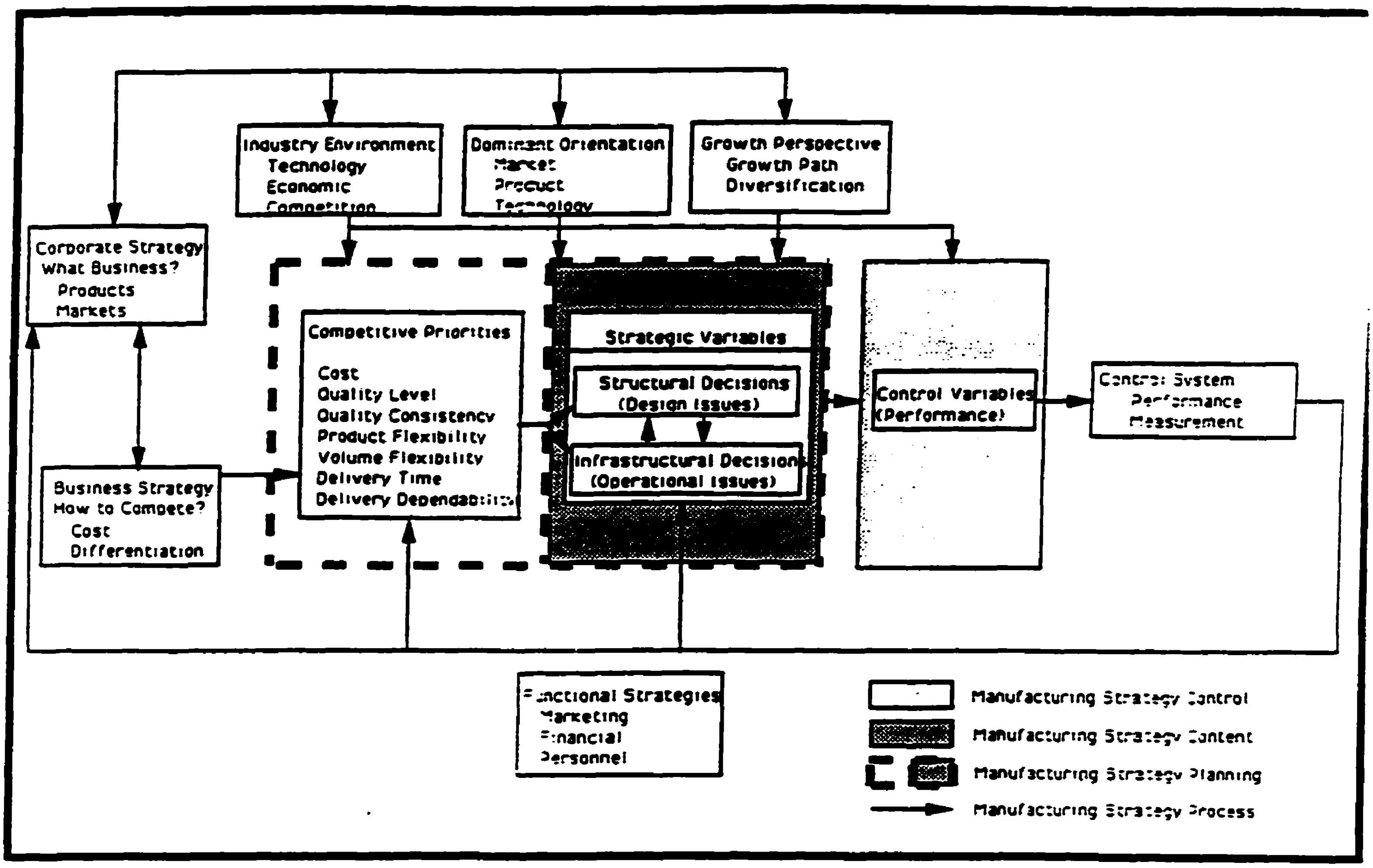

Figure 4. A Manufacturing strategy framework

The management of manufacturing strategy can be described in terms of several dimensions. Planning and control are two aspects of managing strategy. Planning refers to formulation and articulation of strategy. In other words, planning describes what actions to take under different competitive situations. Control refers to implementation of strategy and the evaluation of its effectiveness. Two other dimensions - content and process - are used to describe the management of manufacturing strategy. The content describes what decisions and linkages to consider in planning manufacturing strategy. In other words, content refers to the strategic variables and to the linkages among the variables for planning and controlling strategy. The process refers to the approach and procedures for planning and controlling manufacturing strategy. In other words, process describes how to plan and control strategy.

The strategic variables refer to those aspects of manufacturing decisions or corporate strategy that are important in planning and controlling manufacturing strategy. The framework broadly lists two categories of manufacturing decisions: structural and infrastructural. The structural decisions represent the decisions associated with design of operations and infrastructural decisions with day-to-day management of operations. Both structural and infrastructural decisions include elements that are of greater strategic significance than others.

Competitive priorities are another set of important variables for planning and controlling strategy. Business strategy defines how the company intends to compete in broad terms. Competitive priorities translate business strategy into specific objectives or goals that are meaningful to operations. Competitive priorities are a theoretical construct devised by researchers to understand and explain how the business strategy is articulated in operations. Competitive priorities broadly define the dimensions that are considered important in gaining competitive advantage.

Frameworks for manufacturing strategy typically consider competitive priorities to be above the functional level, at the business strategy level. Recent surveys (Miller et al. 1983, 1984, 1985, 1986; Schroeder et al. 1986; Swamidass 1986) indicate that priorities are developed based on business strategy above the functional level. The surveys also indicate that manufacturing managers do get involved in planning business strategies and competitive priorities. How competitive priorities are established and by whom is still unclear. The framework proposed here suggests that competitive priorities are established by all functional areas, including manufacturing. The competitive priorities are finally reflected in operations by the importance given to variables that are within the control of manufacturing management. The priority given to these variables are presumed to be under the jurisdiction of manufacturing managers.

Manufacturing strategy couples with corporate strategy through three variables: dominant orientation, growth perspective and industry environment. The dominant orientation defines the company's distinctive competence or strength. For example, some firms have strengths in marketing, other firms have competency in developing new products, and others are good at exploiting new technology either in products or processes. The growth perspective defines the amount of resources acquired and deployed by the corporation in manufacturing. The variables that describe the industry environment define the constraints and opportunities that manufacturing must consider in planning its strategy.

The linkages in Figure 4 are the relationships among decisions or strategic variables which include manufacturing decisions, competitive priorities and some corporate strategy decisions. The relationships explain how the decisions relate under different competitive scenarios. In practice, linkages among two actions imply that the two actions reinforce or counteract each other. In other words, when two decisions are linked it implies that the cumulative effect of the two decisions on performance is much less obvious than when the two are not linked. The relationships form the basis on which alternatives for each decision are chosen so that the decisions are consistent with each other and collectively emphasize the dimensions on which the company chooses to compete.

Our paradigm, draws from the various frameworks proposed for managing manufacturing strategy (Skinner 1969, 1974, 1978; Wheelwright 1978; Hayes and Schmenner 1978; Hill 1985; Hax and Fine 1985). The paradigm assumes

(a) a hybrid approach which includes aspects of both rational and incremental approach;

(b) all operations management decision areas must be considered in planning strategy, but only some decisions in each decision area have strategic significance;

(c) the fit between business strategy, functional strategies, and industry environment influences performance (i.e. strategy plays a moderating role);

(d) choice of alternatives should depend on the competitive priorities, industry environment, corporation's orientation and growth perspective;

(e) the dominant orientation and growth perspective come from corporate strategy;

(f) a comprehensive view of strategy;

(g) an underlying logic that determines the choice of alternatives for each decision;

(h) the process of managing strategy includes monitoring and feedback of performance.

2.1.2.3 Research Taxonomy

Only two attempts have been made at organizing the past research. An article in Operations Management Review (St. John, 1986) reviewed some key articles. The second review (Schroeder et al. 1987) classifies the past research. But the classification does not offer any systematic organization to motivate future research or assist strategists in grasping the concepts to manage strategy. Two difficulties encountered in reviewing the literature stand out. First, the body of knowledge seems almost like a collection of independent papers. Second, it is difficult to draw a boundary regarding what constitutes research on manufacturing strategy. I propose a taxonomy (Figure 5) to organize the body of knowledge on manufacturing strategy.

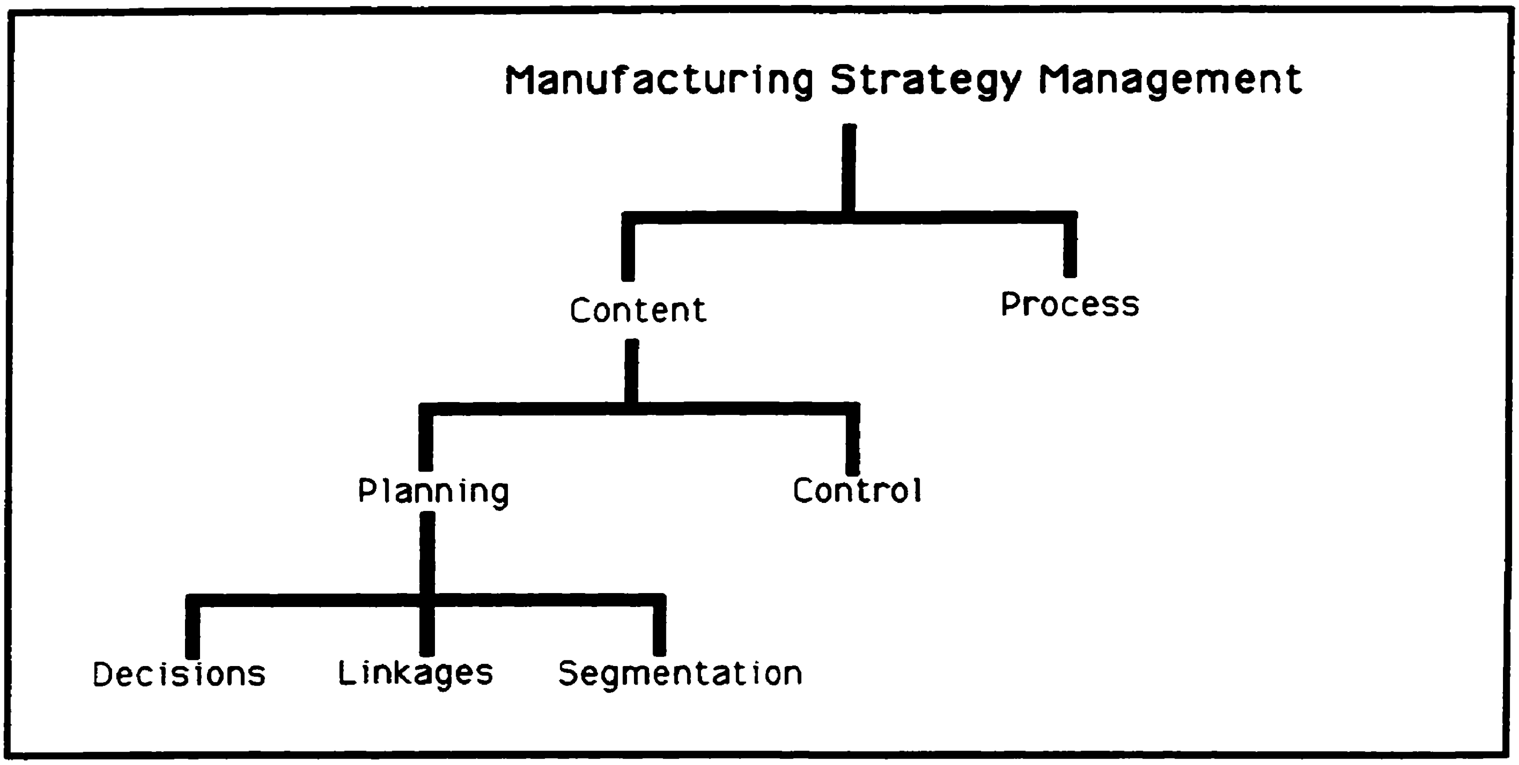

Figure 5. Proposed taxonomy for the study of manufacturing strategy

The literature is classified into two broad areas - content and process. Strategy content includes planning and control aspects of managing strategy. Three areas - decisions, linkages and segmentation - make up the issues involved in planning strategy. Each of the planning areas is discussed in the following separate sections. The section on decisions discusses the variables that are important in developing manufacturing strategy. The section on linkages discusses the relationships among the decisions. The segmentation section reviews variables and propositions in the literature for organizing plants. The control and process issues are also discussed in separate sections.

2.2 DECISIONS

Manufacturing strategy is planned and implemented through decisions, making decisions a key ingredient of manufacturing strategy. A distinction is made between decision area and decisions. Decision area comprises of a set of decisions. For example, there are a number of decisions that have to be made on the product manufactured in the plant such as the number of products, number of options, product commonality, degree of standardization, number of features, type of features and the color the product is painted. These decisions make up the set of the decision on product, and so describe the product decision area.

Some of the product decisions may have greater strategic importance than others. For example, the decision on the color of the product is less important to manufacturing strategy than perhaps decisions on amount of part commonality or the number and type of features. All decision areas are important for developing a sound manufacturing strategy, but some decisions in each decision area are more important than others in planning manufacturing strategy. Note the term "decisions" is used synonymously with the term "strategic variables" in this thesis. The strategic variables pertinent to manufacturing strategy are classified into three categories: corporate strategy elements, competitive priorities and manufacturing decisions. The manufacturing decisions are further categorized into structural and infrastructural decisions.

There are differences in the set of decisions that researchers consider in describing manufacturing strategy, reflecting underlying differences in the theory and in the way researchers conceptualize strategy. The differences stem from the researchers' opinion on how different decisions interact and affect strategic direction.

There is a little empirical evidence to support or explain why some decisions are considered by the researchers and others are not. In other words, there is little available in the literature that explains which decisions to consider in manufacturing strategy. Only recently, researchers (Miller et al. 1983, 1984, 1985, 1986; Schmenner 1982; Schroeder 1986; Swamidass 1986; Roth 1987) have made attempts empirically to identify the variables that have strategic significance.

Corporate strategy interacts and directly influences manufacturing strategy through industry environment, dominant orientation, growth perspective and management philosophy (Skinner 1969; Hayes and Schmenner 1978; Wheelwright 1978; Wheelwright 1984).

Industry environment defines the opportunities and limitations of the business segment in which the corporation chooses to do business. Manufacturing has to confront technological and economic realities of the industry in developing its strategic posture.

The dominant orientation influences the product policies in manufacturing. The dominant orientation defines the range of products and markets the company feels competent in competing with. In some ways dominant orientation refers to distinctive competence - strength of the organization that sets it apart from other companies.

Some researchers (Hayes and Schmenner 1978; Schmenner 1978) argue the importance of growth policies in shaping manufacturing strategy. Two aspects of growth policy - growth rate and diversification pattern - influence manufacturing choices (Schmenner 1978; Wheelwright 1984). Growth policies essentially determine the amount of resources allocated to manufacturing and how the resources are to be deployed in seeking growth. Corporate missions for each business/plant define the unit's growth policy. The deployment of resources are also influenced by the entrance and exit strategies. The entrance and exit strategy (Hayes and Wheelwright 1979) defines the stage of the product life cycle at which the company plans to enter and exit the business.

Business strategy interacts with manufacturing strategy through competitive priorities. The competitive priorities serve the purpose of translating business strategy into objectives that are more meaningful to operations. Skinner (1969) first proposed the notion of manufacturing task as a means of translating business strategy to objectives more meaningful to operations. Other researchers (Wheelwright 1978; Hayes and Schmenner 1978) refined Skinner's ideas and proposed the notion of competitive priorities. More recently Krajewski and Ritzman (1987) further refined the notion. They suggest seven competitive priorities; cost, quality consistency, quality level, delivery time, delivery dependability, product flexibility and volume flexibility. Each of the seven priorities represents a basis for attaining competitive advantage.

The seven competitive priorities can be mapped to Porter's (1980) typology on competitive strategy. Porter (1980) suggests that cost and differentiation are two fundamental ways of achieving competitive advantage. The cost competitive priority relates directly to Porter's cost strategy. Since quality consistency improves productivity and lowers costs, quality consistency can also be viewed as a means by which low-cost strategy can be emphasized at the business level. Quality level and product flexibility enhance the product's differentiation. Delivery time, delivery dependability and volume flexibility offer advantages in marketing. The five competitive priorities - quality level, product flexibility, volume flexibility, delivery time, delivery dependability can be viewed as means of achieving differentiation strategy at the business level.

Structural decisions deal with the design of operations. These decisions relate to the deployment of resources. The structural decisions affect the "physical" aspect of manufacturing such as facility capacity and process.

The infrastructure decisions encompass a myriad of choices related to day-to-day management of operations. The infrastructure decisions include choices on materials management, production planning, quality and information systems.

The structural decisions require substantial capital investment and are more difficult to reverse, so some researchers (Skinner 1969; Wheelwright 1978) initially argued that only these decision areas are important for planning manufacturing strategy. Then in the late 1970's, researchers (Hayes 1979; Wheelwright 1981) recognized that the Japanese used infrastructural decisions to develop competitive advantage. Now researchers emphasize that linking some structural and infrastructural decision areas are necessary for realizing the total competitive potential in operations. Noori (1990) suggests that properly linked decisions in the all manufacturing decision areas can deliver strategic breakpoints, but their interdependencies, if not taken into account, can also pose strategic barriers.

2.3 LINKAGES

Two recent events highlight the importance of integrating decisions in operations: the decline of U.S. competitiveness and the superior performance of Japanese industries. Judson (1982) attributes the competitive decline in U.S. industries to a "lack of consistent or orchestrated decisions". Skinner (1986), surveying the recent efforts at revitalizing manufacturing companies, concludes that the key to success is in integrating decisions. The success of the Japanese companies stems largely from their efforts at integrating and linking decisions consistently (Wheelwright 1981; Schonberger 1986).

Research scholars starting from Thurston (1966) and Skinner (1969) have continued to emphasize the importance of integrating decisions in operations. But few explanations have been offered on the nature of relationships or how to link and integrate these decisions.

Summarizing the research on relationships among decisions of manufacturing strategy is as follows. First, most of the relationships and linkages proposed are deduced from case analysis, personal intuition or logic. There is little empirical evidence to support the propositions hypothesized by the researchers. Second, the empirical analysis has been exploratory in nature. The main focus of the past research has been on hypothesis generation and conceptual development. Further progress and development of theory requires testing and validation of hypotheses. Third, studying relationships among structural decisions have been the main emphasis. More needs to be learned about linkages with and among infrastructural decisions. The next sections briefly describe the relationships that have been addressed by researchers to date.

2.3.1 Linkages With Corporate Strategy

Few research scholars suggest how actually to link corporate strategy with manufacturing decisions. Hayes and Schmenner (1978) suggest that corporate strategy interacts with decisions in operations through three variables - growth perspective, dominant orientation and industry environment. Wheelwright (1984) adds a fourth variable - management philosophy. Wheelwright (1984) contends that management philosophy influences the choices and actions taken in operations.

Hayes and Schmenner (1978) explain how different alternatives for achieving growth influence decisions in operations. They argue that growth influences "learning" and so the organization's experience curves.

The diversification pattern represents strategic direction at the corporate level. Some researchers (Wheelwright 1984; Hayes and Wheelwright 1984) view diversification separately from the growth variable and suggest that different directions affect manufacturing choices.

Heute and Roth (1987) empirically relate corporate strategic directions with manufacturing strategy. They identify four corporate strategic directions: integration, market selection, product innovation and market share. Integration and market share relate with the competitive priority of flexibility. Product innovation relates positively with two competitive priorities - quality and flexibility - and negatively with low price.

Hitt and Ireland (1985) suggest that the degree of importance given to developing a functional area as the corporation's distinctive competence depends on the corporate strategy and the industrial environment. They empirically show that the production function has a positive influence on performance in firms pursuing external acquisitive growth strategy and weak positive influence on firms pursuing stable and internal growth strategies. They also report that the production/operations function is more important in firms pursuing growth (internal and external) strategies in the capital and producer industries.

2.3.2 Linkages With Competitive Priorities

Early proponents (Skinner 1969; Wheelwright 1978) of competitive priorities stressed the notion of trade-offs. Wheelwright (1981) offers a second perspective based on his observations of Japanese companies. The notion of linkages implies that choosing one competitive priority does not mean trading off advantages on other priorities. The linkage notion suggests that competitive priorities should be so emphasized that the desired competitive advantage in quality, flexibility and dependability are achieved without trading off on cost. In some ways the notion suggests that cost as a competitive priority depends on how other competitive priorities are linked. Figure 6 illustrates the two notions. There is nothing available in the literature to support one view over the other. It may be advantageous to complement one view with another. Some researchers (Richardson 1985; Fine and Hax 1985; Schroeder et al. 1986; Roth 1987) suggest that certain competitive priorities bundle together into clusters. The clustering of competitive priorities indicates that competitive priorities link with each other.

Many researchers emphasize the relationships between competitive priorities and decisions in operations. However, few explain the nature of these relationships or how to go about linking competitive priorities and decisions in operations. For example, there is little theory available to show what actions a company should take on inventory decisions when it chooses to give a high priority on cost rather than to emphasize quality level as a competitive priority.

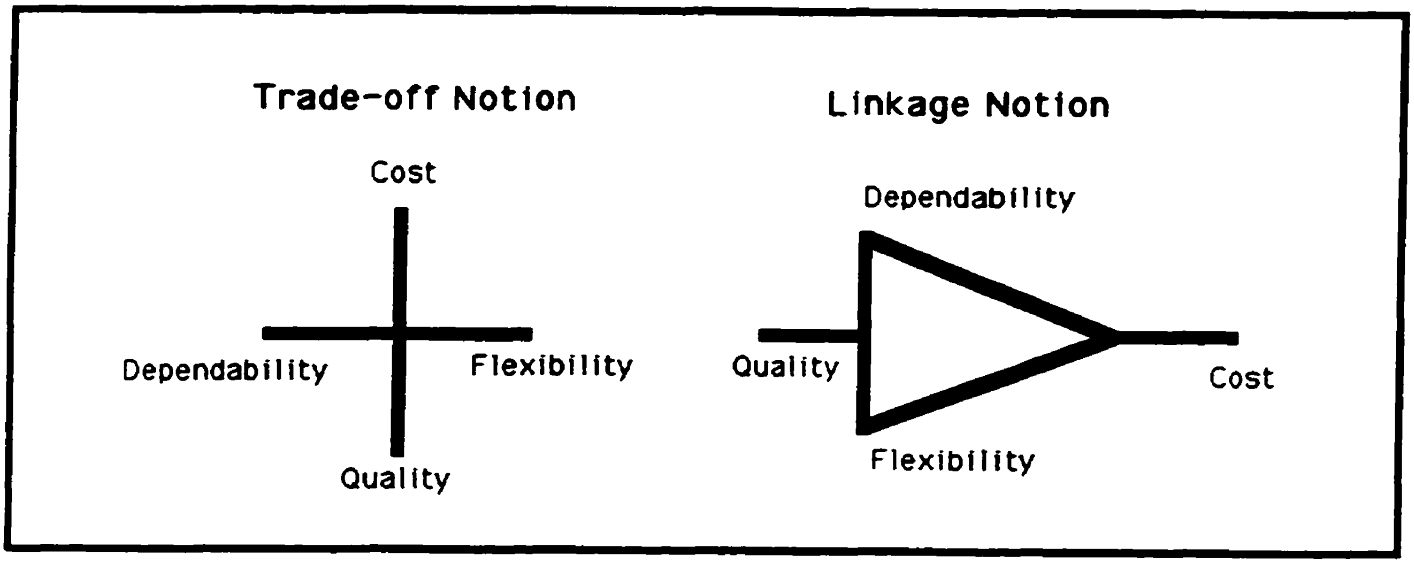

Figure 6. Competitive priorities linkages

Roth (1978), using exploratory factor analysis, identifies strategic actions or programs in manufacturing that relate to different competitive priorities. She analyses "intended" strategies. Swamidass et al. (1987), using a path analytic approach, shows a relationship between flexibility as a competitive priority, perceived uncertainty, role of managers in strategy decision making, and performance. The study examines only relationships with one competitive priority. Two recent studies (Schroeder et al. 1986;

Swamidass 1986) use data from a survey to examine connections between competitive priorities and manufacturing decisions. In both these studies, the researchers consider the relationship to exist when the rank of a competitive priority matches the rank of a manufacturing decision which (presumably) emphasizes the competitive priority. The conclusion based on such analysis is tenuous at best.

2.3.3 Linkages With Structural Decisions

Product policies are primarily determined by corporate strategy. Corporate strategy defines the business segments in which the company chooses to do business. Thereby corporate strategy defines the range of products or market segments for which manufacturing must develop capabilities. Conversely, manufacturing capabilities can also influence the choice of business segments in the corporate strategy. There is little research on the relationships between corporate strategy and product policies. In other words, does manufacturing have a role in determining what businesses the corporation should select in its portfolio?

Several researchers propose relationships between competitive priorities and product policies. However, few provide any validation or empirical support. Using historical data from the Ford Motor Company, Abernathy (1976) concludes that as a product matures, both production volumes and the emphasis on cost increase. Hayes and Clark (1985) empirically show that product complexity influences productivity negatively.

The relationship between process and product is best captured by the product-process matrix (Hayes and Wheelwright 1979). Abernathy (1976), also found relationships between product and process. Hayes and Wheelwright suggest that the type of process must match the degree of product flexibility. They argue that as products are standardized, production volumes increase and companies shift towards production lines and continuous shops.

Using the product-process matrix, Hayes and Wheelwright (1979) suggest a typology on entrance and exit strategies. The strategies define potential points for entering and exiting the business. They also discuss the implication of entrance and exit strategies on the process.

Vertical integration, though considered important in developing manufacturing posture, has received little attention vis-a-vis manufacturing strategy.

The literature on work-force management is large, but there has been little effort at incorporating it into manufacturing strategy research. Few researchers in manufacturing strategy have written about job design (Skinner 1969; Wheelwright 1978; Hayes and Schmenner 1978; Schmenner 1982), incentive and wage systems (Lindholm 1979; Skinner 1978; Hayes and Wheelwright 1984) and their relationship to competitive priorities and other manufacturing decisions. Roth (1987) based on her exploratory factor analysis found that work-force related strategies relate more with low cost as a competitive priority.

Researchers (Raffii 1983; Mcdougall 1986; Swamidass et al. 1987) are beginning to focus attention on the interaction between manager, managerial attributes and strategy. The thrust of the research so far has been on studying the role of manufacturing managers in planning manufacturing strategy. However, there is much to be done in this area, particularly in identifying manager types or managerial attributes suitable for different manufacturing environments and strategies.

2.3.4 Linkages With Infrastructural Decisions

Infrastructural decisions are decisions through which the linkage of operations to corporate and business strategy is maintained on a day-to-day basis. Van Dierdonck and Miller (1981) examine the relationship between competitive priorities and the production planning system. They argue that there are three dimensions underlying the relationship between competitive priorities and the production planning system. The three dimensions - uncertainty, complexity and slackness - essentially describe the production tasks. They define two dimensions - information processing system involvement (IPSI) and integrativeness - to characterize production systems. They suggest two relationships relating IPSI and integrativeness to production tasks. The characteristics of the production tasks are said to depend on competitive priorities. Their relationships link production system design to competitive priorities. They use regression analysis on a small sample to verify the relationships. The empirical validation is weak. Even so, this research in my opinion marks a milestone in manufacturing strategy research (others being Skinner's (1969) paradigm and product-process matrix (1979).

Krajewski et al. (1987), have identified conditions and factors that affect the desirability of different production systems such as material requirement planning system (MRP), re-order point system (ROP) and Kanban. They conclude that the key is not in choosing the right system, but in shaping the environment favorable to the system. Recently, Hayes and Clark (1985) in their empirical study show that scheduling stability significantly affects total factory productivity.

Materials management and purchasing offer a source for gaining competitive advantage on any of the seven competitive priorities. Krajewski et al. (1987) conclude that vendor influence, buffering and inventory decisions have a significant influence on inventory and tardiness performance measures. Other researchers (Roth 1987; De Meyer and Ferdows 1987) empirically show that purchasing and materials management are important. Roth (1987) shows a relationship between material management variables and product flexibility as a competitive priority.

E Yu (1988) through a continuous simulation feedback model along with "Zeta" Bankruptcy analysis attempts to justify Computer Integrated Manufacturing (CIM). Results suggest that the development of Group Technology is the best transitional approach from traditional technology to CIM technology. It has the lowest initial investment requirement, and it provides the highest gain.

Quality has emerged as an important topic in operations in the last decade. Quality gurus (E. Deming, P. Crosby, J. M. Juran) continue to preach the importance of quality in achieving a competitive edge. Buzzel et al. (1983) empirically show a relationship between quality, direct cost, market share, and return on investment. Fine (1986), with an analytical model, shows the benefit of quality in improving productivity. He argues that improvement in quality results in "induced learning" in the organization which leads to improved productivity. Hayes and Clark (1985) also empirically show the relationship between quality (waste) and total factory productivity. Roth (1987) factor-analytically shows a relationship between process statistical quality control and low price, volume flexibility, quality level and quality consistency competitive priorities. She also found a relationship between product statistical quality control and product flexibility and quality competitive priority. Surprisingly, Roth (1987) found no relationship between product statistical quality control (acceptance sampling) and quality level as a competitive priority. De Meyer and Ferdows (1987) also identify quality as one of eight managerial focal points in manufacturing strategy.

2.4 SEGMENTATION

The concept of segmentation in operations management is becoming important. Researchers, strategists and consultants consider segmenting operations, so as to develop a focused plant, a key to superior performance. The notion of segmentation is not new. Marketers apply the notion to develop market groups. Business strategists use the concept to define strategic business units (SBU). The objective in both cases is to develop a focus on some criteria, be it customers, products, or some other strengths of the organization. The underlying objective is to capitalize on strengths and do a few things well- produce few products well, perform few related processes well, and emphasize one or two competitive priorities.

Skinner (1969) introduced the notion of focus in planning manufacturing strategy. Since then other researchers also have stressed the importance of focusing. Focusing plants means doing fewer things in a plant, but doing them well. Though researchers concur on the benefits of focusing, they differ on the criteria or dimension for segmenting operations. These differences may be attributable to the variation in the ways researchers discuss segmentation, they are basically describing different ways in which linkages in operations may be accomplished. It seems that segmentation is a manifestation of linkages. Relationships are the foundation on which manufacturing strategy is developed. Therefore, propositions on segmentation also give insights into manufacturing strategy.

2.5 CONTROL

The purpose of control is to monitor performance, to identify and to diagnose inconsistencies in operations. Ruefli et al. (1981) suggest that control in strategy management is more than performance measurement. Control involves examining premises on which the strategy is planned, measuring performance and correcting actions to change the strategy. In essence, control ensures that strategy is implemented as intended. When the strategies are not planned, then control has the crucial function of scanning for gaps and opportunities to gain an edge over their competitors.

To exercise control, there must be a good understanding of the variables appropriate for measuring performance and how the variables relate to manufacturing decisions. The performance variables, the relationships among the control variables, and planning variables, corporate goals and business performance measures constitute the content of control aspect of manufacturing strategy.

A goal model and a system model are two extremes on how to measure performance (Bourgeouis 1980). A goal model advocates comparing performance against stated goals. The system model advocates comparing performance against standard measures; the standard measures are derived externally from expectations of investors and corporate management or based on the industry performance. Skinner (1969) adopts a goal model to measure performance. Wheelwright (1978) recommends using a combination of goal and systems approach to measuring performance. Other researchers (Hax and Fine 1985; Krajewski and Ritzman 1987) also suggest a combination of goal and systems approach for evaluating and diagnosing performance.

Gordon et al. (1980) examine the relationship between manufacturing performance variables and corporate strategy goals. Based on their empirical analysis, they conclude that measures appropriate for an environment in which mature products are produced inhibit product innovation. They further observe that managers respond to measures of performance more than formal statements on strategy. When the measures are incongruent with corporate goals, there are dysfunctional consequences. Banks et al. (1979) also caution against measures that emphasize short-term over long-term goals. They offer some suggestions and ideas to avoid trading off long-term benefits to gain short-term performance.

The performance measures suggested in the literature primarily focus on efficiency of manufacturing rather than on effectiveness. There are a few variables proposed to measure performance using effectiveness criteria, even though criteria for evaluating effectiveness are suggested in the literature. Wheelwright (1984) proposes criteria for evaluating effectiveness. He proposes two sets of criteria on each competitive priority: consistency and degree of emphasis. He does not suggest specific measures for operationalizing consistency or measuring the degree of emphasis on competitive priorities.

2.6 PLANNING AND CONTROL PROCESS

The process of planning and controlling manufacturing strategy refers to approaches, procedures, methods or systems that describe how to develop and control strategy. The process focuses on the steps involved in making decisions that are consistent with each other and with competitive priorities.

Skinner in his pioneering article in 1969 proposed an approach for planning strategy. His approach essentially is a rational comprehensive approach that plans strategy top down. Starting from goals, it chooses the alternatives that optimally satisfy the goals. The key elements of this top-down approach include (a) establishing goals - economic (e.g. growth) and non-economic goals (e.g. employee relations) - and dominant orientation based on corporate strategy, (b) establishing competitive priorities based on business strategy, and (c) making decisions and choosing alternatives to align manufacturing capabilities with goals and competitive priorities. Two other steps - defining performance measures and the process of controlling strategy - focus on control of strategy. Other researchers (Wheelwright 1978; Hayes and Schmenner 1978; Hill 1985; Fine and Hax 1985) also present frameworks for planning strategy which are essentially top-down approaches.

The top-down approaches suggest a narrow role for manufacturing. The approaches presume that manufacturing plays a reactive role; manufacturing responds and reacts to the dictates of corporate and business strategy. The approach does not allow a proactive role for manufacturing. Recognizing the limitations of the top-down approach, Hayes and Schmenner (1978) suggest a line management approach which essentially is a bottom-up approach. The bottom-up approach implies that goals are developed on the basis of means in the organization. In other words, corporate strategy and business strategy are established based on the manufacturing capabilities or strengths. Hayes (1985) also suggests that strategy be developed based on means. In other words corporate strategy is formulated based on the capabilities of manufacturing. He argues that this paradigm is essential for realizing the potential of manufacturing. Heute and Roth (1987) concur with Hayes (1985) and propose a planning approach in which corporate strategy is developed based on manufacturing capabilities.

The top-down and bottom-up approaches suggest extreme roles for manufacturing. In the top-down approach manufacturing is driven by the needs of the business and in the bottom-up approach manufacturing and other functional areas drive the business. In reality, the ideal role may be somewhere between the two extremes. Hayes and Wheelwright (1984) suggest four stages through which manufacturing goes. The four stages implicitly define different roles manufacturing can play. Their fourth stage, which they call "externally supportive", comes close to the ideal role referred to earlier.

Ebert et al. (1985) present an approach that uses simulation and "human judgment capturing methods" to help managers achieve consistency in planning strategy. Cohen and Lee (1985) present an analytical approach to planning strategy. They propose a hierarchy of analytical models to plan and control strategy.

McDougal (1986) empirically examines the process of planning strategy in diversified firms. He concludes that Skinner's (1969) paradigm is suitable for planning strategy at the divisional level in diversified firms. Most researchers are not explicit about the organization level at which their framework can be applied in planning strategy. Moreover, the authors of various frameworks implicitly assume that manufacturing strategy is planned at only one level. Wheelwright (1984) suggests that manufacturing strategy can be planned at two levels in the organization: corporate and business unit. He proposes three alternate approaches for planning strategy at the corporate level. It is unclear why Wheelwright and other researchers do not consider the plant as another level for planning manufacturing strategy. After all, strategies are realized at the plant level. Thus there are three levels at which manufacturing strategy can be managed - corporate, business (strategic business unit) and plant.

Strategic control literature offers many paradigms and approaches for controlling strategy which are also adaptable for controlling manufacturing strategy. Krajewski and Ritzman (1987) suggest two alternate approaches for controlling manufacturing strategy: operations audit and ongoing reports. The approaches provide a structure for controlling strategy. However, they do not explicitly explain how these approaches systematically guide managers in recognizing the inconsistencies. Cohen and Lee (1985) propose analytical models for controlling manufacturing strategy. Though they suggest a framework, they yet have to publish the explicit procedure for using their framework to control strategy.

Research scholars in general have paid less attention to strategy control. More needs to be learned about the process of planning and controlling manufacturing strategy.

2.7 FUTURE RESEARCH DIRECTION

This section presents some ideas on the direction for future research on manufacturing strategy. Manufacturing strategic decisions lack reliable measures. Infrastructural decisions also need attention. More measures for aiding infrastructure decisions need to be generated.

The measurement of concepts has been lacking in operations management. Researchers (Roth 1987) are beginning to pay attention to measurement issues in operations management, but a lot more needs to be done. Measurement research must be pursued to test the validity and reliability of constructs such as competitive priorities. Measures for constructs in structural and infrastructural decisions also need to be developed. The reliabilities and validities for the measures must be assessed to build confidence in the constructs. Assessing validities means analysis with multiple data samples.

The thrust of future research also must focus on understanding linkages in operations management. To develop effective strategies, strategists need to understand why some alternatives work better under certain competitive scenarios. The future research should focus on understanding (a) how and why decisions in operations link the way they do in practice and (b) how linkages among operations management decisions affect performance. The first emphasizes descriptive analysis - delineating and explaining the logic behind the linkages. The second focuses on normative analysis to uncover relationships that explain superior performance in manufacturing. Linkages between operations management decisions and other functional areas also need to be examined.

Descriptive analysis on both intended and realized strategies should be pursued to see if the relationships and linkages differ among the two strategy types. Normative analysis should be pursued only on realized strategies. Since there is always a time lag between when the decisions are taken (strategy planned) and when the decisions (strategy) are implemented, the issue of time lag must be also taken into account.

Future research also must examine differences in strategies and relationships within industry and across industry. It may also be interesting to investigate whether the notion of strategic groups applies to manufacturing strategy or not. In other words, are there companies within the same business (same markets and products) competing head on with the same strategies.

The agenda for future research also should examine the process of planning and controlling strategy. The paradigms for planning strategy in the literature assume a rational approach to managing strategy. A paradigm based on the incremental approach is an area worth looking into. An interesting issue would be to look at conditions or criteria under which the alternate approaches are effective. The development of approaches for planning strategy based on decision support technology (like that suggested by Cohen and Lee 1985) is another dimension that will make planning and implementation of manufacturing strategy more effective. Artificial intelligence offers a broad array of tools for developing expert systems for diagnosing and planning strategies.

There are other process related issues still open for research. Manufacturing strategy can be planned and controlled at more than one level. Corporate, divisional (SBU) and plant are three levels in the organization at which strategy can be planned. How the strategies at different levels should be related seems to be another area worth investigating. Wheelwright's (1984) three alternatives for managing manufacturing strategy at the corporate level would be a good starting point.

More fundamentally, the premise guiding the current thinking in operations management needs to be addressed. Ferdows and Skinner (1987) suggest that new perspectives in manufacturing require giving up Taylorism. They suggest that the fundamental basis of manufacturing thinking must be examined. For example, the idea of stable efficient factories no longer satisfies the needs of today's business environment. Mcdonald's (1987) idea of floating factories offers a new perspective on things to come. Mcdonald (1987) argues that factories in 1960's were fixed assets, and markets changed. When a company could not compete in a market they moved into a new market or just quit the business segment and started producing different products for the same market. Today when companies cannot compete, they are more likely to move the factory or production elsewhere - probably to a country where the labor is cheap or where the exchange rates are favorable. Buffa et al. (1985) also bring out the influence of exchange rates on productivity. Exchange rates are beginning to play greater role in location of factories. This suggests that volume flexibility may become a dominant competitive priority in future. There also seems to be a trend towards greater fragmentation of markets, resulting in lower volumes per product. Researchers in manufacturing must recognize these trends in developing a new and bold thinking for managing manufacturing strategically.

Future research should go beyond theory development. The effort should be concentrated on theory testing. Relationships among manufacturing decisions, competitive priorities, corporate strategy and other functional decisions should be examined. New approaches for managing strategy should be pursued. Finally, changing business trends should be considered in searching for new ways to think about manufacturing.

CHAPTER 3

SYSTEMS DYNAMICS MODELLING

3.1 INTRODUCTION

System dynamics modelling was pioneered at MIT by Professor Jay Forrester and derived from control systems engineering. After doing groundbreaking work on servomechanisms during World War II, Professor Forrester hypothesized that viewing social systems as complex analogs of mechanical systems may be useful for understanding them better. He argued that the same processes of control through information feedback, and of flow and accumulation of material or information, occurs in social as well as in mechanical systems.

As previously defined, system dynamics is a rigorous method for qualitative analysis of complex systems which facilitates quantitative simulation modelling and analysis for the design of system structure and control. This methodology can be described in two distinct phases - the first being a qualitative analysis followed by quantitative simulation modelling.

3.2 QUALITATIVE ANALYSIS

Qualitative analysis consists of defining and conceptualizing the problem by constructing an influence diagram according to precise and rigorous rules. Included in the process of developing an influence diagram is the solicitation of opinions and advice of people in the system, explicitly stating assumptions, validating the assumptions with empirical evidence if available and obtaining general agreement that the model mirrors reality for the purpose in hand (Hall, 1978).

Once the influence diagrams are drawn, the system flow diagrams can then be developed. Through this step the people involved in the analysis can gain a better understanding of how the system under study works. The different components in the system can be linked together by means of physical flows. Examples are inventory, workers, capital and other physical quantities. They can also be linked by the information flow, which is built in the dynamic simulation system to give the real life effect. The standard symbols in a system flow diagram are illustrated in Figure 7 below.

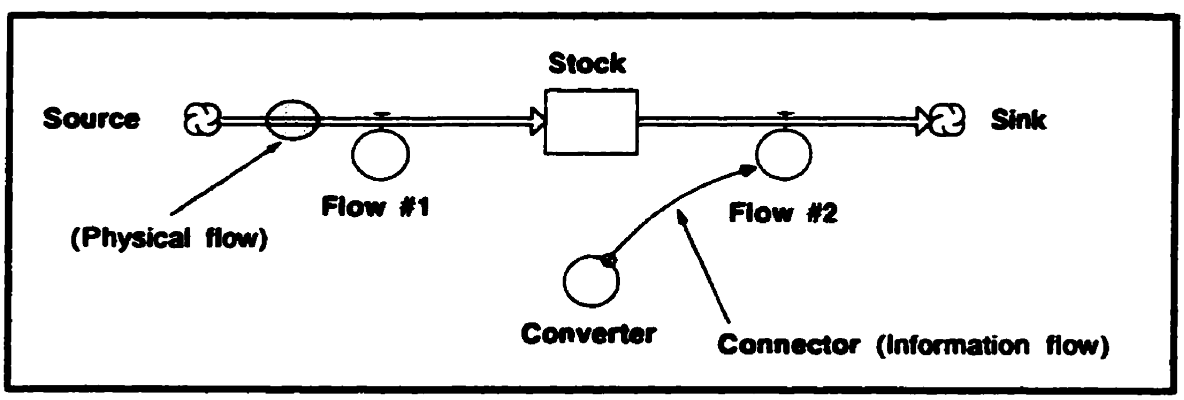

Figure 7. Standard system flow diagram symbols

3.2.1 Stocks

Stocks are like bath tubs, in the sense that they accumulate, or collect, flows. Stocks reflect conditions within the system at a point of time. Stocks are what you would see if you suddenly froze the activity within the system.

3.2.2 Flow

A flow in a system flow diagram can be thought as a water tap. The incoming rate of the water from a source outside the model increases the level of the water in a tub. The level of the water will also be affected by the outgoing rate, which controls the amount of water which goes into the sink outside the model. There can be many flows going into the level variable and many coming out. However, a conserved flow in a system usually start with a source and finishes with a sink. Sources and sinks serve to define the boundary of the model.

3.2.3 Converters

Converters are used to convert dimensions and to add details to the model. Converters are used to represent a chain of information linking stocks to flows. They add the driving forces to the stock and flow structure of models. Unlike stocks, converters do not accumulate flows. The magnitude of a converter changes instantaneously with the magnitude of the stocks and other converter to which it is linked.

3.2.4 Connectors

The final building block is the connector. Connectors link stocks to converters, and converters to other converters. Connectors do not take on numerical values - they represent inputs not outflows. Connectors depicts the casual linkages between the variables in the model. They reflect the assumptions about "what depends on what" in the structure of the model.

By requiring that the key elements of a system be understood and put into proper relationship with each other, people are forced to think about how the individual parts fit together to form the entire system. Clearly, having an overall picture of the system is key to understanding it. However, in a society where we have become increasingly specialized, having this kind of holistic view is not common. Even after diagramming the system and striving to capture what is most important, what we are left with can still be quite complicated. It is often not clear how systems with many stocks, flows, and feedbacks behave, which is the reason people often cannot agree on whether a particular policy will be beneficial or detrimental. It seems, then, that if it is difficult for most of us to envision how a multitude of stocks and flows act together to produce the behavior of a system, that it would be useful to have some way of being able to simulate how a system evolves over time. System dynamics going beyond the diagramming to offer such a method of simulation depicts the second phase of the methodology - quantitative simulation modelling.

3.3 QUANTITATIVE ANALYSIS

The first step in quantitative simulation modelling is to specify the values of parameters and initial conditions that is gained through research and interviews with the specialists. These values of parameters will influence the behavior of the system throughout the simulation. Moreover, certain parameter values represent the company's policies which the company personnel follow. For instance, machine availability is ninety five percent accurate (ie. 95% of the time, production allows the equipment to be available for maintenance to perform preventive maintenance schedules). A small variation in machine availability may significantly affect the overall performance of equipment over time due to lack of preventive maintenance. Therefore, the analyst must do sufficient research on these constraints to assure that the model represents reality for the purpose in hand. The system dynamic simulation approach is a very effective way of testing new policies before implementation.

Once these values and parameters are set for the model, the model is ready for trial runs. The purpose of the trial run for the model is to correct all the syntax and logical errors. This step is also commonly known as the debugging stage, and the results have to be evaluated. Model evaluation is an important step in system dynamic programming. The purpose of the evaluation is to ensure the model is functioning properly. Different scenarios are tested to evaluate the system performance, a section at a time, under different circumstances or policies. This can be easily achieved by changing certain constant variables. If the model is not functioning properly, the conceptual equations in the program or the parameters may require some adjustment. In some cases, the error may come from an incorrect conceptual assumption. In order to ensure the program is simulating the actual situation closely, the programmer should trace the results from the initial period of the simulation by hand. In doing so, the analyst or programmer will know if the simulation model is functioning as expected. A number of simulations are conducted once the analyst is confident of the model structure. This is followed by an interpretation of the results by the analyst in terms of the structure of the system. The main responsibility of the analyst at this point is to find the feedback loop structure creating the observed behavior of the model system. The interpretation or evaluation of the results is highly dependent on the judgment of the analyst. From the insights gained, the users can usually suggest actions to improve the behavior of the system.

3.4 SUMMARY

System dynamics does not provide an optimum solution, but is useful for providing insights into the inner workings of a complex system. Sensitivity of decision variables and structural changes can be tested, allowing policies to be evaluated ahead of implementation (Hall 1985). In short, system dynamics provides a framework for understanding systems composed of parts or elements that influences each other over time. Even though the elements of the system may be well known, the interconnections between the elements produce behavior too complex for people to fully understand without special learning tools. System dynamics provides such a tool.

There are a number of different simulation languages that can be used in system dynamic modeling. The STELLA (High Performance Systems, 1990) language has been selected for the computer simulation model in this research. Advantages of the system STELLA simulation language are as follows. The language is user oriented and its underlying principles are easily understandable to the analyser and to the eventual decision maker (Chen et al. 1995). The software automatically maintains a one-to-one correspondence between the system model flow diagrams and the programs. It contains simple instructions for printing and plotting time series of variables and running the simulation. The equation and documentation facility encourages users to layout their assumptions for inspection; and it contains built-in functions of frequent use.

Potential problem areas of the STELLA language may be: (1) the methodology is easy to learn but difficult to apply, (2) it does not guarantee a realistic or valid model and (3) it is not an optimizing technique (Hall 1985).

CHAPTER 4

QUALITATIVE ANALYSIS

4.1 INTRODUCTION

As previously mentioned, time based competitiveness was rated highly as a competitive priority for businesses in the nineties. To be effective in time-based competition, managers must carefully define steps and time involved in processing customer orders whether it is providing a service or manufacturing a product. Next, they must critically analyze each step to see where production time can be shortened without compromising the quality of the product or service. Significant time reduction in operations (cycle time) can often be achieved by changing the way current technologies are used, by identifying and reducing non-value-added time resulting from the way operations are laid out within the facility, by turning to automation, by identifying and reducing non-value-added time that may result from delays due to poor delivery and quality performance of part suppliers, or from delays due to internal scrap or rework, by effective maintenance and by effective management of workforce.

With these thoughts in mind, the following sections identify the key variables that may have significant influences with relevance to cycle time within the decision areas of process, quality, material management, workforce management and maintenance. Influence diagrams are constructed to explore the problem thoroughy.

4.2 PROCESS DECISION AREA

Process decisions define how the inputs are transformed into outputs based on product diversity. Specific process decisions include the type of manufacturing operations (e.g. fabrication and assembly) that transform inputs into outputs, technology to perform the operations, and organization or layout of the operations in the plant. These decisions essentially determine what work is performed in the plant and how the work flows in the plant.

Positioning strategy refers to the degree to which resources (equipment and workforce) are dedicated in the plant around processes as opposed to products. Such a classification is a synthesis of views suggested by several researchers (Skinner 1969, Wheelwright 1978; Hayes and Schmenner 1978; Hayes and Wheelwright 1979; Schroedor 1984; Hax and Fine 1985; Hayes and Clark 1985; Krajewski and Ritzman 1987).

Positioning strategy characterizes layout of equipment and flow of work in the plant. Layout of equipment relates to how the resources are dedicated in the plant. Two entirely different alternatives for layout of equipment are process and product layout. With a process layout, the resources are organized around the process and shared across all the products produced in the plant; the resources that perform similar functions are clustered together. In a product layout, resources are organized around the product and typically resources are dedicated to few products. These two alternatives represent extremes of a continuum of alternatives for organizing the resources in the plant. A third alternative is a combination of both process and product layout. Therefore, a manufacturing organization may have a process layout or product layout, or a combination where process layouts maybe mixed in with product layouts. For example, there may be the situation where a number of product lines share machine centers, welding shops, and paint shops instead of having their own.

The flow of work refers to how the work progresses through manufacturing stages at the plant. The work can flow intermittently or continuously in a plant and is determined by the batch sizes of the products produced in the plant. Batch sizes influence how the resources are consumed in the plant. Large batch sizes means large amounts of resources are consumed between machine setups, so the pattern of consumption is relatively smooth. With small batch sizes, machines are set up more frequently and small amounts of resources are consumed between set ups. Batch size determines the type of material handling and the amount of material handling that would be required to move work during the manufacturing process. For example, a large batch size may require specialized material handling; where as small batches of one or two could be moved manually. With the small batch size there may be the requirement for frequent material handling. There are four levels of batching:

1) Job shop representing products produced in small batches and similar equipment performing the same processes are grouped together.

2) Batch shop representing products produced in moderately large batches and similar equipment performing the same functions are grouped together.

3) Production line representing products produced in batches and equipment is laid out in sequence in which the products are manufactured.

4) Continuous shop representing products produced in large batches or in a continuous flow and work centers are laid out in sequence in which the products are manufactured.

Figure 8 below illustrates positioning strategies.

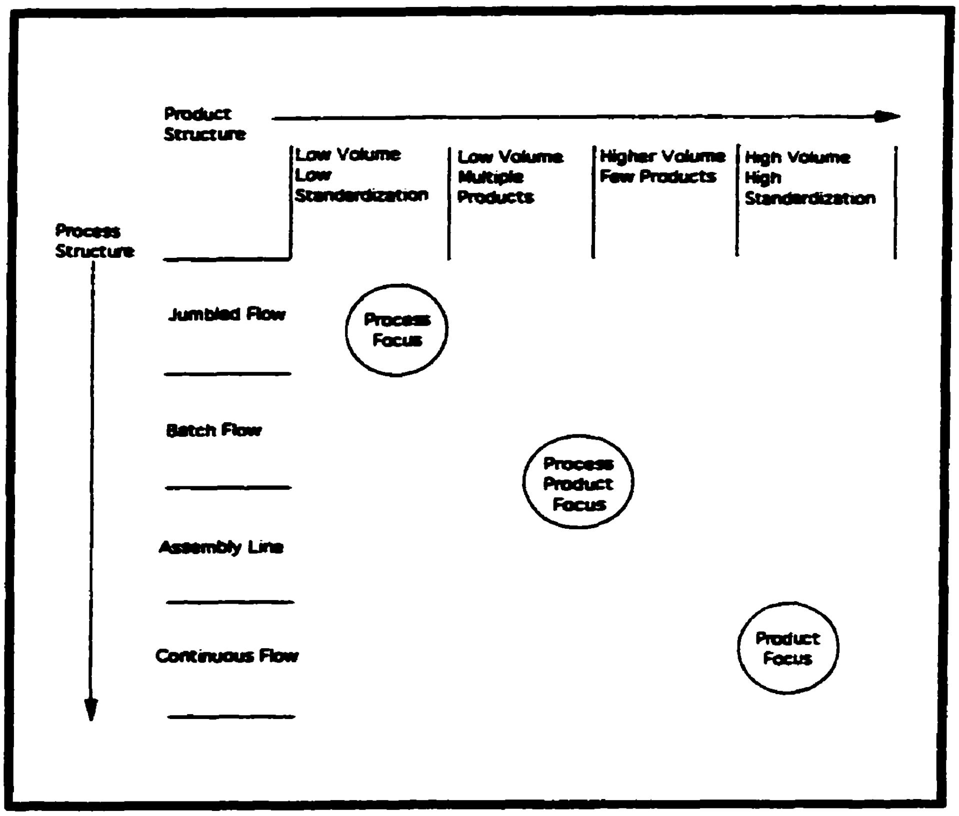

Figure 8. Positioning strategies

Based upon the above information, the variables identified for the process decision area are as follows. Degree of process layout, batch size, number of machine set-ups, amount of material handling, material handling time, queue time due to machine set-ups, number of workcenters, and travel time between workcenters, the number of similiar pieces of equipment, and process innovation. Figure 9 below illustrates the influence diagram for the process decision area. The thinking behind the construction of Figure 9 will now be discussed.

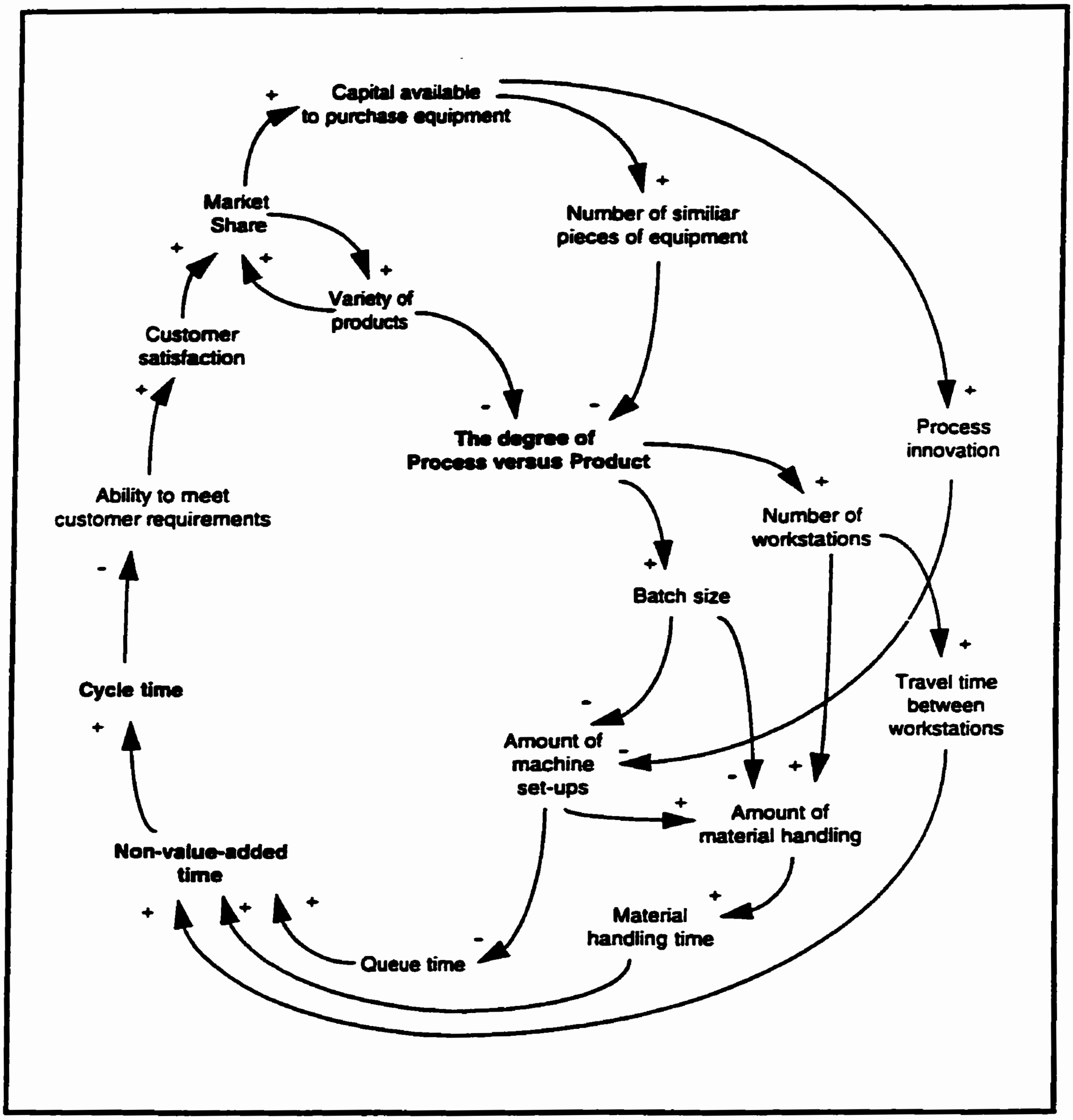

Figure 9. Influence diagram for the process decision area

To use influence diagrams comprehensively, it is vital to have a thorough understanding of the concept of correlation. In this dissertation, the following applies. If a change in the magnitude of the tail variable of an influence arrow causes a change in the magnitude of the head variable in the same direction, then the link has a positive correlation. Conversely, if a change in the magnitude of the tail variable of an arrow causes a change in the magnitude of the head variable in the opposite direction, then the link is a negative one. For the purposes of providing an example, let us examine the following illustration in Figure 10 which is a section of the influence diagram presented in Figure 9.

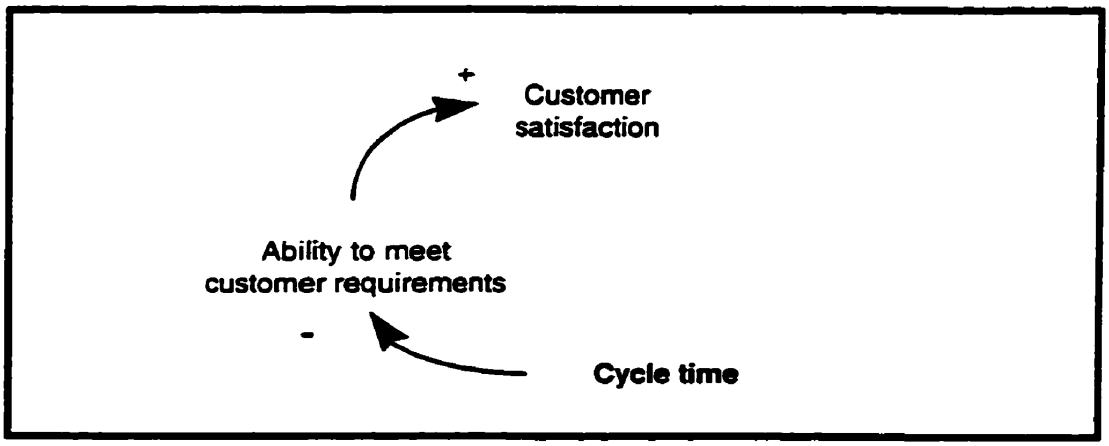

Figure 10. Illustration of the concept of polarity

If one's ability to meet customer requirements increases, this will increase the customer's satisfaction. This influence is indicated by a plus (+) sign at the head of the arrow between "Ability to meet customer requirements" and " Customer satisfaction"; i.e. the magnitude of both variables are increasing. However, if cycle time increases, the ability to meet customer requirements decreases. This influence is indicated by a minus (-) sign at the head of the arrow between "Cycle time" and "Ability to meet customer requirements"; i.e. the magnitude of one variable is increasing causing a decrease in the magnitude of the other variable.

Decisions external to the process decision area are: the variety of products selected by the organization, capital available to either acquire additional equipment or improve current technology and the cycle time to manufacture the product.

The degree of process versus product layout can be influenced negatively by the number of similiar pieces of equipment from the perspective that to set up product lines, there may be the need to have similiar equipment in each product line which may have economic implications. For example, each product line may require large mechanical presses or paint booths which may not be possible not only from an economic standpoint but also the facility configuration may prevent such equipment layouts. Hence, the smaller the number of similiar equipment, the higher the degree of a process layout.

A high degree of process orientation will positively influence batch sizes which inturn will reduce the number of machine set-ups required. Machine set-up is defined as the time required to get the equipment ready for a production run. For example, a process layout usually consists of the types of equipment that typically have large capacity, and requires lengthy periods of time to set-up for production. In order for the equipment to operate effectively, it needs to produce more than a few parts to justify its large capacity and long set-up times. A product layout, on the other hand, usually consists of a number of dissimiliar equipment with low capacity and requiring little set-up time. Therefore a product layout will operate efficiently with small batch sizes.

The number of machine set-ups will have a positive correlation or influence on the amount of material handling and the material handling time. As the number of machine set-ups decrease so will the amount of material handling and the time it takes to handle the work. Material handling adds no value to the product even though it is essential within the manufacturing process. Material handling time therefore will increase the non-value-added time within the manufacturing process. In addition, the number of machine set-ups will affect the queuing time which will also increase the non-value-added time within the manufacturing process. Queue time is defined as the time in which no value-added activities are performed on the work in process.

The degree of process versus product layout positively influences the number of workcenters within the manufacturing process. A highly process orientation will have many workcenters; whereas a product layout will have few workcenters. The more workcenters there are, the more travel time there will be between workcenters. This again will increase the non-value-added time within the manufacturing process.

Process innovation can have a positive influence on process layout in that improved technology may be used to reduce the number of machine set-ups which in turn can reduce queue time and material handling time resulting in reducing the non-value-added time within the manufacturing process.

As mentioned earlier, the measure for the overall model is cycle time which is the time required to manufacture a part or a unit of product. Significant time reduction in operations can be achieved by reducing non-value-added time. Within the process decision area, non-value-added time consist of queue time, material handling time and travel time between workcenters. Reducing both queue time and travel time between workcenters would suggest reducing the degree of process layout, hence, increasing the focus on product layout. This approach maybe somewhat counterproductive because increasing product focus means small batch sizes which would increase material handling and material handling time. The increase in material handling time may be greater than the queue time and travel time between workcenters that was eliminated as a result of reducing the degree of process layout.

Without fully understanding the interrelationships within the decision area, it becomes obvious how easily inappropriate and counterproductive decisions can be made.

4.3 MATERIAL MANAGEMENT DECISION AREA

Materials management covers decisions about suppliers, inventories, production, staffing patterns, schedules and distribution. Materials management is usually divided into three departments: 1) purchasing, 2) production control, and 3) distribution. Purchasing is the area under examination in this study.

Purchasing is the management of the acquisition process, which includes which vendors to use, negotiating contracts, and deciding whether to buy locally or centrally. Purchasing is the starting point of the materials management cycle of acquisition, storage, conversion and distribution.

Purchasing is the eyes and ears of the organization in the supplier marketplace, continuously seeking better buys. This process begins with the vendor selection decision. Purchasing agents for some companies establish formal rating procedures to help them select new suppliers or periodically review the performance of current suppliers. Two of the many criteria considered in a selection decision almost always are quality and delivery. The quality of a suppliers materials can be very important. The hidden costs of poor quality can cause unnecessary delays thereby increasing cycle time. The second criteria is delivery. Shorter lead times and on-time delivery helps the buying firm to maintain acceptable customer service with less inventory. Cycle time can be increased if parts are delivered late.

A second purchasing issue of strategic importance is the type of relations maintained with vendors. A firm can relate to a supplier either competitively or cooperatively. The competitive orientation is particularly prevalent in North America. The cooperative orientation to supplier relations is attracting more attention particularly because of the success certain Japanese firms have had with it. The cooperative orientation is examined in this study. In cooperative orientation, the buyer and seller are seen as partners, with each helping the other as much as possible. The buyer shares information on future buying intentions which allows suppliers to make better forecasts of future demand, making them more efficient and reliable. The buyer visits vendors' plants cultivates cooperative attitudes, and jealousy guards the relationships. The buyer may even suggest ways to improve the suppliers' operations.

Based upon the above information, the variables identified for the materials management decision area are as follows. Parts on time, late parts, delays due to late deliveries by the supplier, defective parts supplied by vendor, effort by the vendor to improve quality and on-time delivery, and delays as a result of defective parts supplied by vendor. Figure 11 illustrates the influence diagram for the purchasing section of the material management decision area. The thinking behind the construction of Figure 11 will now be discussed.

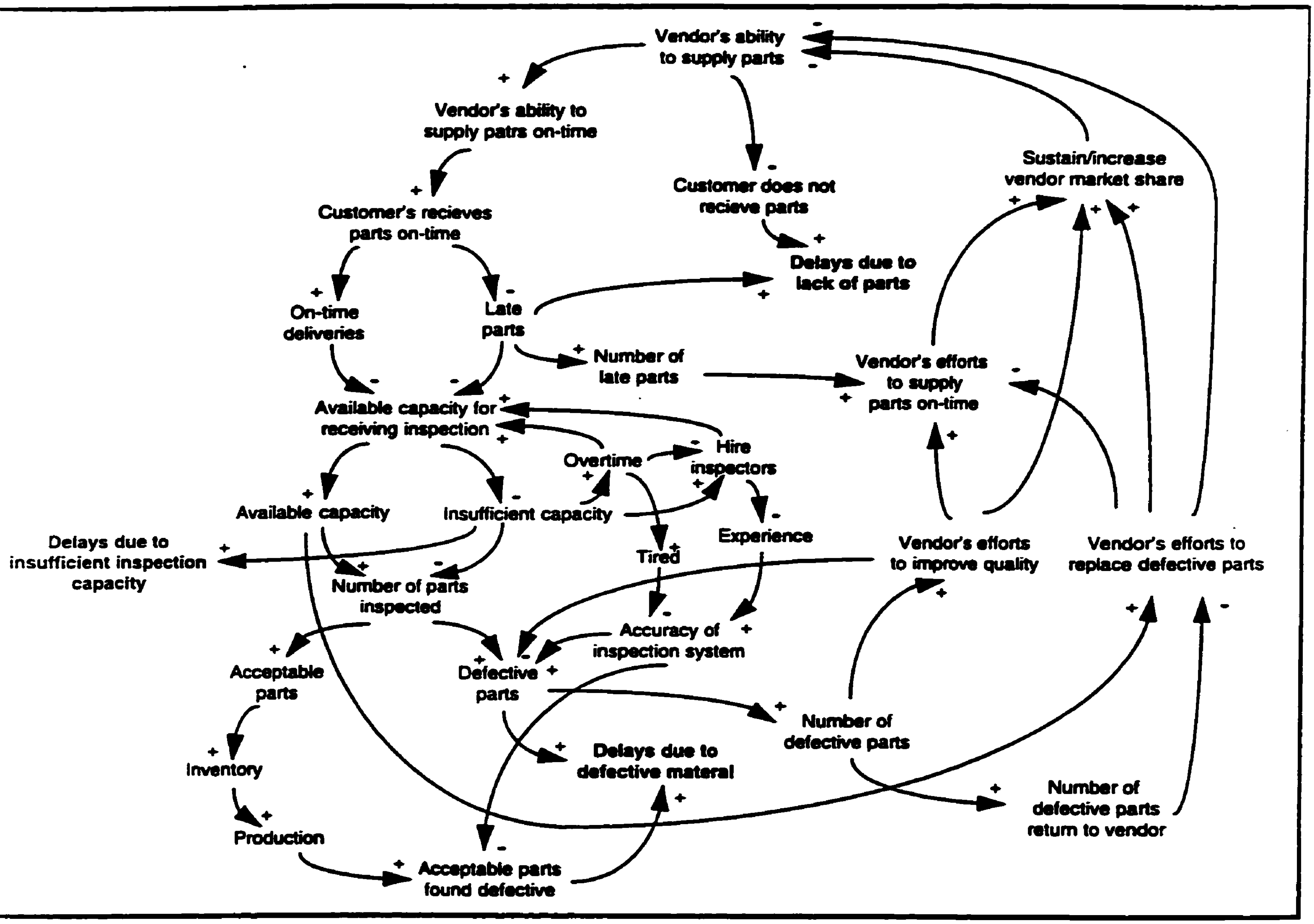

Figure 11. Influence diagram for purchasing section Of materials management

The market share captured by the vendor can either positively or negatively influence the vendor's ability to supply parts to the customer (the customer being the manufacturing organization). The vendor's ability to supply parts would be dependent on the size of its organization and resources available to it. The vendor's ability to supply parts on-time will be positively influenced if it is able to deliver parts. However, this ability does not guarantee that all parts will be delivered on-time. The parts that are delivered late will cause time delays that can impact the cycle time to manufacture the product. For example, parts that may be partially assembled on an assembly line may be held up from being completed due to late deliveries from a supplier. The number of late parts are monitored by the supplier, and used as a trigger to ensure that appropriate efforts would be expended by the vendor to correct late deliveries and ensure future improvements.

The parts that are delivered on-time may also experience a time delay from the perspective of capacity to inspect the quality of parts received from the vendor (in the aerospace industry, there is a regulatory requirement for receiving inspection). In addition to the receiving inspection capacity constraint, there is the possibility that some of the parts that were delivered on-time maybe defective which will also add to the time delays since those defective parts cannot be used, and will have to be returned to the vendor for replacement. Ensuring that the defective parts are replaced in a timely manner may negatively influence the efforts that are being expended to improve on current delivery committments. Therefore, a thorough analysis should be made to understand where the vendor should focus its efforts.

In dealing with the receiving inspection constraint, the decision may be to hire additional inspectors which may be counterproductive. On the one hand, hiring more inspectors may alleviate the inspection resource issue, however, the newly hired inspectors may not have the appropriate experience required to accurately inspect resulting in additional defects found prior to completing the manufacturing process which can significantly impact cycle time due to lateness of discovering those defects.

The defects that are found during the receiving inspection process are monitored and used as a trigger for the supplier vendor to increase the resources (money and/or people) to mitigate the quality problems. In addition, the number of late parts are also monitored and used as a signal to increase the effort to ensure parts are delivered on-time.

The amount of effort that the vendor demonstrates to mitigate quality problems and late deliveries can positively influence the amount of market share that the vendor is able to sustain or increase. However, these efforts may be counterproductive in the sense that the vendor may have expended great amounts of effort to sustain or increase market share and is now unable to meet its commitments due to the negatively influence of the vendor's efforts to replace defective parts that had been delivered.

Significant time reduction in operations can be achieved by identifying and reducing non-value added time that may result from delays due to poor delivery and quality performance of part suppliers. The above analysis indicates a number of counterproductive decisions that can significantly impact the non-value added time that may result from time delays due to poor delivery and quality performance of part suppliers. These counterproductive decisions re-emphasize how important it is to really understand the effects of each variable within the decision area. In making a decision around the receiving inspection capacity constraint, one really needs to understand the impact of hiring additional inspectors that may pass on defective parts versus not hiring with the potential for time delays. In correcting poor quality and delivery performances, the vendor needs to carefully analyze where its efforts will have the most favorable impact.

4.4 QUALITY DECISION AREA

Managers have a good cause to be concerned with quality, because quality is an issue that pervades the entire organization. In the past, price was considered to be the key factor in gaining market share, but this is no longer true. Consumers are much more quality minded and in many cases would prefer to spend more for a product if it will last longer. A survey of 2,000 business units conducted by the Strategic Planning Institute of Cambridge, Massachusetts, indicated that the degree of product quality affects a firm's chances of increasing its market share. If a product quality is stable, a high quality product stands a much better chance of gaining market share than those of a low quality product.

Good quality can also pay off in higher profits. High quality products can be priced higher than comparable, lower quality products and yield greater return for the same dollar. In addition, higher quality can reduce costs, which in turn increases profits.

In a recent poll by the American Society for Quality Control, executives seemed to underestimate the cost of poor quality to their companies. The majority claimed that poor quality accounted for less than 10 percent of gross sales. Most experts on the costs of poor quality estimated losses in the range of 20 to 30 percent for defective or unsatisfactory products.

Four major costs are associated with quality management and are described below. Prevention costs are those costs that are associated with preventing defects before they happen. Included are the costs of process design, product design, employee training, and vendor programs. Appraisal costs are incurred in assessing the level of quality attained by the operating system. Included are the costs of quality audits and statistical quality control programs. Internal failure costs result from scrap parts and the need to rework products because of defective workmanship. Finally external costs are those costs that include warranty repairs, loss of market share, and lawsuits arising from injury or property damage from the use of the product. Internal costs will be the issue under examination in this study. Internal failure costs result from defects generated during production of a product and fall into two major cost categories: scrap and rework costs. Parts or a product is scrapped if found defective, and cannot be repaired. With rework, the defective item is rerouted to some previous operation(s) for correction.

One's first thought about scrap may be about the cost of the material lost. Although that is only a fraction of the total cost involved, it is a good place to start. Suppose that as a result of defective parts, a plant needs 120 units of raw materials to produce 100 units. Other than the obvious fact that raw material costs have been increased by 20 percent, what are the hidden costs if the 120 units are moved from one operation to the next and finally checked for quality after the last operation, a common practice in many firms? More labor and machine hours are required to produce the same quantity of product than for a defective free process which of course will impact cycle time due to the delays created as a result of the additional labor and machine time.

Sometimes when a defective part or production lot is discovered, it can be sent back to a previous operation to be corrected. How does this action affect day to day operations? Obviously, more labor, machine and inspection hours are required for the operation where rework occurs. In addition, most situations involving rework will result in an increase in the number of machine set-ups, even if only a portion of the lot must be reworked. Furthermore, work-in-process inventory levels increase because the units to be reworked will stay in a semi-finished state longer. The cost of that product also increases because of the added labor and machining time required to produce it correctly.

Based on the above information, the variables identified for the quality decision area are as follows. Available capacity to inspect parts, insufficient capacity to inspect parts, accuracy of inspection system, number of parts to be reworked, number of scrapped parts, training to reduce scrap and rework, time delays due to insufficient capacity to inspect, scrapped parts and reworked parts, scrap rate, and the degree of self inspection. Figure 12 illustrates the influence diagram for the internal failure section of the quality decision area. The thinking behind the construction of Figure 12 will now be discussed.

Available capacity to inspect parts can have significant influence in the quality decision area. The degree of self-inspection (defined as inspection done by the production employee who has worked on the part as opposed to inspection performed by the quality inspectors) can positively influence the capacity available for inspecting parts. This means that some of the inspection work that is typically done by quality inspectors would now be done by production operators. However, as the degree of self-inspection increases, it negatively influences the morale of the current quality inspectors which will inturn decreases the productivity of the inspectors resulting in an increase in insufficient inspection capacity.

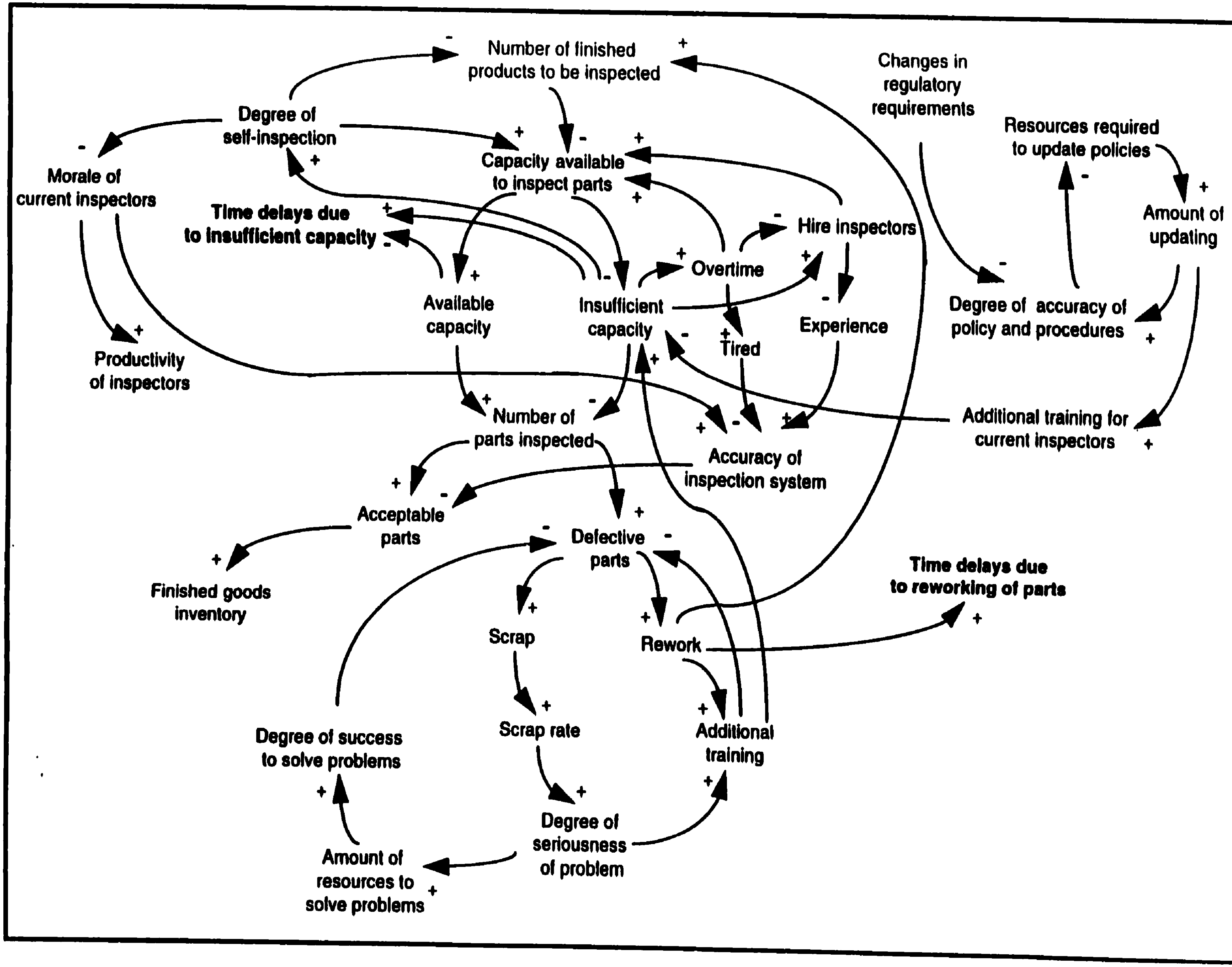

Figure 12. Influence diagram of internal failures for the quality decision area

There is therefore a counterproductive action resulting from increasing self-inspection. Insufficient capacity to inspect parts results in a time delay which would impact the overall cycle time to manufacture parts. The situation of insufficient capacity creates the need for decision making to correct the deficiency. Possible decisions could be to work overtime, or to hire additional inspectors which at a glance would appear to resolve the insufficient inspection capacity. However, both of these decisions could be counterproductive, in that they could negatively influence the accuracy of the inspection system resulting in incorrectly inspected parts. Hiring new inspectors could potentially mean inexperience inspectors who may pass on defective parts as acceptable which could negatively impact customer's satisfaction resulting in reducing the manufacturer's market share. Working extensive overtime will tire the inspectors reducing their effectiveness to accurately inspect parts. Inaccurate inspections can result in passing on defective parts as being acceptable; but also may identify good parts as being defective which of course would increase time delays as a result of rework or scrapped parts. If a part is reworked or scrapped, additional labor and machining time would be required to either rework the part or build a new part if the defective one was scrapped. The additional labor and machining time are the reasons for the increased cycle time.

If the scrap rate becomes increasingly high, it triggers a decision to immediately commit resources to resolving the problems that are causing the scrapped parts. The degree of success in resolving the problems will be dependent upon the demonstrated urgency along with the amount of resources, and level of expertise provided. The degree of success will directly impact the amount of defective parts that are produced in the future which inreturn would reduce time delays, hence impacting the overall cycle time to manufacture the product. There may only be a need to provide additional training depending upon the seriousness of the problems that are causing the defective parts. However, providing additional training for the inspectors would impact available inspection capacity which would drive the need to either work overtime or hire additional inspectors. As previously mentioned, these decisions could be counterproductive.

Changes in regulatory requirements can negatively impact the accuracy of the quality policies and procedures which could influence the accuracy of the inspection system resulting in passing on defective parts as being acceptable. Changes to the policies and procedures in an effort to ensure the integrity of the inspection system could be counterproductive from the perspective that changes would mean additional training for the inspectors which could negatively influence inspection capacity resulting in time delays and a reduction in the accuracy of the inspection system

Significant time reduction in operations can be achieved by identifying and reducing non-value added time that may result from delays due to scrap or reworked parts. The above analysis indicates a number of counterproductive decisions that can significantly impact the non-value added time that may result from time delays due to scrap or reworked parts. These counterproductive decisions re-emphasizes how important it is to really understand the effects of each variable within the decision area. In making a decision around increasing the degree of self-inspection in an effort to increase available capacity for inspecting parts, one really needs to understand the impact on the morale of the quality inspectors which could negatively impact both the capacity for inspecting parts, and the integrity of the inspection system. Negatively influencing the integrity of the inspection system can have significant impact on the manufacturer's ability to maintain or even increase market share.

4.5 WORKFORCE MANAGEMENT

This section explores the human side of manufacturing today. Competing on science and technology means competing on the organization of information; invariably one thinks of a battle of computers. But the machine is not at the center of the competition, knowledge workers are, and they are a corporate assest that last if they are committed. People are a key means to achieving the organization's goals. Even a technology - based strategy has its foundations in people. Without the right people, the most streamlined processes make no difference to the bottom line.

CIM, JIT, GT, MRP II, TQM - none of these systems, methodologies, or techniques serves as an end in itself. Each is just one part of a larger vision of a flexible and responsive manufacturing enterprise. Getting it right in the marketplace means that firms must respond quickly to changing customer demand and customer satisfaction. The ability to reduce cycle time is necessary to make the changes required by customer demands and desires. In order to acquire the ability to reduce cycle time, an organization must be flexible. A flexible organization leads to an improved strategic position and a competitive advantage that helps to ensure long term viability.

Three values concerning people management essential to a corporation in pursuit of flexibility are diversity, discourse and empowerment.

Firms need to pay attention to diversity for a couple of reasons. First, business is increasingly complex. Work that individuals used to perform is now done more effectively by teams. For this reason, companies may need to transform a collection of individuals of all genders and of different ethnic, racial, and religous backgrounds into a cohesive team sharing a common goal, trust and interdependence.

Secondly, companies must attract and motivate its employes in an effort to retain the best and brightest people from every available source and coax the greatest contribution from each person. Companies can't afford to have people working at fifty percent capacity because they feel that certain of their abilities and attributes aren't useful.

What should companies hope to accomplish by valuing diversity? First and foremost, companies will be creating an environment in which every employee can make his or her fullest contribution to the company goals. This will boost productivity in the long run. Secondly, diversity will change the psychological contract between employees and employer. When an employer works to create an environment in which diverse people and talents are valued, people get motivated and energized. They work at full capacity and get something back from the system in terms of career and personal growth. People usually respond positively if they know that they are truly part of the company team.

What does the diverse work force want?

- People want to feel included, heard, valued, trusted, safe, treated like adults. They want to feel that somebody is willing to take a risk on them. In short, they want to know that they will be treated fairly and equitably.

- They want to know that opportunities for jobs, recognition, promotion, and compensation are open to all; that these can be theirs too. That if they work hard they can get the rewards the system has to offer.

- They want responsive management.

These desires pose challenges for managers. They will need to find ways to utilize the full talents of this workforce, to practice management processes that are bias-free, and to have the personal comfort, knowledge and skills to deal with people who are different from themselves.

Diversity leads to a participatory culture full of respect for each individual. As a result, individuals will get involved. In the workplace, people will sit together with management on committees to solve company problems and promote company goals. Employees will work with managers to create visions and strategic directions for the company. There are celebrations of diversity, and conflicts are embraced as opportunities for change and learning. People can successfully work conflicts through to resolution and new understanding.

The second value essential to corporate flexibility is communication. Communication too often becomes a one-way street; emanating from the top down. Communication gives rise to the belief that information sharing is right and necessary. Sharing the corporate vision, strategies and goals is fundamental, as is getting input and reactions to refine them. People believe that listening is a way to learn and that ongoing learning keeps an individual and an organization vital. They believe that the exchange of ideas leads to innovation and discovery and that no one person has all the answers (Leavitt 1988).

In a culture that grows these beliefs; people are informed. They learn from their own experiences and from those of others. This is a culture in which it is acceptable to take risks and to fail. The most characteristic behavior in this culture is people working in teams. There is ongoing, multidirectional, honest communication. There are human networks and a human scale to the work, the processes, and the infrastructure. Internal employees innovate and create new business ventures through entrepreneurship. People work in concert with company goals, secure in the knowledge that what they do is connected to the larger picture. The organization is aligned.

More than any other variable, communication works best in flat organizational structures. Information that travels by the shortest distance and most direct is the freshest, most accurate, and most relevant. Given the distance between the top and the bottom of organizations in pyramidal, hierarchial structures, it is not suprising that the top and bottom are disconnected, don't understand each other, can't communicate, and (more often than not) are working on entirely different agendas, goals, and programs.

They are literally living in different worlds. A flat structure, with its quick access, puts everyone back on the same team on the same playing field on the same day. It is a huge step toward a winning attitude and the success that results (Leavitt 1988).

The third value essential to corporate flexibility is empowerment. Technically, to empower means to invest with legal power, or to authorize. In today's human resources vernacular, however, the word is used more for its connotative than literal sense. Empowered people operate out of the passion and courage of their convictions. They do the right thing, live out their values and beliefs, behave authentically, and follow through on commitments. They are honest and fair with themselves and others, upfront and nonmanipulative. The definition of empowerment is difficult to pin down exactly because it deals with the elusive world of feelings. People feel empowered when their head and heart and gut are synchronized and they are centered in the feeling of being in control that results. Everyday people all around us are empowered as they accomplish their potentials. Beliefs that grow from valuing empowerment are:

- People are trustworthy
- Motivation is a function of self-esteem and self-determination
- Recognition of good performance makes people feel good about themselves

All these feed self-esteem. Again, we see reciprocity in operation.

The culture that springs from empowerment is a meritocracy. It invests in humans and their growth and development, takes a long-term perspective, and supports personal commitment and responsibility. The behaviors in this culture revolve around high motivation with low supervision. This results from the combination of teamwork, shared vision, and self-determination. People express loyalty and achieve quality and excellence in processes and products. They follow through on commitments and take initiative by signing up for work that contributes to company goals. They seek innovation and renewal (Oakley 1993).

The final link in the chain leading to flexibility is the human resources practices and programs. It is difficult to predict accurately just what programs and systems an organization should design. However, it is important to note that whatever programs are chosen, they should be tied together into a system, and must all be directed at achieving flexibility; in contrast to a traditional structure for personnel in which there are seperate departments of compensation, benefits, training, development and employee relations. It is critical to ensure that all functions are mutually reinforcing.

Some of the most powerful tools that an organization can use to motivate employees are: recognition and reward systems, benefits and training.

Reward systems which include compensation, need to be designed to reward the values of the organization. There needs to be rewards for quality, not quantity, for diversity, not sameness, for innovation and risk taking, not for staying in line and doing things by the book. A company should look at what its system outcomes currently are, for that is what the company is rewarding now, whether it intends to or not.

Firms must close the gaps between what they protray and what they do. People see right through these inconsistencies. They will act in accordance with what is seen to be rewarded. The greater the gap between what a company protrays as it values and what it actually rewards, the greater the management credibility gap.

Recognition, if used effectively can be very motivating. Recognition covers everything from a nod and hello from a senior manager to an on-time and accurate performance appraisal; from verbal praise for a job well done to a plaque in recognition of performance; from a mention in the company newsletter to a stock grant. For the most part recognition is free, abundant and easy. It is also consistently overlooked. Everyone likes recognition. It simulates people to perform well and to repeat good performance.

Benefits are intended to reduce risks and protect employees from hardships. They should enhance an employee's ability to contribute. They include such elements as medical and dental plans, vacation, sick days, tuition assistance, maternity/paternity leave, disability compensation, adoption assistance and childcare. Companies need to hear from employees what coverage is relevant. The needs of a new college graduate, a single parent, and a disabled veteran are different.

If an employee has difficulty in any nonwork area of his or life, the firm has trouble. Companies are dealing with people; they have to take the good, the bad and the ugly. Good firms take the childcare issues along with the leadership capabilities. Good firms take the temporary instability and productivity drop during the crisis of divorce along with the excellence in closing sales. Progressive firms take the request for leave of absence (to hike, golf, renew and contemplate) along with the innovative product development. People need to have options for benefits that are relevant to them as they pass through various life stages. Self-selection of benefit packages empowers employees because it puts them in control - they can take care of the important aspects of their lives.

Why devote the considerable time and expense necessary for employee training? The answer is so obvious that it escapes many executives' notice. Current employees are a rich resource. They know the products, corporate culture, customers, other internal players, and the industry; they grasp company vision and strategies. They are context-rich. For many reasons they are an obvious choice for investment.

- Reading, writing and empowerment are linked together. When a firm invests in and develops its employees, it is furthering their empowerment.

- Training and education sends employees the message that they are being supported to be successful. They have the means to do a better job. When a firm invests in and develops its employees, it is furthering its partnership with them.

- Increased productivity and improved quality are two outcomes of training a workforce. When a firm invests in and develops its employees, it is furthering its business goals.

Training and development solutions will be unique to each firm because they are responses to unique business situations and problems. At the same time, surveying what other businesses are doing maybe helpful, for many of their ideas and successes can be tailored to a different company's situation. One firm can also learn from the experiences of others and possibly avoid some of their failures.

Based on the above information, the variables identified for the workforce management decision area are as follows. Skill levels, level of morale, productivity, the degree of tooling effectiveness and the degree of empowerment and the number of employees assigned to a manager. Figure 13 illustrates the influence diagram for the workforce management decision area. The thinking behind the construction of Figure 13 will now be discussed.

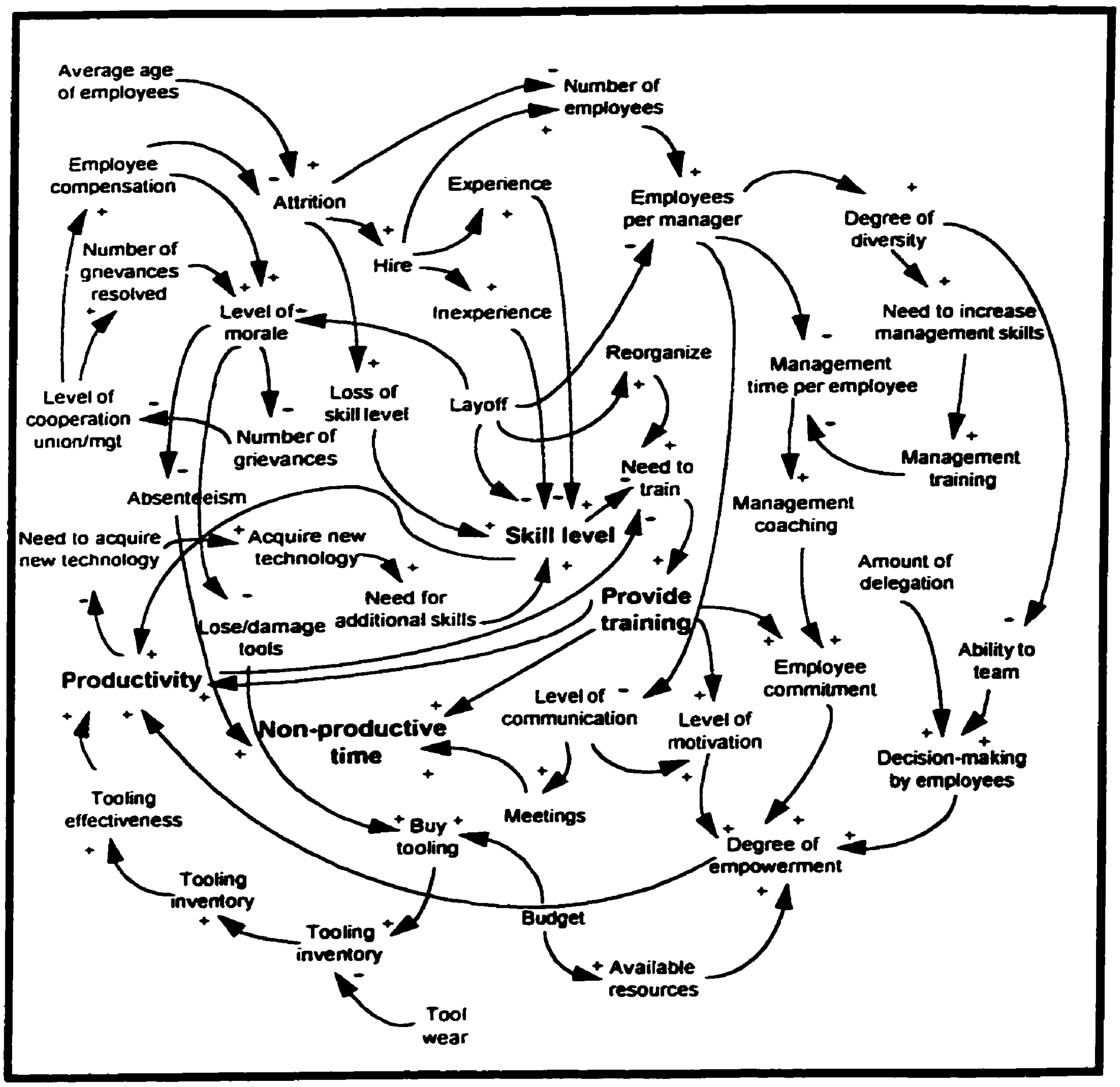

Figure 13 Influence diagram for workforce management

At the core of the workforce management decision area is the productivity of employees which depends upon skill levels, the effectiveness of tooling, degree of empowerment and the level of morale. However, fundamental to workforce management is the stability of the workforce due to the negative influence of layoffs. Layoffs can have a widespread effect within workforce management influencing skill levels, the morale of employees, and creating the need to shift employees from department to department (assuming a unionized environment).

Increasing layoffs negatively influences skill levels (i.e. loss of specialized skills) reducing productivity driving the need for additional training which if provided can impact the level of motivation of employees affecting the degree of empowerment. The degree of empowerment if increased, which may be the case, as a result from increasingly motivated employees will increase productivity. Hence, on one hand, layoffs may reduce productivity but on the other hand, layoffs may be offset by variables such as training and motivation. This apparent paradox raises the question of which of the two actions have a greater effect on productivity. Are productivity losses due to the lowering of skill levels greater than the productivity gains from the increase in the degree of empowerment? An additional effect of layoffs is the need to shift employees from department to department (assuming that the manufacturing environment is unionized). If employees are shifted, then there is also the need to provide additional training for the employees that are being transferred to a new department which as explained before can positively impact productivity.

Training as previously explained, can positively motivate which may increase the degree of empowerment resulting in an increase in productivity. However, on the other hand, training takes away from production in the sense that if an employee is in training, then the employee is not working on manufacturing parts resulting in lower productivity. Again, another paradox; and hence, one really needs to understand the implications of providing training from the perspective of its effectiveness so that the appropriate decision can be made on how much training should be provided (i.e. at what point does training become non-value-added, since it does take the employee away from production.)

Another influence of layoffs is the negative impact to the morale of the employees. In an unionized environment, low morale may affect the number of grievances that are being generated by employees; and depending upon the relationship between the union and management, can influence the number of grievances resolved. If there are a high number of outstanding grievances, then there would be a reinforcing effect on further reducing the morale of the employees. The number of grievances generated may negatively impact the level of co-operation between the union and management which may impact employee compensation causing employees to leave the organization (early retirement). Employees leaving the organization worsens the already bad situation of a reduction in skill levels due to layoffs. The need to hire may arise in the situation where there may have been a high attrition rate which can impact the low skill level situation either positively or negatively. Depending on the availability of highly skilled workers, hiring may positively influence skill levels. On the other hand, hiring a number of inexperienced workers would negatively influence skill levels driving up the need for further additional training.

The type of tools that employees work with can significantly affect productivity. For example, an employee that does not have the correct tooling cannot be effective in doing their job, from the standpoint of maybe not being able to do the job at all, or doing a poor quality job or even taking twice as long to get the job done. Any one of those situations can lead to lower productivity. The type of tooling is affected by tooling inventory from the perspective of not having enough tools for the employees, incorrect tooling, damaged tooling or even worn out tooling that maybe in need of repairs. Worn tools are typically a result of excessive use without being properly maintained or repaired. Damaged or lost tooling however, may be a result of low morale of employees which of course could have been influenced by a number of different issues such as layoffs, poor relationship between the union and management, or an inappropriate employee compensation system. The need to buy tools is directly influenced by the number of occurances of damaged or lost tools which inturn can negatively impact the budget. Of course decreasing the budget can have widespread effects such as negatively influencing the amount of training that can be provided, the amount of resources that could be made available to positively influence the degree of employee empowerment, or even capital funds to acquire new technology that could potentially increase manufacturing's capacity.

So far we have discussed issues surrounding layoffs, training, skill levels, tooling, morale and their effects within workforce management. It is interesting to note that the number of employees, specifically the number assigned to a manager, can have significant influence on empowerment, and hence, on productivity. Assuming that the number of managers does not change, the impact of increasing the number of employees would suggest that managers would have less time with their employees which would influence the amount of coaching that a manager conducts with their employees, negatively impacting the level of committment by the employee reducing the desire to be empowered. Another effect of increasing the number of employees is that there is the potential to increase the diversity of the workforce which would suggest the need for managers (depending on their capabilities), to acquire additional training to deal with diversity issues among their employees. The need for additional training takes away from time that managers would spend with their employees reinforcing the negative influence of managers not having enough time with their employees. One positive result that may occur which may not have been necessarily planned is that as managers have lesser amounts of time available for their employees, they tend to delegate more decision making to the employees which can positively impact empowerment.

One point to be aware of is that with more decision making comes the desire for more compensation which if not made available for the employees may negatively impact the morale affecting their motivation resulting in negatively impacting empowerment. Another paradox; on one hand more decision making by the employees can elevate the level of empowerment, but on the other hand, if appropriate compensation does not follow, then the impact to empowerment can be a negative one. Another effect of increasing the ratio of employees to managers is the reduction of the frequency of communication between employees and management. As previously mentioned, communication can have a significant impact on the level of motivation among employees which can tremendously impact the degree of empowerment. On one hand, communication is essential for the employees to be knowledgable of current situations whether it is market conditions, upcoming events, or the company's business plans. A knowledgable worker is more likely to be motivated than one that does not even understand the importance of their contributions within the organization. However, on the other hand, too much communication maybe counterproductive, in the sense that employees maybe receiving non-relevant information, and each communication session will increase non-productive time resulting in lowering the level of productivity.

The above discussion explains some of the influences that the variables identified within workforce management can have on each other, and their effects on productivity which directly affects the cycle time to manufacture product. However, one point that is being clearly made, is the effects the variables can have on each other is not explicit; and in making a decision there can be many implications which may not be apparent without extensive analysis. For example, at a glance, one may think that the more training that is provided, the higher the productivity; but this scenario may not hold true. Training is beneficial to a certain point; after which it becomes non-productive. Inaddition, the time that is spent training is not being utilized for actual manufacturing which increases non-productive time, hence, lowering productivity. Another example, where all of the effects of a decision may not be obvious is as follows. Initially, one may believe that the immediate effects of a layoff to be a drop in skill levels which would lower productivity. Another effect however, that may not be explicit, is the fact that layoffs in a unionized environment may result in employees being shifted around to various new departments. An employee coming into a new department would not only have to go through a learning curve but also may require additional training. Both the learning curve and the time spent for additional training will initially result in lower productivity. Hence, not only is there a decrease in productivity from the layoffs; but inaddition, there will be a decrease in productivity due to the shifting of employees from department to department and the initial learning curves that they will go through. Therefore, the initial estimated decrease in productivity due to the layoffs maybe completely incorrect.

4.6 MAINTENANCE

Today, the automotive, electronic, textile industries and many more, including the aerospace industry, are being severely challenged by foreign-based manufacturers. Producing a quality product or providing quality services at competitive prices in a timely manner has become a key issue for survival in today's environment.

If a facility is not kept operable within reasonable cost limits in today's competitive environment, the whole organization will suffer, or perhaps even be forced to close its doors. To keep a facility operationally cost effective, the resources required (such as people, equipment, and material) must be utilized efficiently. Maximizing the operating conditions of the production equipment (i.e maintaining the equipment as close as possible to design specifications and minimizing equipment breakdowns) to manufacture a product is a key factor in continuously improving cycle time to maintain the competitive edge. If the equipment is down because of failure or other operational problems, it delays the completion of products resulting in additional costs and late deliveries to the customer. A manufacturing facility with poorly operating equipment conditions usually has higher maintenance and poor delivery performance; and requires additional equipment to compensate for lost capability and capacity. Therefore, the cost of the products produced usually go up. Other factors such as increasing labor costs, complex and state-of-the-art equipment, specialized training costs, union/company policies, and low labor utilization/high work delays also contribute to the upward trend in maintenance costs.

Maintenance managers must continually find ways to ensure adequate output performance while minimizing those costs incurred in attempting to maintain the desired output rate and the costs incurred when the system fails to perform at the desired output range. System failures never happen at a "good time", typically requiring emergency measures, and can be extremely costly. In a Just-In-Time manufacturing environment hundreds of workers on a production line can be idle, along with expensive equipment, and customer shipments delayed just because one machine fails.

To reduce maintenance cost and improve productivity, changes in the traditional way of managing maintenance must be made. We cannot afford to live with the old way of thinking: "If it ain't broke, don't fix it". It is the time to think: "If it ain't broke, predict when it will break and fix it before it happens" so that it is available whenever it will be needed.

Maintenance plays a key role in meeting the operational and organizational goals. However, there is evidence of lack of management support resulting in part from an existing perception that maintenance is a necessary evil, an indirect cost and cannot be managed effectively. On the contrary, maintenance can be managed effectively. An effective maintenance system is a key element in keeping equipment running smoothly and efficiently (i.e. maximizing the operating conditions) minimizing cycle time to manufacture the product resulting in products delivered on-time to the customer.

The prime reason for higher maintenance costs is equipment failure. Excessive equipment failure causes two problems: It increases the cost of maintenance; and more importantly it reduces equipment availability for production. The application of prevention techniques to reduce failures is fundamental and essential for an effective maintenance system. One such preventive technique is preventive maintenance.

4.6.1 Preventive Maintenance

Preventive maintenance is preventive medicine and health maintenance for equipment; very similiar to preventive health care for people which has reduced the incidence of disease and increased the human life span significantly. In preventive health care, emphasis is placed on the prevention of illness, so that disease will not be contracted at all. Thus, preventive maintenance can be seen as a means to decrease the number of breakdowns (equipment disease) and increase equipment life span. The practicality of preventive medicine is easy to grasp. The cost of daily prevention and periodic checkups is minimal compared to expenses incurred when health care is neglected and when illness leads to hospitalization. Similarily, it is cheaper to repair the equipment on a preventive basis than to wait until it has completely deteriorated. At that stage the cost of restoring equipment can be exorbitant. Oddly enough, however, many companies choose not to practice preventive maintenance or practice it only halfheartedly, even though they understand its importance.

Preventive maintenance involves a pattern of routine inspections and servicing at regular intervals. These activities are intended to detect potential failure conditions and take steps to prevent their occurrence. Traditionally, preventive maintenance programs are set up to carry out equipment maintenance, on a regular calendar schedule or by hours of operation, based on the manufacturer's recommendations. These recommendations are usually based on an average operating environment. Routine inspections often highlight problems that may cause equipment to operate below its normal efficiency. A piece of equipment that suffers a breakdown, experiences periodic speed loses, or lacks precision and produces defects would indicate poorly operating conditions.

Factories that fail to implement preventive maintenance are, in essence, accelerating the deterioration of their equipment. In such factories, powdered dust and chips fly in all directions and lubricants and oil drip while the equipment and floor are littered with dirt, dust, oil, and raw materials. When dust and dirt adhere to moving parts and sliding surfaces of the machinery, the surfaces are scratched, causing deterioration. And, when lubrication is neglected, excessive friction or burning can result, wasting energy. In addition, when loosened nuts and bolts go unattended, they can cause excessive shaking, which encourages abnormal abrasion and triggers further deterioration. Moreover, when plumbing maintenance is inadequate, leaks may develop resulting in excessive waste of precious materials and energy. In factories where such neglect is rampant, sudden failures and minor stoppages are inevitable and common causing a reduction in overall equipment operating condition lowering production capacity.

In the analysis in this dissertation, preventive maintenance activities (schedules) are proposed in the form of preventive maintenance hours to be completed which is based on the number of pieces of equipment that are currently in operation. Preventive maintenance schedules are the daily scheduled preventive maintenance activities that are deemed necessary to prevent machine breakdowns. These hours will vary over time as a result of gaining a better understanding of the type and frequency of preventive maintenance that is effective.

The percentages of the preventive maintenance that are to be completed on a weekly basis can influence the generation of maintenance tasks. In this analysis, maintenance tasks, also referred to as work requests are grouped into three major categories: emergency, operations and scheduled.

- The emergency tasks (usually unplanned critical production machine breakdown) are usually performed when the equipment fails to operate, often at a premium cost.

- Operation tasks are those that are generated from the daily operations of the facility.

- Scheduled tasks are maintenance tasks that are scheduled to be completed sometime in the future.

Hypothetically, the amount ofmaintenance tasks should decrease if scheduled preventive maintenance work orders are completed as per schedule and vice-versa. There are a number of techniques/tools that can be applied to optimize the resources required for maintenance activities. Some of these techniques/tools include:

- Equipment history analysis
- Application of work standards and planning,
- Computerized maintenance management systems.

4.6.2 Equipment History Analysis

An equipment history analysis data base is the foundation of any maintenance system. This data base aids in the decision-making process to maintain the equipment in a cost-effective and timely manner. The equipment data base should contain the following information:

- Failures: i.e. breakdown events
- Preventive maintenance data
- Planned/scheduled repairs
- Operating/usage hours
- Repair time and cost

Information from the equipment data base can be used to perform failure analyses to identify problem areas. This allows cost-effective corrective actions to be taken to reduce failure rates and repair time increasing equipment availability.

4.6.3 Application of Work Standards and Planning

The average utilization of the North American maintenance workforce is approximately 40 percent. The low utilization is one of the major contributors of poor maintenance effectiveness and high maintenance cost. To improve utilization of a maintenance workforce, an improvement in maintenance planning is required. Planning is best facilitated by reviewing the total work flow process, from work requests to job completion, and then making changes for improvements.

To plan maintenance work effectively, it is very important to know how long it should take to do a specific job. Estimating the time required to do a job is a key element in maintenance planning. Work/time standards have been used in production areas very effectively. It has been often thought that the work/time standards concept cannot be used in the maintenance area since every job is unique. However, work/time standards for maintenance work have been developed and are being used successfully with positive results.

4.6.4 Computerized Maintenance Management System

An effective maintenance management system requires accurate and timely information relating to the resources available, work required or to be performed, and equipement history including failure data, materials, and inventory costs. A computerized Maintenance Management System (CMMS) can provide the necessary information. It helps the maintenance department operate in a much more structured manner. CMMS, or simply maintenance software, can allow maintenance departments to organize and plan all maintenance activities (e.g. preventive maintenance, equipment records, work orders, spare parts, etc). It can help to establish a good equipment history database to perform a variety of analyses.

The success of some techniques/tools used in optimizing the work is very dependent upon the culture within the maintenance and production operations departments; and the spirit of cooperation and cordial relationship between those departments. In typical operations, when failure of equipment occurs, a maintenance crew is usually called in to fix the problem. The maintenance crew could be late in responding to the request as they may be tied up with other repairs. In the mean time, the operations crew is idle during this period and throughout the repair. It would be ideal if the operations crew (operators) could fix the equipment themselves; if the fix is small, instead of waiting for a maintenance crew. If the fix is major and requires large resources, they could become part of the repair crew. Operations and maintenance could become partners in maintaining the equipment, as well as in producing quality products.

In this joint venture between maintenance and production, the maintenance worker takes on the role of consultant and advisor to the manufacturing organization. Machine operators take on the duties of simple routine maintenance tasks. The skills of the maintenance workers are reserved for more complex projects, and the diagnostics and analysis of major equipment breakdowns. Hence, maintenance workers develop and enhance a greater range of skills to play a wider role in the organization.

Maintenance and production workers must take responsibility, ownership of the process for providing the manufacturing organization with reliable equipment, regularly scheduled preventive maintenance and by minimizing breakdowns and disruptions to the manufacturing production process.

4.6.5 Automation

Technology is changing so rapidly that it is now more important than ever for operations managers to make intelligent, informed decisions about the levels of automation. Many new opportunities are the result of advances in computer technology. Deciding whether to take advantage of such opportunities can significantly affect the cycle time to manufacture product and the morale of the work force. Cycle time may decrease dramatically with automation, however, jobs at all levels within manufacturing could also be affected. Some maybe eliminated, some upgraded and some downgraded. Even where the changes resulting from automation are small, people-related issues become significant. For example, poorly trained and poorly motivated workers can cause enormous damage to newly acquired automated equipment. The transition is easiest when automation is part of a capacity expansion or a new facility and doesn't threaten existing jobs. In other situations, early education and retraining is essential.

As previously mentioned, cycle time is a key measure of delivery time which an increasing number of companies are using as a basis for gaining competitive advantage. The operating conditions of the production equipment can negatively influence equipment availability causing a reduction in production capacity and hence, affecting cycle time. Based on the above information, the variables identified for the maintenance decision area are as follows. Preventive maintenance efficiency, maintenance requests efficiency, effectiveness of the maintenance employee, production machine operator's involvement with maintenance and levels of automation. Figure 14 illustrates the influence diagram for the maintenance decision area. The thinking behind the construction of Figure 14 will now be discussed.

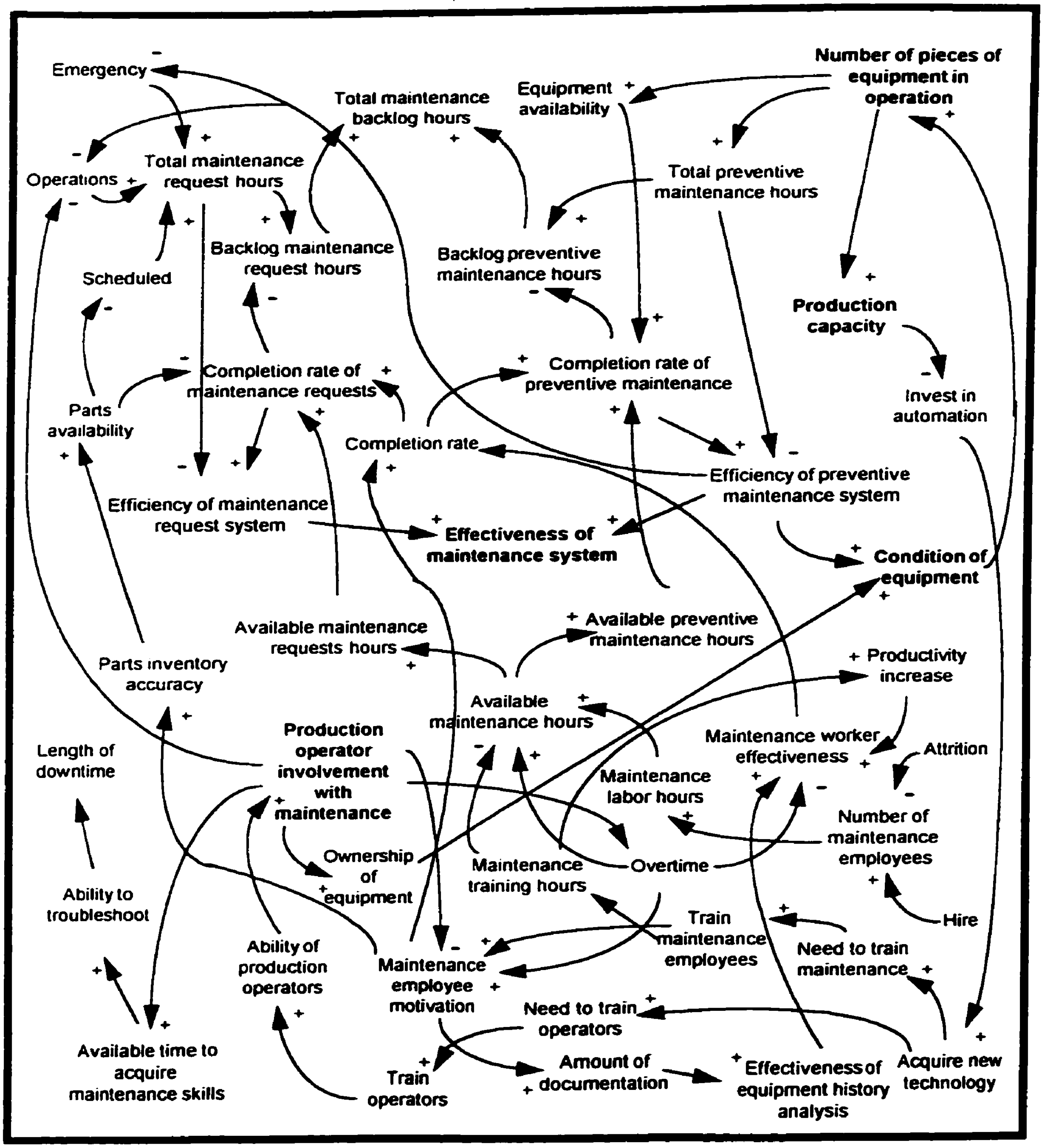

Figure 14. Influence diagram for maintenance

The efficiency of both the preventive maintenance and maintenance requests systems (i.e. percentages of preventive maintenance and maintenance requests that are completed on a weekly basis) directly affects the operating conditions of the production equipment (i.e. the reduced performance of machinery due to discrepancies between design and actual speed of the equipment). The operating conditions of the equipment can affect the number of pieces of production equipment that are in operation which can impact production capacity, and hence, the cycle time to manufacture the product.

The efficiency of the preventive maintenance system is directly affected by both the total number of preventive maintenance tasks that are scheduled and the completion rate of preventive maintenance tasks. The total number of preventive maintenance tasks to be completed is determined by the current number of pieces of equipment in operation, plus any additional preventive maintenance tasks that may be needed due to a change in production requirements. For example, there may be a need to increase the frequency of certain preventive maintenance checks (oil level, filter condition, etc) due to production shifting from eight hours a day, five days a week to operating twenty-four hours a day, seven days a week. The completion rate of preventive maintenance is influenced by the level of motivation and effectiveness of the maintenance employee, availability of maintenance resources and the availability of the equipment. The availability of equipment for preventive maintenance can have a counter-intuitive effect on production capacity. Production may decide not to make the equipment available for preventive maintenance due to insufficient production capacity. This decision by production would result in failure to complete the preventive maintenance as scheduled, reducing the completion rate of preventive maintenance and hence, lowering the efficiency of the preventive maintenance system. These actions would lead to deterioration in the operating conditions of the equipment resulting in equipment inefficiencies and unscheduled (emergency) breakdowns which further reduces the already low production capacity.

Another effect that may not be readily obvious from not freeing up equipment for preventive maintenance occurs within the maintenance labor resource. The impact of not having the production equipment available during a regular day shift may force maintenance employees to work large amounts of overtime inorder to complete the regularly scheduled preventive maintenance. Working overtime can either positively (from a financial perspective) or negatively (cancelling personal appointments) motivate the employees. But more importantly, working long hours may reduce the effectiveness of the maintenance workers resulting in the employees putting in a halfheartedly effort in completing the preventive maintenance which would eventually impact the operating condition of the equipment.

The efficiency of the maintenance request system is directly affected by both the total number of maintenance requests that are scheduled and the completion rate of the maintenance requests. The total number of maintenance requests to be completed is determined by unscheduled equipment breakdowns, daily maintenance requests typical of operating a manufacturing facility, and scheduled maintenance repairs. The completion rate of maintenance requests depends upon the availablity of maintenance resources, material availability, the level of motivation and effectiveness of the maintenance employee. For example, the probability of repairing an unscheduled machine breakdown expeditiously will depend upon the facility's on-site spare parts inventory and the troubleshooting diagnostic abilities of the maintenance employees. Not having the correct spare parts readily available can negatively impact the timeliness for completing the repairs. Hence, a decrease in the maintenance requests completion rate reduces the efficiency of the maintenance request system which directly impacts the downtime for equipment repairs. As downtime increases, production capacity decreases, reducing the availability of production equipment, and hence, decreasing the efficiency of the preventive maintenance system. Decreasing the efficiency of the preventive maintenance system leads to further deterioriation of the equipment, and eventually more unscheduled breakdowns which further decreases the efficiency of the maintenance request system exhibiting a reinforcing behavior.

The amount of training provided for maintenance can impact the effectiveness of the maintenance employee which influences both preventive maintenance and maintenance request completion rates. It is interesting to note, however, that the amount of training provided is a very sensitive issue. Even though training takes away from available resources to do maintenance requests and preventive maintenance, one would expect that the increase in the maintenance employee's effectiveness from the additional training would off-set the loss time because theoretically the employees should not require as much time to complete their work as they had required in the past. However, the above scenario does not hold true in all cases because the expected productivity improvements may not be realized. The training may not have been effective; or the employees may not be capable of further improving. Hence, in making a decision around the amount of training to provide, one should thoroughly understand all of the implications for providing such training.

The production operator can play a significant role in improving the operating conditions of the equipment. For example, the production operator can perform simple maintenance tasks on the machinery that they operate - check oil levels, minor adjustments, calibration, and general cleaning, etc. By becoming involved with doing simple preventive maintenance tasks, the operator increases ownership of the equipment which generally results in an overall improvement in the equipment's operating condition. Their involvement also frees up maintenance resources to improve the efficiencies of both the preventive maintenance and maintenance request systems which leads to the reduction of the total maintenance backlog and improvements in the operating conditions of the equipment. However, the production operator's involvement may negatively influence the level of motivation among the maintenance employees because there maybe less of a requirement for maintenance to work overtime. Inaddition, maintenance employees may be upset at the fact that production operators are doing maintenance work which is typically not an acceptable activity in a unionized environment. Therefore, on one hand, the operator's involvement can free up maintenance resources to reduce total maintenance backlog. But on the other hand, their involvement can negatively impact the level of motivation of the maintenance employee reducing their effectiveness which may lead to a higher total maintenance backlog Therefore, one needs to be cautious if making the decision on the level of involvement of the production operators in performing maintenance activities no matter how elementary they may be.

The above section discusses some of the influences that the variables identified within maintenance can have on each other, and their effects on the operating conditions of the production equipment which directly affects cycle time to manufacture product. The point that is being made in the above discussion, is that the effects the variables can have on each other are not always explicit or obvious; and in making decisions there can be many implications which may not be apparent without extensive analysis. For example, it would appear that motivating the production operators to become involved with performing the simple maintenance tasks, would free up maintenance resources to improve the operating conditions of the equipment and reduce the total maintenance backlog. However, this decision may be counterproductive from the perspective that increasing the involvement of production operators may demotivate maintenance employees, reducing their productivity which in the long run would lead to an increase in the total maintenance backlog Another example, there may be an assumption that providing additional training to the maintenance staff would increase the effectiveness of the maintenance worker which in turn could lead to an increase in the efficiencies of both the preventive maintenance and maintenance request systems. However, the decrease in available maintenance resources due to the time spent in training, may cause a reduction in both the completion rates for preventive maintenance and maintenance request which of course would reduce the efficiencies of the preventive maintenance and maintenance request systems - opposite to what was initially assumed. The author cannot emphasize enough of how important it is to fully understand the effects that the variables can have on each other when making decisions because the influences among the variables are not always explicit or obvious; and many implications may not be apparent without extensive analysis.

The discussions so far have provided additional insights into the interrelationships among the variables of the decision areas of process, workforce management, maintenance, materials management and quality in relation to cycle time. Cycle time directly affects a firm's delivery commitments; a competitive priority that is becoming increasingly important as global competition continues to grow.

The next section, deals with how do the above mentioned decision areas relate to each other so that operations management can become a competitive weapon. The following sections suggest insights into the relationships between decision areas. That is, how do the decision areas affect each other when meshed together, and why certain conditions lead to more successful outcomes than others.

4.7 INTERRELATIONSHIPS AMONG DECISION AREAS

4.7.1 Process Versus Product

Positioning strategical operational decisions (i.e. process focus versus product focus) serve as the basis for decisions at other levels. A process focus strategy means jumbled routings of products through the system. Flexibility is maximized by organizing resources around the process (or function). A product focus strategy is just the opposite, trading off flexibility to achieve standard routings, line flows, and resources organized by product. The best focus for a specific company depends on its product plans, competitive priorities, and quality choices.

When product plans call for more customized products, prices will be high and volumes low. Life cycles are shorter, and products tend to be in the earlier stage of their life cycles. With such flux in product plans, dedicating resources to specific products is unwise. If on the other hand, product plans require standardized products with higher volumes and longer life cycles, then a product focus would be more appropriate.

4.7.2 Quality

The linkages between quality management and positioning strategy lies with product specifications. A firm choosing high performance design quality as its competitive priority is likely to have a process flow. Prices must be higher, resulting in lower product volumes. Firms choosing product or volume flexibility as a competitive priority are likely to be small and have a process focus. Their quality control procedures are less formal, and they depend largely on the workforce to achieve reliable quality. High volume firms with a product focus tend to have more staff specialists and inspectors, and the inspection operation might even be automated. To ensure consistent quality these firms have formal procedures for monitoring incoming materials, process yields, and outgoing products. Scrap and rework are particularly disruptive to the line in a product focused plant.

4.7.3 Materials Management

In a process focus environment, low repeatability and jumbled routings cause complexity in materials management. Last minute changes by customers and vendors, imprecise time standards, and difficulties in predicting capacities create uncertainty. Because of the complexity and uncertainty, plans cannot be made far in advance. Planning is done more at a local decentralized level to adapt to the latest conditions. Greater workforce and inventory cushions are tolerated because of the dynamic environment. No long term contracts are negotiated with key vendors. Raw material volumes are low, so the firm has less control over suppliers, who naturally cater to larger customers. The product flexibility of a process focus means that inventory must be created lower in the bills of materials. Inventory is not created by plan at higher levels because of low turnover and the fear of obsolescence. More intermediate items are likely to be produced to help increase part commonality, keep customer delivery times at acceptable levels, cut losses owing to setups, and buffer against bottlenecks. With a process focus, information tends to be oriented to the bidding process and specific customer orders. Output plans are communicated by releasing jobs with detailed routing information. With a product focus, information is orientated more to demand forecast and current inventory positions, rather than individual customer orders. Product focused firms produce more to stock and less to order. A final link with materials management is with a process focus, where volumes are low and unit costs are high, a firm tends to rely on outside suppliers to manufacture parts and assemblies for its products. Whereas, firms with a product focus and high volumes tend to do more part and assembly work in-house.

4.7.4 Workforce Management

A product focus production system is labor intensive and labor costs can be a concern. Efficiency losses caused by setups, materials handling and component delays have to be continually monitored. Process focus on the other hand, requires attention in ensuring effective facility utilization because of high capital investments and the controlling of various overhead costs. A product focus favors the utilization of a flexible workforce. A flexible workforce usually receives more cross-training so that they can help out with the capacity imbalances and frequent shocks at a product focussed facility. This approach creates enlarged, broader jobs, which often serve to motivate workers and to increase wage rates. Small product focussed plants have less formal promotion channels and are less likely to be unionized than large firms. Only until recently, have innovative contracts between unions and management, created a working environment conducive to a flexible workforce. In the past, unions favored narrow job boundaries and formal promotion channels where filling one opening would set off a chain reaction of bumping under the provisions of most labor contracts. Promoting the individual was based on seniority and not on whether or not they would be suitable for the position. The unpredictability of day-to-day production requirements of a product focus places great importance on two-way communication between workers and supervisors to identify which work to do next and how to do it. Fewer supervisory tasks are diverted to tasks specialists.

Changing the output rate to meet seasonal or cyclical demand by using overtime, subcontracting and extra shifts is about twice as common with product focus. A process focus is usually accompanied by a level strategy, letting anticipation inventory build during the slack season. A firm may even have enough clout to require customers to take early delivery of the inventory. The last resort for a process focussed firm is to shut down one of its plants entirely. Overtime and extra shifts tend to be infeasible options, as the plant is more likely to be operating with three shifts already in order to maximize facility utilization. A process focus implies low variability costs, making the extra costs of subcontracting prohibitive. Too much is lost by going outside to have the work done. It is also unlikely that a subcontractor can be found to supply the necessary volumes when business is booming.

Process focus operations are more rigid and tend to be set at specific output rates. Rebalancing process focus operations may mean changing the jobs of many individuals. It is simpler to temporarily shut down parts of the operation when demand falls.

4.7.5 Maintenance

Maintenance effects in a process focused production system is not as severe as it is in a product focused system. In a process focus environment, there is less automation; and the cost of breakdowns is not so high, since a machine failure may only affect a small area of the plant. Workstations tend to be decoupled from each other because of larger capacity cushions and substantial work-in-process inventories. Since equipment is more general purpose, jobs often can be rerouted to another piece of equipment. Disabling one work station does not shut down others, at least in the short run. Product focus, on the other hand, can be highly automated and one machine failure can quickly shut down an entire production line. This situation not only idles the workforce but it could also result in lost business opportunities. The highly automated equipment in a product focus plant creates the need for highly skilled maintenance employees.

Techniques such as preventive maintenance become very important because the key to an effective product focus production system is to prevent equipment failures. It is important to be able to predict when a piece of machinery could possibly fail. Programs such as Total Productive Maintenance are essential to both process and product focused systems. Minimizing maintenance costs can have a significant effect on profit margins. Also highly maintained equipment are more likely to produce less scrap.

Maintenance can have a significant effect on plant capacity especially in a product focused environment. As mentioned earlier, equipment breakdowns in product focused production system can be very detrimental to the plant. Not only does the workforce become idle but also delivery dates promised to customers could be missed. In a just-in-time product focus production system, the effects of machine failures can be disastrous. A single machine failure can literally shut down an entire plant. These effects are not as significant in a process focus environment. Capacity cushions in process focus are usually high because of low capital intensity, shifting product mixes, increased demand and supply uncertainties, greater scheduling complexity, and more variable demand. Hence, a machine failure causing a stoppage to producing parts may be offset by the capacity cushion - that cushion being either excess machine capacity or excess finished parts inventory.

4.8 SUMMARY

The discussion above touched on many issues. The first half of this section discusses the inner workings of the decision areas of process, materials management, quality, workforce management, and maintenance in relation to cycle time. Through the qualitative analysis, the author has been able to examine the influences of the identified variables within each of the decision areas to gain further insights on their interrelationships and their effects within their respective decision areas.

In the second half of this section, the author attempts to provide further insights into how the decision areas relate to each other when meshed together. For example, what are the implications of having minimal maintenance, an inflexible workforce, and intense quality inspection policies in a process focus production environment? Minimal maintenance may not significantly affect production since the capacity cushion is high. But what happens if as a result of an increased production demand or an unusually high absenteeism, there is a need for production operators to operate different machines. With an inflexible workforce, it would be very difficult if not impossible for the production operators to effectively operate other equipment. Intense quality inspection policies may require every part to be inspected after every operation. This would mean that there would be a need for a very large number of quality inspectors unless the operators were trained to do self-inspection. Operators performing a quality function may not be allowed due to the union contract or the fact that the workforce is inflexible . From this example, one can see that the interrelationships of variables among decision areas are very complex and if the appropriate decisions are not effectively linked, then operations management cannot become a competitive weapon.

CHAPTER 5

QUANTITATIVE ANALYSIS - MAINTENANCE DECISION AREA

5.1 INTRODUCTION

Chapter 4 demonstrated some of the ways in which qualitative systems analysis can be used to gain a better understanding or insight into systems. This chapter tries to show how such diagrammatic models might be converted into quantitative models to explore the control of the system's behavior more rigorously. The quantitative analysis will be conducted on one specific sector of the manufacturing strategy model - the maintenance decision area. The purpose of this analysis is to illustrate how a systems dynamic approach can offer a means to visualize how a system in its entirety works. The analysis should demonstrate that by better understanding relationships among and within a system, policies can be evaluated in a more concrete and decisive manner, thus leading to better decision making.

The author, as a result of the last ten years of experience acquired from managing maintenance departments of two very large manufacturing facilities in North America in the aerospace and farm equipment industries, had a thorough understanding of the elements that were most important for the maintenance system. Using the knowledge gained from those experiences, he developed an initial systems flow diagram for the maintenance system. In order to ensure that the basic key elements were representative of the system, group elicitation sessions were held with maintenance managers from other manufacturing facilities. The focus of these meetings was two-fold. First, to determine exactly the kind of things that were poorly understood from a holistic perspective within maintenance, and in what areas would insight be most welcome. Secondly, to ensure that the systems flow diagram was truly representative of how a maintenance department functioned. After many iterations, a representative systems flow diagram was developed. After outlining the structure, it was necessary to obtain real data in order to make the initial parameters realistic. The data used is from an accumulation of the various maintenance strategies and policies that the author as a maintenance manager has implemented over the last ten years while managing the maintenance departments of both a large aerospace and a heavy industrial manufacturing facilities in North America. As a final check to ensure a high level of confidence in the structure of the model, the author asked maintenance supervisors, along with maintenance workers, to criticize every aspect of the model from its structure to the initial conditions and assumptions.

The initial conditions of this model do matter in determining both the specifics and the general trend of the output. The author admits that there are some inadequacies in the initial conditions used especially in some of the softer areas where it was very difficult to gather hard facts.

Although inadequacies in the initial conditions make precise predictions an exercise in futility, as shall be discussed later, they still enable the model to be useful as a tool for understanding and discussing about the system in a more precise and meaningful way.

The following sections illustrate the systems flow diagrams for the maintenance sector along with the associated equations for the flow diagram. Included with each equation is a brief description of the role it represents including any assumptions made by the author in developing the model. For ease of discussion, the maintenance section has been divided into five areas called sectors: the maintenance request sector, the preventive maintenance sector, the production equipment capacity sector, the operator involvement/maintenance worker motivation and skill level sector, and the maintenance resource sector. Each sector represents key issues for the maintenance decision area. The information about the five sectors is provided in the following format. For each sector, there is a brief description of its role within the maintenance model followed by a systems flow diagram, after which, the equations specific to that sector will be provided, including a description of the equation along with any assumptions that were made by the author.

To reiterate, all data and relationships between variables that have been used in the model come from data gathering by the author over the past ten years in an area in which the author has had a significant experience. The relationships, especially among the softer variables, are based on the author's perspections gained through the experience of managing maintenance departments for the past ten years. Other managers may have completely different perspectives. However, the reader needs to keep in mind that the accuracy of the output is not as important as gaining a better understanding of the interrelationships among the variables that would result in better decision making.

5.2 PREVENTIVE MAINTENANCE SECTOR

The preventive maintenance sector represents the area within maintenance that pertains to performing preventive maintenance on the production equipment. Within this sector, preventive maintenance activities represented in hours per week are generated, and based upon factors such as maintenance resource hours that are available to do the scheduled activities, equipment availability and the level of productivity of the maintenance worker, a certain number of those activities are completed. Preventive maintenance that is not completed is measured and recorded as preventive maintenance backlog. The number of preventive maintenance hours generated weekly are based upon the number of pieces of production equipment in operation. The percentages of preventive maintenance completed on a weekly basis are calculated and monitored because of the impact that preventive maintenance can have on the operating condition of the equipment, and because of its influence on increasing or decreasing maintenance requests that may be generated from normal operating of the facility or from unexpected production equipment failures. Figure 15 illustrates the systems flow diagram of the preventive maintenance sector.

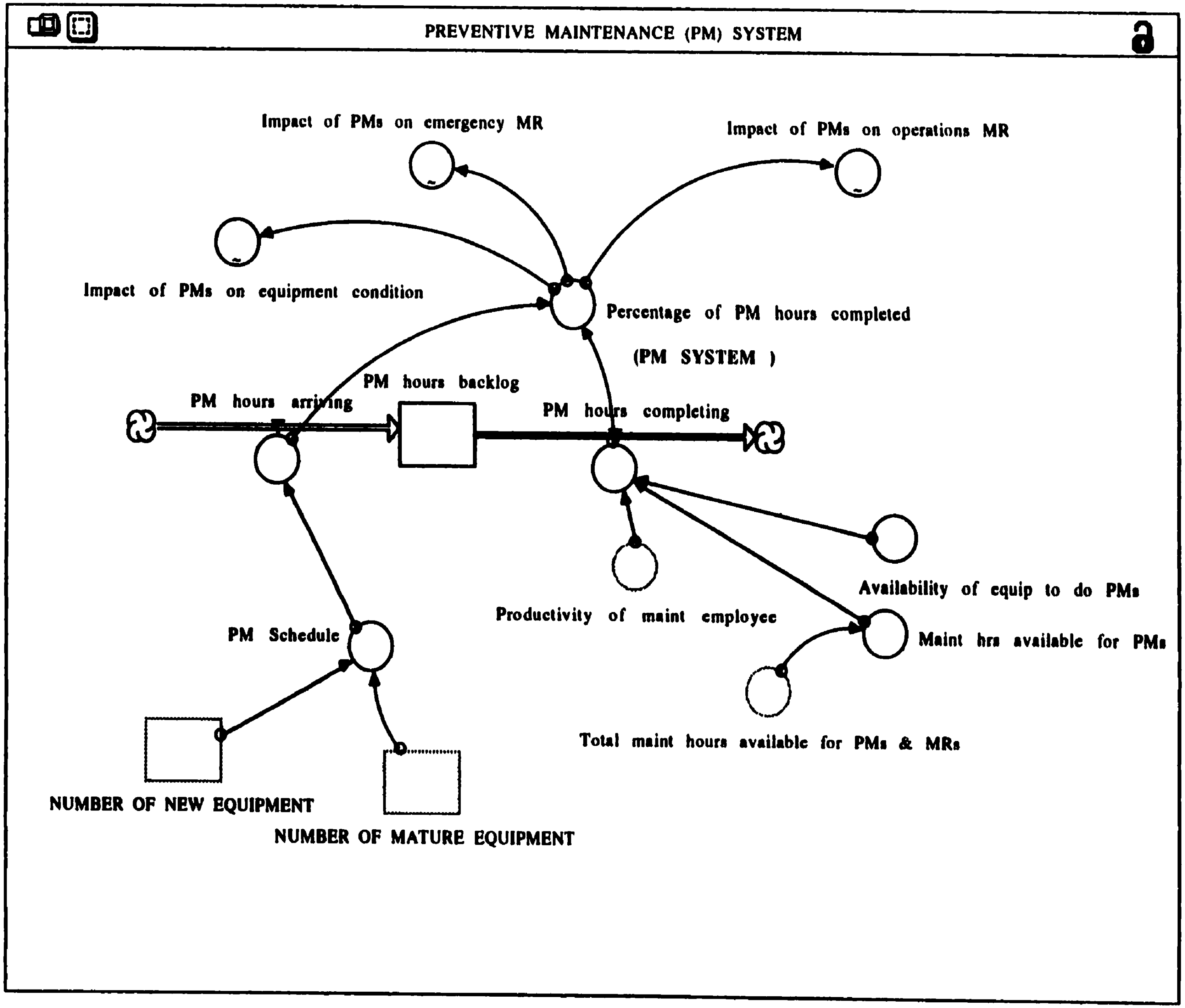

Figure 15. Systems flow diagram of preventive maintenance sector

5.2.1 Equations for the Preventive Maintenance Sector

☐ PM_hours_backlog(t) = PM_hours_backlog(t - dt) + (PM_hours_arriving - PM_hours_completing) * dt
INIT PM_hours_backlog = 350 {Hours}

DOCUMENT: Represents the current backlog of preventive maintenance activities in hours that have not been completed due to reduced productivity of the maintenance worker and/or the maintenance worker unable to access the production equipment to do the preventive maintenance activities.

INFLOWS:

PM_hours_arriving = PM_Schedule {Hours/week}
DOCUMENT: Represents the preventive maintenance hours that are scheduled to be done in the current week.

OUTFLOWS:

PM_hours_completing = Maint_hrs_available_for_PMs*Availability_of_equip_to_do_PMs * Productivity_of_maint_employee {Hours/week}
DOCUMENT: Calculates the number of preventive maintenance hours that are completed within a week. The number of hours completed is determined by the available maintenance resources that are assigned for working on preventive maintenance (Available_PM_hours) including factors such as the availability of equipment to perform the preventive maintenance, and the productivity of the maintenance workers.

○ Availability_of_equip_to_do_PMs = 0.9 {Non-dimensional}
DOCUMENT: Represents the percentage of time that the equipment is available as scheduled for preventive maintenance. A one indicates that 100% of the time the equipment is available as scheduled. A 0.5 value would represent 50% equipment availability. The percentage of time that the equipment is made available for performing preventive maintenance can significantly affect the completion rate of preventive maintenance work orders. In many situations, production is unable to free up the equipment for preventive maintenance due to being behind schedule or reduced production equipment capacity as a result of earlier machine breakdowns. Hence, not allowing the equipment to be available when scheduled would mean that Equip_availability would have a value of less than 1.

○ Maint_hrs_available_for_PMs = Total_maint_hours_available_for_PMs_&_MRs*0.5 {Hours/week}
DOCUMENT: Determines the number of maintenance resources hours (which is a percentage of the total available maintenance resources) that are assigned for working on preventive maintenance work orders. Typical percentages for splitting up the total available maintenance resources between maintenance requests and preventive maintenance is 50% for each. These values are based on the author's "best estimate" from his experiences.

Percentage_of_PM_hours_completed = (PM_hours_completing/PM_hours_arriving)*100 {Percent}
DOCUMENT: Indicates the current percentage of completed preventive maintenance hours. A 100% would indicate that all preventive maintenance hours that are generated is being completed, resulting in no PM hours backlog. However, 80% completion would indicate that there is a 20% PM backlog. The percentage of PM hours completed during the week represents the efficiency of the preventive maintenance system. A highly efficient preventive maintenance system can have many positive impacts. First, a very efficient preventive maintenance system can significantly increase the lifespan of the production equipment. It prevents the equipment from deteriorating ensuring that the equipment is functioning as per design specifications. Secondly, an efficient preventive maintenance system can reduce the number of "Operations maintenance requests" that are genearated in the normal day to day operating of the facility. In addition, there is less frequent unexpected machine breakdowns reducing the number of "Emergency maintenance requests".

PM_Schedule = (NUMBER_OF_NEW_EQUIPMENT*1) + (NUMBER_OF_MATURE_EQUIPMENT*3) {Hours/Week}
DOCUMENT: Represents the number of preventive maintenance hours that are scheduled to be done each week. The number of preventive maintenance hours are based on the number of new and mature pieces of equipment that are currently in operation as production equipment. Typically, new equipment would require on the average one hour of preventive maintenance per piece of equipment per week, and mature equipment would require approximately three hours per piece of equipment per week. These values are based on the author's "best estimate" from his experiences.

Impact_of_PMs_on_emergency_MR = GRAPH(Percentage_of_PM_hours_completed {Hours})
(0.00, 1.50), (10.0, 1.40), (20.0, 1.30), (30.0, 1.20), (40.0, 1.10), (50.0, 1.00), (60.0, 0.975), (70.0, 0.95), (80.0, 0.9), (90.0, 0.85), (100, 0.8)
DOCUMENT: A multiplier representing the relationship between the percentage of preventive maintenance hours completed during that week and the impact on the weekly number of "Emergency maintenance requests" generated from unscheduled production equipment breakdowns. The higher the percent of preventive maintenance hours completed, the stronger the influence in reducing "Emergency maintenance requests". Values for the above relationship are based on the author's "best estimate" from his experiences.

Impact_of_PMs_on_equipment_condition = GRAPH(Percentage_of_PM_hours_completed {Percent})
(0.00, 50.0), (10.0, 52.0), (20.0, 54.0), (30.0, 56.0), (40.0, 60.0), (50.0, 75.0), (60.0, 80.0), (70.0, 85.0), (80.0, 90.0), (90.0, 92.5), (100, 95.0)
DOCUMENT: A multiplier representing the relationship between the percentage of preventive maintenance hours completed and its influence on preventing deterioration of the equipment. For example, completing all of the weekly preventive maintenance hours will ensure that the equipment will operate as closely as possible to the equipment original design specifications. Completing 50% of the preventive maintenance hours will result in a 25% reduction in the operating condition of the equipment. Values for the above relationship is based on the author's "best estimate" from his experiences.

Impact_of_PMs_on_operations_MR = GRAPH(Percentage_of_PM_hours_completed {Hours})
(0.00, 2.00), (10.0, 1.90), (20.0, 1.80), (30.0, 1.70), (40.0, 1.60), (50.0, 1.50), (60.0, 1.30), (70.0, 1.20), (80.0, 1.10), (90.0, 1.00), (100, 0.9)
DOCUMENT: A multiplier representing the relationship between the percentage of the preventive maintenance hours completed and the impact to the weekly "Operations maintenance requests" that are generated through normal operating of the facility. A high percentage of completed preventive maintenance hours can reduce the number of "Operations maintenance requests" that would normally be generated. The values for the above relationship is based on the author's "best estimate" from his experiences.

5.3 MAINTENANCE REQUEST SECTOR

The maintenance requests sector represents the area within maintenance that deals with maintenance requests that are generated through the normal operating of the facility. Maintenance requests may be in the form of Operations, Emergency and/or Scheduled maintenance requests. Operations maintenance requests consist of minor maintenance requests that are generated from either deficiencies of production equipment or from the daily operating of the facility. Emergency maintenance requests are generated from unexpected production equipment breakdowns. Scheduled maintenance requests include those Operations and Emergency maintenance requests that could not be completed at the time of initiation and had to be rescheduled. Within this sector, Operations, Emergency and Scheduled maintenance requests are represented in hours generated per week. A certain amount of these maintenance requests are completed based upon factors such as maintenance resource hours that are available to do the maintenance requests activities, parts availability and the level of productivity of the maintenance worker. Maintenance requests that are not completed are measured and recorded as maintenance requests backlog. There is also the situation where the focus on completing the Operations maintenance work requests may become a lesser priority if the Scheduled maintenance backlog increases significantly. In this situation, there is an increase in available hours for working on Scheduled maintenance, and a decrease in the hours available for the Operations maintenance requests. Figure 16 below illustrates the systems flow diagram of the maintenance request sector. The equations representing the system flow diagram are listed in section 5.3.1.

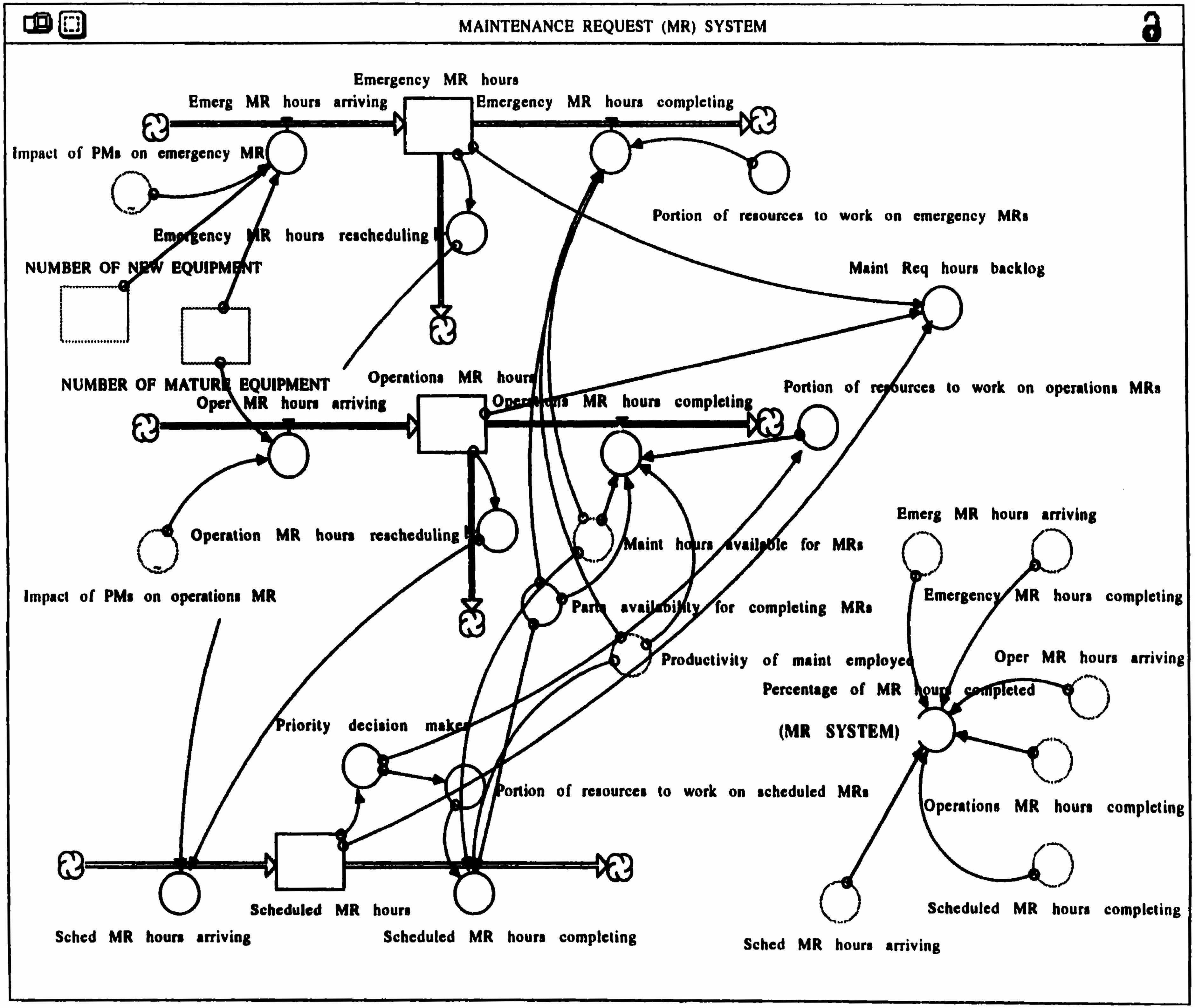

Figure 16. Systems flow diagram of maintenance request sector

5.3.1 Equations for the Maintenance Requests Sector

☐ Emergency_MR_hours(t) = Emergency_MR_hours(t - dt) + (Emerg_MR_hours_arriving - Emergency_MR_hours_completing - Emergency_MR_hours_rescheduling) * dt
INIT Emergency_MR_hours = 50 {Hours}

DOCUMENT: Represents the current backlog of emergency maintenance requests. (i.e. maintenance requests that were generated from unscheduled production equipment breakdowns and to date, are still outstanding).

INFLOWS:

Emerg_MR_hours_arriving = ((NUMBER_OF_MATURE_EQUIPMENT*1)+(NUMBER_OF_NEW_EQUIPMENT*0.2)) * Impact_of_PMs_on_emergency_MR {Hours/Week}
DOCUMENT: Represents the average number of hours from unexpected production equipment breakdowns that occur during a week. The number of emergency hours generated are based upon the number of pieces of equipment (both new and mature) that are currently in operation. Typically, the average number of hours generated from unscheduled breakdowns of new equipment is about 10 to 15 minutes per piece of equipment per week (0.2 hours), and for mature equipment about 1 hour per piece of equipment per week. The_impact_of_PMs_on_breakdowns_MR represents either an increase or decrease in hours generated from unexpected machine failures based upon percentages of Preventive Maintenance that are completed weekly. For example, consistently having a 100% completion of Preventive Maintenance each week can decrease the hours generated from unexpected machine failures by about 25%.

OUTFLOWS:

Emergency_MR_hours_completing = Maint_hours_available_for_MRs * Portion_of_resources_to_work_on_emergency_MRs * Parts_availability_for_completing_MRs * Productivity_of_maint_employee {Hours/week}
DOCUMENT: Calculates the amount of hours that are being completed weekly for repairing unexpected production equipment failures. The number of hours completed is determined by the available maintenance resources that are assigned to repairing unscheduled equip. breakdowns (Maint_hours_available_for_MRs * Portion_of_resources_to_work_on_emergency_MRs) including factors such as the productivity of the maintenance workers and parts availability. The spare parts on hand (parts_availability_for_completing_MRs) can significantly impact the number of hours completed for repairing unexpected machine failures.

Emergency_MR_hours_rescheduling = Emergency_MR_hours*0.1 {Hours/week}
DOCUMENT: The amount of "Emergency maintenance requests" that have to be rescheduled as "Scheduled maintenance requests" due to the lack of materials to properly complete the repairs. Approximately ten percent of "Emergency maintenance requests" have to be rescheduled as "Scheduled maintenance requests" to be completed some time in the future. The ten percent value is based on the author's "best estimate" from his experiences.

☐ Operations_MR_hours(t) = Operations_MR_hours(t - dt) + (Oper_MR_hours_arriving - Operations_MR_hours_completing - Operation_MR_hours_rescheduling) * dt
INIT Operations_MR_hours = 100 {Hours}

DOCUMENT: Represents the current backlog of maintenance work requests (equipment or facility related) that have been generated through normal operating of the facility.

INFLOWS:

Oper_MR_hours_arriving = ((NUMBER_OF_MATURE_EQUIPMENT*1.0) + 25) * Impact_of_PMs_on_operations_MR {Hours/week}
DOCUMENT: Represents minor maintenance work requests that are being generated weekly from the daily operation of the facility, inaddition to work requests that are generated from mature equipment deficiencies. The average weekly minor maintenance work requests over the past ten years have been approximately 25 hours. Typical maintenance requests due to deficiencies of mature equipment average about 1 hour per piece of equipment per week. The_impact_of_PMs_on_operations_MR represents the impact from either completing or not completing the preventive maintenance as scheduled on generating general minor maintenance work requests.

OUTFLOWS:

Operations_MR_hours_completing = Maint_hours_available_for_MRs * Portion_of_resources_to_work_on_operations_MRs * Productivity_of_maint_employee * Parts_availability_for_completing_MRs {Hours/week}
DOCUMENT: Calculates the number of "Operations maintenance requests" hours that are completed weekly. The number of hours completed is determined by the available maintenance resource hours that are assigned for working on "Operations maintenance requests" (Maint_hours_available _for_MRs * Portion_of_resources_ to_work_on_ operations_MRs) including factors such as the productivity of the maintenance worker and parts availability. For example, some maintenance tasks may not be completed due to the lack of the appropriate materials being available at the time required.

Operation_MR_hours_rescheduling = Operations_MR_hours*0.25 {Hours/week}
DOCUMENT: Represents the number of maintenance work requests hours that are generated daily from normal facility operations which have to be rescheduled as "Scheduled maintenance requests" hours to be completed some time in the future due to lack of materials and/or maintenance workers unable to access the equipment or area in which the repairs are required. Typically twenty five percent of the maintenance request hours that are generated are usually rescheduled to be done some time in the future. The value of twenty five percent is based on the author's "best estimate" from his experiences.

☐ Scheduled_MR_hours(t) = Scheduled_MR_hours(t - dt) + (Sched_MR_hours_arriving - Scheduled_MR_hours_completing) * dt
INIT Scheduled_MR_hours = 50 {Hours}

DOCUMENT: Represents the current backlog of "Scheduled maintenance work requests" that have been generated as a result of those "Operation and Emergency maintenance requests" that could not be completed at the time of initiation due to lack of materials and/or maintenance workers unable to access the equipment or area that required the repairs.

INFLOWS:

Sched_MR_hours_arriving = Emergency_MR_hours_rescheduling +Operation_MR_hours_rescheduling {Hours/week}
DOCUMENT: Represents maintenance work requests scheduled to be done some time in the future consisting of those maintenance work requests that were initially either Operations_ MR_hours_rescheduling or Emergency_MR_hours_ rescheduling, and have been rescheduled due to lack of materials, or maintenance workers unable to access the equipment or area in which the repairs are required, or a low priority maintenance request that did not need immediate attention.

OUTFLOWS:

Scheduled_MR_hours_completing = Maint_hours_available_for_MRs * Portion_of_resources_to_work_on_scheduled_MRs * Parts_availability_for_completing_MRs* Productivity_of_maint_employee {Hours/week}
DOCUMENT: Calculates the number of Scheduled maintenance work requests in hours that are completed during the week. The number of hours completed is determined by the available maintenance resources that are assigned for working on Scheduled maintenance work requests (Maint_hours_available_for_MRs * Portion_of_resources _to_work_on_scheduled_MRs) including factors such as the productivity of the maintenance worker and the availability of material or parts.

○ Maint_Req_hours_backlog = Emergency_MR_hours + Operations_MR_hours +Scheduled_MR_hours {Hours/week}
DOCUMENT: Represents a snapshot at any time of the current overall maintenance requests backlog in hours excluding preventive maintenance hours. All outstanding maintenance work requests that were generated as a result of Operations, Emergencies, and Scheduled work requests.

○ Parts_availability_for_completing_MRs = 0.9 {Non-dimensional}
DOCUMENT: Factor representing material/parts availability which may be required to complete maintenance requests (Operations, Emergencies or Scheduled). Parts or appropriate material that are not available when required for equipment repairs can significantly affect the completion rates for maintenance work requests impacting the overall maintenance requests backlog. The value 0.9 represents the fact that ninety percent of the time all material or parts are available. This value is based on the author's "best estimate" from his experiences.

○ Percentage_of_MR_hours_completed = ((Emergency_MR_hours_completing/Emerg_MR_hours_arriving)+ (Operations_MR_hours_completing/Oper_MR_hours_arriving)+ (Scheduled_MR_hours_completing/Sched_MR_hours_arriving)) /3*100 {Percent}
DOCUMENT: Indicates the current percentage of completed maintenance request hours. A 100% would indicate that all maintenance request hours that are generated is being completed, resulting in no MR hours backlog. However, 80% completion would indicate that there is a 20% PM backlog. The percentage of MR hours completed during the week represents the efficiency of the maintenance request system.

○ Portion_of_resources_to_work_on_emergency_MRs = 0.4 {Non-dimensional}
DOCUMENT: Represents the number of maintenance resources hours that are typically assigned to work on unscheduled production equipment breakdowns. 0.4 represents 40% of the available hours that have been designated for working on maintenance requests (which is usually a percentage of the overall maintenance resource hours that are available).

○ Portion_of_resources_to_work_on_operations_MRs = IF(Priority_decision_maker=1)THEN(0.2)ELSE(0.4) {Non-dimensional}
DOCUMENT: This variable establishes the percentage of the hours (a percentage of the available maintenance request hours) for working on the "Operations maintenance requests" hours which is typically 40%. However, if the backlog of the Scheduled maintenance hours become higher than 160 hours, then the value of 40% switches to 20%. These values are based on the author's "best estimate" from his experiences.

○ Portion_of_resources_to_work_on_scheduled_MRs = IF(Priority_decision_maker=1) THEN (0.4) ELSE (0.2) {Non-dimensional}
DOCUMENT: Represents the percentage of hours (a percentage of the available maintenance requests hours) for working on "Scheduled maintenance requests" which is typically 20%. However, if the Scheduled backlog hours rise above 160 hours, then the amount of effort is increased from 20% to 40%. Once the backlog falls below 160 hours, the effort reduces back to 20%.

○ Priority_decision_maker = IF(Scheduled_MR_hours) > 160 THEN (1) ELSE (0) {Non-dimensional}
DOCUMENT: Priority_decision_maker is used as a priority mechanism for changing the emphasis on whether to work on "Scheduled maintenance work requests" or "Operations maintenance work requests". Based on the author's "best estimate" from his experiences, the following is a typical breakdown for assigning the maintenance request hours (Available _MR_hours which is usually a percentage of the Total_available_hours). Approximately 40% of the maintenance resource hours available for Maintenance Requests is assigned to work on "Operations maintenance work requests", 20% of the available hours for Maintenance Requests assigned for working on "Scheduled maintenance work requests", and the remaining 40% is usually spent on repairing unexpected production equipment breakdowns. If the backlog of current "Scheduled maintenance requests" rises higher than 160 hours, then there is a change in priorities. The initial 20% of the available maintenance hours changes to 40%, and there is a reduction from 40% to 20% of the available maintenance hours for "Operations maintenance work requests". Once the "Scheduled maintenance" backlog hours fall below 160 hours, there is a switch back to the original focus of 40% for "Operations" and 20% for "Scheduled maintenance".

5.4 PRODUCTION EQUIPMENT CAPACITY SECTOR

The production equipment capacity sector represents the production equipment capacity which is directly related to the number of pieces of equipment (both new and mature) that are currently in operation. New equipment is defined as equipment that has been in operation for less than two years. Beyond two years of operation, the new equipment becomes mature equipment which can be operated for another eight years (assuming overhauls and retrofitting to the equipment may occur) before becoming obsolete and scrapped. Therefore, production equipment has a life of ten years which may increase or decrease depending upon the ongoing day to day operating conditions of the equipment with respect to its original design specifications. The equipment's operating condition may significantly be affected by both the efficiency of the preventive maintenance system (i.e. percentages of preventive maintenance completed on a weekly basis) and the level of operator involvement in performing simple maintenance activities. The ongoing operating condition of the equipment can either improve or deteriorate depending upon the direction of change in the equipment's operating condition which directly impacts both the aging rate of new equipment and the scrapping rate of mature equipment. Figure 17 below illustrates the system flow diagram of the equipment condition sector. The equations representing the system flow diagram are listed in section 5.4.1.

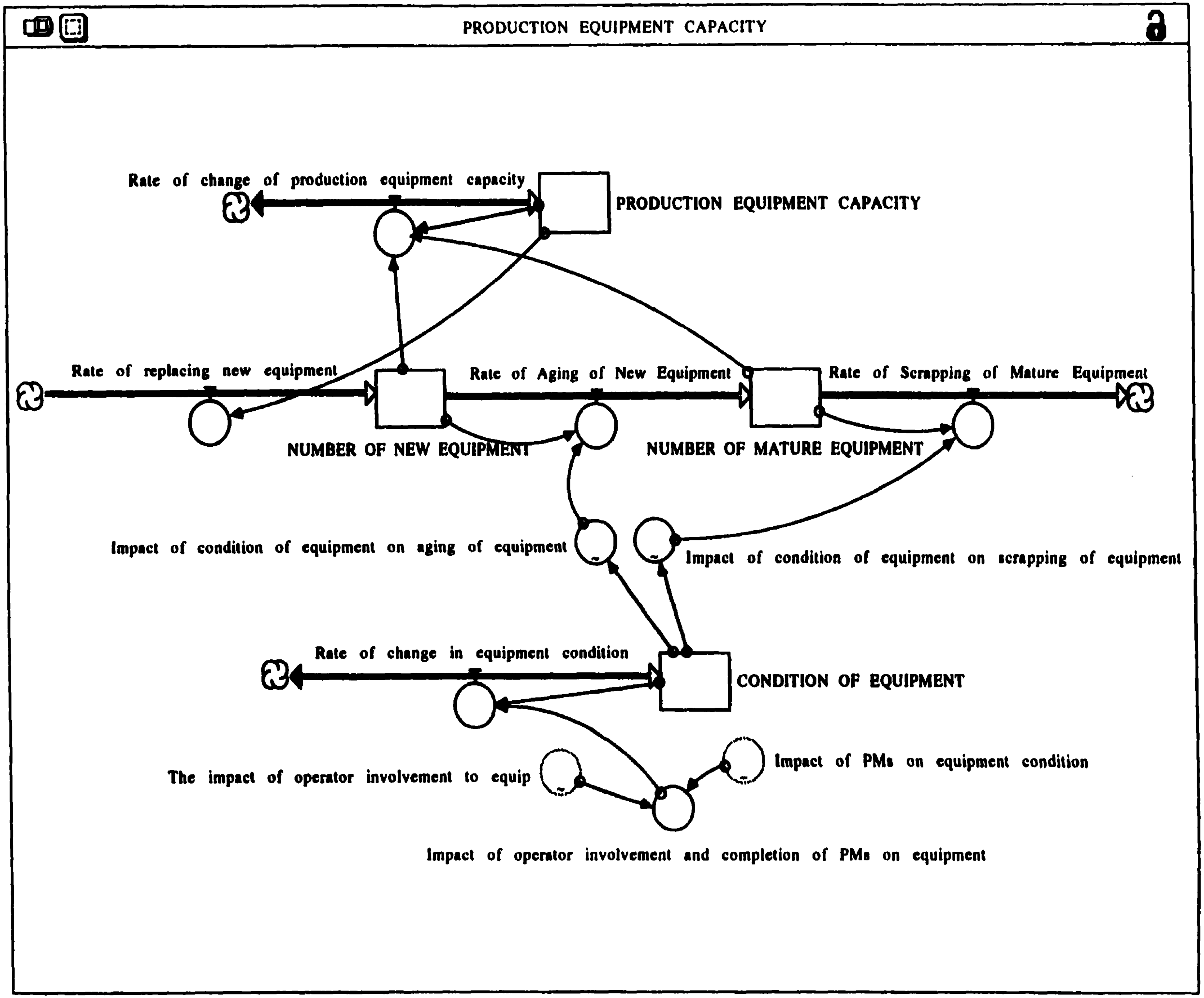

Figure 17. Systems flow diagram of equipment condition sector

5.4.1 Equations for the Production Equipment Capacity Sector

☐ CONDITION_OF_EQUIPMENT(t) = CONDITION_OF_EQUIPMENT(t - dt) + (Rate_of_change_in_equipment_condition) * dt
INIT CONDITION_OF_EQUIPMENT = 80 {Percent}

DOCUMENT: Indicates the average condition of all of the production equipment currently in operation on a percentage basis. One hundred percent would indicate that all of the equipment is in perfect working condition (i.e. operating to original design specifications - equipment operating speeds and accuracy). The author assumes that the equipment is functioning at approximately 80% of its original design specifications at the beginning of the simulation.

INFLOWS:

Rate_of_change_in_equipment_condition = ((Impact_of_operator_involvement_and_completion_of_PMs_on_equipment-CONDITION_OF_EQUIPMENT)/100) {Percent/week}

DOCUMENT: Represents any changes to the condition of the equipment due to an increase or decrease in operator involvement and/or an increase or decrease in the completion of the preventive maintenance hours.

The level of operator involvement is based upon a range of 1 to 5. One representing little or no involvement, and five representing high involvement from the operator. Operator involvement of 3 or less would represent a deterioriation of the equipment's condition due to poor effort from the operator to effectively operate the equipment. For example, operating the equipment outside of its effective range or operating the equipment with low lubrication levels. Operator involvement of 3.33 or greater would represent ongoing improvements to the equipment's condition due to the diligence of the operator in effectively operating the equipment. For example, performing minor maintenance task.

Completion of preventive maintenance hours represent the preventive maintenance hours completed during the week versus the number of hours scheduled for that week and is based on a range between 0 and 100%. Completing 50% of the preventive maintenance hours will result in a 25% reduction in the operating condition of the equipment. For example, operating speed of the equipment may reduce and the accuracy of the equipment would deterioriate.

Changes to the equipment's condition could either be positive or negative.

☐ NUMBER_OF_MATURE_EQUIPMENT(t) = NUMBER_OF_MATURE_EQUIPMENT(t - dt) + (Rate_of_Aging_of_New_Equipment - Rate_of_Scrapping_of_Mature_Equipment) * dt
INIT NUMBER_OF_MATURE_EQUIPMENT = 80 {Pieces of Eqipment}

DOCUMENT: Represents the number of pieces of mature production equipment in operation at the beginning of the simulation. Mature production equipment in this simulation is defined as equipment that is older than two years and less than ten years old. Mature equipment is usually in operation for eight years before being scrapped. New equipment becomes mature equipment after being in operation for more than two years.

○ Impact_of_operator_involvement_and_completion_of_PMs_on_equipment = ((Impact_of_PMs_on_equipment_condition+The_impact_of_operator_involvement_to_equip)/2) {Percent}
DOCUMENT: Represents the combined impact of both the efficiency of the preventive maintenance system (i.e. the percentage of preventive maintenance tasks completed), and the amount of operator involvement in performing simple maintenance task (e.g. cleaning the equipment, making minor adjustments, checking the fluid levels, etc.).

INFLOWS:

Rate_of_Aging_of_New_Equipment = NUMBER_OF_NEW_EQUIPMENT * (0.5 + Impact_of_condition_of_equipment_on_aging_of_equipment) {Pieces of equipment/Week}
DOCUMENT: Represents the aging of new pieces of equipment. In two years, new pieces of equipment become mature equipment. The aging of new equipment can either increase or decrease depending upon the operating condition of the equipment which is directly affected by the completion rate of preventive maintenance and/or the degree of involvement of the equipment operators. Completing the required preventive maintenance and a high level of involvement will improve the operating condition of the equipment which can decrease the aging of new equipment. Therefore, new equipment can still be catagorize as new even after the two year period. Of course the opposite can also occur, that is if the operating condition of the equipment deterioriates; the aging of new equipment can increase and become mature equipment before the two year period is up. All values for the aging of the new equipment and the impact that the operating condition of the equipment can have on aging are based on the author's "best estimate" from his experiences.

OUTFLOWS:

Rate_of_Scrapping_of_Mature_Equipment = NUMBER_OF_MATURE_EQUIPMENT*(0.125 + Impact_of_condition_of_equipment_on_scrapping_of_equipment) {Pieces of equipment/week}
DOCUMENT: Represents the aging of mature pieces of equipment. In eight years, mature pieces of equipment become obsolete and are scrapped. The rate of scrapping of mature equipment can either increase or decrease depending upon the operating condition of the equipment which is directly affected by the completion rate of preventive maintenance and/or the degree of involvement of the equipment operators. Completing the required preventive maintenance and a high level of involvement will improve the operating condition of the equipment which can decrease the rate of scrapping of mature equipment. Therefore, mature equipment can still be catagorize as mature even after the eight year period. Of course the opposite can also occur, that is if the operating condition of the equipment deterioriates; the rate of scrapping of mature equipment can increase and become obsolete and scrapped before the eight year period is up. All values for the aging of the mature equipment and the impact that the operating condition of the equipment can have on aging are based on the author's "best estimate" from his experiences.

NUMBER_OF_NEW_EQUIPMENT(t) = NUMBER_OF_NEW_EQUIPMENT(t - dt) + (Rate_of_replacing_new_equipment - Rate_of_Aging_of_New_Equipment) * dt
INIT NUMBER_OF_NEW_EQUIPMENT = 20 {Pieces Of Equipment}

DOCUMENT: Represents the number of pieces of new production equipment in operation at the beginning of the simulation. New production equipment in this simulation is defined as equipment that is less than two years old. New equipment becomes mature equipment after being in operation for more than two years. New equipment can still be catagorize as new even after the two year period if the rate of aging of new equipment decreases which is directly affected by the operating condition of the equipment.

INFLOWS:

Rate_of_replacing_new_equipment = IF(PRODUCTION_EQUIPMENT_CAPACITY < 100) THEN(10) ELSE(0) {Pieces of equipment/week}
DOCUMENT: Represents the number of pieces of new equipment to be replaced based on the current number of pieces of equipment that are in operation. The author assumes for the purposes of this simulation that if the current number of pieces of equipment falls below 100, then new equipment is replaced in lot sizes of ten.

OUTFLOWS:

Rate_of_Aging_of_New_Equipment = NUMBER_OF_NEW_EQUIPMENT * (0.5 + Impact_of_condition_of_equipment_on_aging_of_equipment) {Pieces of equipment/Week}
DOCUMENT: Represents the aging of new pieces of equipment. In two years, new pieces of equipment become mature equipment. The aging of new equipment can either increase or decrease depending upon the operating condition of the equipment which is directly affected by the completion rate of preventive maintenance and/or the degree of involvement of the equipment operators. Completing the required preventive maintenance and a high level of involvement will improve the operating condition of the equipment which can decrease the aging of new equipment. Therefore, new equipment can still be catagorize as new even after the two year period. Of course the opposite can also occur, that is if the operating condition of the equipment deterioriates; the aging of new equipment can increase and become mature equipment before the two year period is up. All values for the aging of the new equipment and the impact that the operating condition of the equipment can have on aging are based on the author's "best estimate" from his experiences.

PRODUCTION_EQUIPMENT_CAPACITY(t) = PRODUCTION_EQUIPMENT_CAPACITY(t - dt) + (Rate_of_change_of_production_equipment_capacity) * dt
INIT PRODUCTION_EQUIPMENT_CAPACITY = 100 {Pieces of equipment}

DOCUMENT: Represents the number of pieces of equipment in production. The author assumes for the purposes of the simulation that there are 100 pieces of production equipment at the beginning of the simulation (20 new pieces of equipment and 80 mature pieces of equipment).

INFLOWS:

Rate_of_change_of_production_equipment_capacity = ((NUMBER_OF_NEW_EQUIPMENT+NUMBER_OF_MATURE_EQUIPMENT) - PRODUCTION_EQUIPMENT_CAPACITY)/100 {Pieces of equipment/Week}
DOCUMENT: Represents any changes to production equipment capacity which is based on the number of both new and mature equipment that are currently in operation. Changes in production equipment capacity could either be positive or negative.

Impact_of_condition_of_equipment_on_aging_of_equipment = GRAPH(CONDITION_OF_EQUIPMENT {Non-dimensional})
(75.0, 0.15), (77.5, 0.125), (80.0, 0.1), (82.5, 0.075), (85.0, 0.05), (87.5, 0.025), (90.0, 0.00), (92.5, -0.025), (95.0, -0.05), (97.5, -0.1), (100, -0.2)
DOCUMENT: A multiplier representing the relationship between the operating condition of the equipment and impact on the rate of aging of new equipment. If the equipment is maintained at 90% of its original condition, then the aging rate is unaffected. That is, the new equipment will become mature equipment in two years. However, if the equipment is allowed to operate below 90% of its original condition, then the aging rate will increase resulting in new equipment becoming mature equipment in less than the typical two years. On the other hand, if the equipment is maintained at above 90% of its original condition, then the aging rate decreases resulting in the new equipment staying in the new category for more than two years. All values for the above relationship are based on the author's "best estimate" from his experiences.

Impact_of_condition_of_equipment_on_scrapping_of_equipment = GRAPH(CONDITION_OF_EQUIPMENT {Non-dimensional})
(75.0, 0.125), (77.5, 0.1), (80.0, 0.00), (82.5, -0.01), (85.0, -0.02), (87.5, -0.03), (90.0, -0.04), (92.5, -0.05), (95.0, -0.075), (97.5, -0.1), (100, -0.125)
DOCUMENT: A multiplier representing the relationship between the operating condition of the equipment and impact on the scrapping rate of mature equipment. If the equipment is maintained at 80% of its original condition, then the scrapping rate is unaffected. That is, the mature equipment will become obsolete and scrapped in eight years. However, if the equipment is allowed to operate below 80% of its original condition, then the scrapping rate will increase resulting in mature equipment becoming obsolete and scrapped in less than the typical eight years. On the other hand, if the equipment is maintained at above 80% of its original condition, then the scrapping rate decreases resulting in the mature equipment staying in the mature category for more than eight years. All values for the above relationship are based on the author's "best estimate" from his experiences.

5.5 OPERATOR INVOLVEMENT AND MAINTENANCE MOTIVATION/ SKILL LEVEL SECTOR

The operator involvement and maintenance motivation/skill level sector represents the effects of different levels of operator involvement on both the condition of the equipment as well as motivation/skill levels of the maintenance worker.

The degree of operator's involvement with respect to performing minor maintenance tasks or adjustments to the equipment is very rarely consistent (i.e. it is neither steadily increasing or decreasing from week to week). The variability of the operator's involvement is represented by the statistical function NORMAL with a standard deviation.

Within this sector, there are a number assumptions regarding the relationships among operator's involvement, maintenance motivation and skill level, effectiveness of equipment history, overtime and the productivity of the maintenance worker. The assumptions are as follows. As the operator's involvement increases, the level of motivation of the maintenance workers decreases negatively impacting both the productivity of the maintenance worker and their desire to document their activities. The lack of documentation reduces the completeness of equipment history which inturn impedes the maintenance worker's ability to troubleshoot problems in the future. In addition, it is also assumed that with the increased level of involvement of the operators, the maintenance workers are able to spend their time resolving the more difficult maintenance problems, since the operators would now perform the minor maintenance tasks. Having the opportunity to work on the more troublesome maintenance problems, the maintenance workers are able to continuously improve their diagnostic skills which further enhances their overall skill level. Further enhancement of the maintenance workers' skills will improve both their levels of motivation and productivity.

Also simulated within this sector is maintenance training. The collective skill level of the maintenance workers are continuously monitored; and if the skill level drops below a certain level, training is provided. The effectiveness of the training is also monitored, since the training does not guarantee that the maintenance worker's skill level or productivity will improve. A certain amount of training hours must be provided, inaddition to being effective inorder for the maintenance workers' skill level to increase.

As mentioned before, these relationships are drawn from the author's experiences which he has acquired over the last ten years during which he played a significant role in the data gathering due to his responsibility as the manager of two large maintenance departments. Figure 18 below illustrates the system flow diagram of the operator involvement/maintenance motivation and skill levels sector. The equations representing the system flow diagram are listed in section 5.5.1.

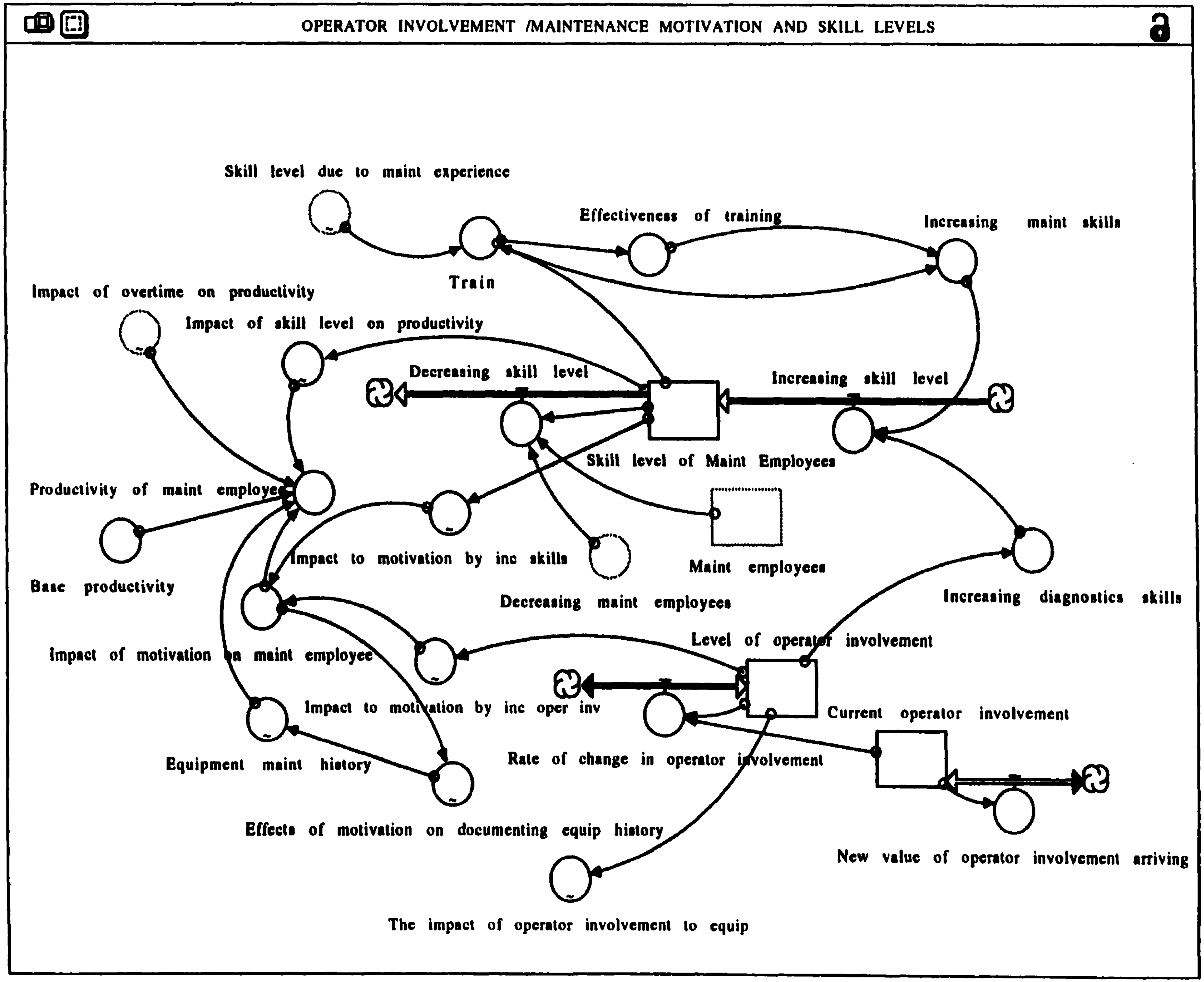

Figure 18. Systems flow diagram of operator involvement/maintenance motivation and skill level sector

5.5.1 Equations for the Operator Involvement/Maintenance Motivation and Skill Levels

Current_operator_involvement(t) = Current_operator_involvement(t - dt) + (New_value_of_operator_involvement_arriving) * dt
INIT Current_operator_involvement = 3.0 {Non-dimensional}

DOCUMENT: Changes once a week in response to the level of involvement of the production operator.

INFLOWS:

New_value_of_operator_involvement_arriving = PULSE((NORMAL(Current_operator_involvement,2,111) - Current_operator_involvement),1,4) {Non-dimensional/Week}
DOCUMENT: Generates a new value weekly indicating the level of operator's involvement for that week. One being little to no involvement and five being a high level of involvement where the operator may perform all daily and weekly preventive maintenance on the equipment including minor adjustments where ever required. The varying involvement by the operator maybe due to many reasons. Poor or good relationships with their supervisor, poor work ethics, just having a bad week, or the complete opposite where the worker demonstrates good work ethics and is very interested in expanding their knowledge base.

Level_of_operator_involvement(t) = Level_of_operator_involvement(t - dt) + (Rate_of_change_in_operator_involvement) * dt
INIT Level_of_operator_involvement = 3.0 {Non-dimensional}

DOCUMENT: Represents the current level of involvement of the production operator with respect to performing the simplier maintenance tasks on the production equipment that they operate. The level of involvement is based upon a range of 1 to 5. One representing little or no involvement, and five representing high involvement from the operator. The level of the production operator's involvement is very significant from a number of perspectives.

Due to the fact that the environment in which this model is being simulated is unionized the implications of a production operator performing maintenance activities are generally damaging. The maintenance worker percieves the operator involvement as an action of taking work away from the maintenance department; hence, reducing their opportunities for overtime. This perception demotivates the maintenance worker resulting in reduced productivity.

Another implication of the level of operator involvement is that as the operator becomes more involved, there is an increased feeling of pride and ownership which tends to make the operator operate the equipment with care which promotes the life span of the equipment and its ongoing condition.

Another positive perspective on increasing the operator's involvement is by having the operators perform the simplier maintenance tasks, maintenance resources are freed up to work on increasingly more difficult maintenance tasks which allows the maintenance workers to further develop and enhance their trouble shooting skills. In addition, maintenance workers may use the available time for additional training to increase their skill increasing the department's overall skill level. Increasing the department's skill level will reduce the length of downtime of unexpected production breakdowns and also increase the productivity of the maintenance worker which could reduce the overall maintenance backlog.

Of course, the opposite of the above may occur with a decrease in the production operator's involvement with respect to maintenance activities. Noticeably, in the areas of the condition of the equipment, and the maintenance worker's skill levels.

INFLOWS:

Rate_of_change_in_operator_involvement = (Current_operator_involvement-Level_of_operator_involvement)/Level_of_operator_involvement {Non-dimensional/Week}
DOCUMENT: Represents the change in operator's involvement with respect to performing simple maintenance tasks. The change may be positive or negative depending upon the operator.

Skill_level_of_Maint_Employees(t) = Skill_level_of_Maint_Employees(t - dt) + (Increasing_skill_level - Decreasing_skill_level) * dt
INIT Skill_level_of_Maint_Employees = 2.5 {Non-dimensional}

DOCUMENT: Represents the current average skill of the maintenance worker for the maintenance department. The value is based upon a range of 1 to 5, where one being a very low skill level and five being a very high skill level. The purpose of monitoring the department's skill level is two fold. One, the skill level heavily impacts the maintenance workers' level of productivity, and also affects how motivated the maintenance workers are. Two, the skill level is monitored to address training issues. If there is a decrease in the department's average skill level and falls below 4.5, then a signal is triggered to provide training. It is important to ensure that the department's average skill is maintained to a high level because of the direct impact that the maintenance worker's skill level has on expediting unexpected critical production equipment failures, and secondly the impact on both the level of motivation and productivity of the worker.

INFLOWS:

Increasing_skill_level = SMTH1((Increasing__maint_skills + Increasing_diagnostics_skills),13) {Non-dimensional/Week}
DOCUMENT: Sends a signal to increase the average skill level of the maintenance department by 0.5 which is based upon receiving a certain amount of training that has a certain level of effectiveness. Training is sometimes provided for the sake of satisfying some corporate or regulatory requirement without a high degree of effectiveness. For example, training may be improperly delivered or provided to the employee but not used until sometime later in the future which at that point, the employee may have forgotten most of the training. The SMTH1 function indicates that the increase in skill level is not instantaneous and occurs over a period of time.

OUTFLOWS:

Decreasing_skill_level = Skill_level_of_Maint_Employees* (Decreasing_maint_employees/Maint_employees) {Non-dimensional/Week}
DOCUMENT: Causes a decrease in the average skill level of the maintenance department which usually occurs from an experienced employee leaving the organization as a result of retirement, termination or a better opportunity with another organization.

○ Base_productivity = 1 {Non-dimensional}
DOCUMENT: The value one represents 100% productivity.

○ Effectiveness_of_training = IF(Train>0) THEN (RANDOM(0.5,1)) ELSE(0) {Non-dimensional}
DOCUMENT: Establishes the effectiveness of training which may vary from 50% to 100%. Even though training maybe provided, there is no guarantee that the training will be 100% effective. The effectiveness of training maybe reduced if not delivered properly or if the timeliness of the training was inappropriate. For example, training maybe provided earlier than when actually required, hence becoming ineffective.

○ Impact_of_motivation_on_maint_employee =
(Impact_to_motivation_by_inc_skills+Impact_to_motivation_by_inc_oper_inv)/2 {Non-dimensional}
DOCUMENT: Combines the effects of both increasing the maintenance worker's skill level and the level of involvement of the production operator in performing maintenance activities on the impact to the motivation of the maintenance worker.

○ Increasing_diagnostics_skills = IF(Level_of_operator_involvement > 3.5) THEN(0.01) ELSE(0)
{Non-dimensional}
DOCUMENT: This converter represents an opportunity for the maintenance worker to work on increasingly difficult maintenance tasks as a result of an increase in the production operator's involvement (represented by operator involvement that is greater than 3.5) in performing the simplier maintenance tasks on the equipment that they operate . Each opportunity for the maintenance worker will further enhance their diagnostic skills represented by the value of 0.01.

○ Increasing__maint_skills = IF(Train > 240 AND (Effectiveness_of_training > 0.75))
THEN (0.5) ELSE(0) {Non-dimensional}
DOCUMENT: This converter determines if the appropriate amount of training has been provided and at a certain effectiveness rate. If training has exceeded 240 hours at higher than 75% effectiveness, then the average skill level of the department is increased by 0.5, keeping in mind that a 1 is a low skill level and a 5 indicates highly skilled.

○ Productivity_of_maint_employee = ((Base_productivity*Impact_of_skill_level_on_productivity)+
(Base_productivity*Impact_of_motivation_on_maint_employee)+
(Base_productivity*Impact_of_overtime_on_productivity)+
(Base_productivity*Equipment_maint_history)) / 4 {Non-dimensional}
DOCUMENT: Determines the level of productivity of the maintenance worker as affected by skill levels, motivation, overtime, and the effectiveness of equipment history. The impact of skill levels, motivation, overtime, and the effectiveness of equipment history to the productivity of the maintenance worker are illustrated in this model through relationships which is the author's best estimation based on the data and experiences gathered and gained from managing maintenance departments over the last ten years.

○ Train = IF(Skill_level_due_to_maint_experience < 2.5 AND Skill_level_of_Maint_Employees < 4.5)
THEN(RANDOM(160,320)) ELSE(0) {Hours}
DOCUMENT: Establishes the need to train based on specific guidelines. That is, if the skill level due to cumulative experience is less than 2.5 (which represents 200 years of accumulative experience) and the overall department average skill level is less than 4.5, then there is a need to train. The amount of training hours that is provided is between 160 to 320 hours which is the equivalent of one to two eight hour days for each maintenance worker. One point to keep in mind that inorder to increase the skill level, the amount of training has to be greater than 240 hours at about 75% effectiveness.

⊘ Effects_of_motivation_on_documenting_equip_history = GRAPH(Impact_of_motivation_on_maint_employee {Percent})
(0.00, 7.50), (0.1, 10.0), (0.2, 15.0), (0.3, 35.0), (0.4, 40.0), (0.5, 42.5), (0.6, 45.0), (0.7, 47.5), (0.8, 50.0), (0.9, 75.0), (1, 90.0)
DOCUMENT: A multiplier representing the relationship between the degree of motivation of the maintenance worker and the amount of documentation that the worker completes. One hundred percent documentation about unexpected equipment failures is fundamental to an effective maintenance department. Documentation includes the time of failure, troubleshooting steps, how the repairs were done, spare parts that may have been used in the repairs and the length of downtime. A high degree of documentation can potentially reduce the length of downtime in the future because the technicians may not have to start from ground zero. The problem may have previously occured; and since there is complete documentation on how to do the repairs, downtime is minimized. Values for the above relationship are based on the author's "best estimate" from his experiences.

⊘ Equipment_maint_history = GRAPH(Effects_of_motivation_on_documenting_equip_history {Non-dimensional})
(0.00, 0.00), (10.0, 0.05), (20.0, 0.125), (30.0, 0.25), (40.0, 0.55), (50.0, 0.6), (60.0, 0.625), (70.0, 0.65), (80.0, 0.675), (90.0, 0.7), (100, 0.95)
DOCUMENT: A multiplier representing the relationship between the amount of documentation that the maintenance worker completes and the effectiveness of equipment history. The effectiveness of the equipment history is one of the four factors identified in this model that impacts the productivity of the maintenance worker. Therefore, any reduction in the effectiveness of the equipment history can reduce the productivity of the maintenance worker by as much as twenty five percent. For example, 50% completion of documentation has approximately a 0.60 impact on the effectiveness of equipment history which will reduce the productivity of the maintenance worker by approximately 15% (0.60 * 0.25 = 0.15) . All values for the above relationship are based on the author's "best estimate" from his experiences.

⊘ Impact_of_skill_level_on_productivity = GRAPH(Skill_level_of_Maint_Employees {Non-dimensional})
(1.00, 0.6), (1.50, 0.7), (2.00, 0.75), (2.50, 0.85), (3.00, 0.95), (3.50, 0.975), (4.00, 1.00), (4.50, 1.05), (5.00, 1.10)
DOCUMENT: A multiplier representing the relationship between skill level and the impact to productivity. As mentioned under effectiveness of equipment history, skill level is one of the four factors identified in this model that may impact the productivity of the maintenance worker. All values for the above relationship are based on the author's "best estimate" from his experiences.

⊘ Impact_to_motivation_by_inc_oper_inv = GRAPH(Level_of_operator_involvement {Non-dimensional})
(1.00, 0.995), (1.33, 0.95), (1.67, 0.925), (2.00, 0.9), (2.33, 0.875), (2.67, 0.785), (3.00, 0.49), (3.33, 0.3), (3.67, 0.2), (4.00, 0.175), (4.33, 0.15), (4.67, 0.125), (5.00, 0.1)
DOCUMENT: A multiplier representing the relationship between the level of operator involvement and the impact to the motivation of the maintenance worker. For example, high involvement by the operator in performing simple maintenance tasks (4.67 from the graph) will significantly demotivate the maintenance worker (.125 or 12.5% out of a possible 100%) resulting in low productivity from the maintenance worker. The values for the above relationship are the author's "best estimate" from his experiences.

⊘ Impact_to_motivation_by_inc_skills = GRAPH(Skill_level_of_Maint_Employees {Non-dimensional})
(1.00, 0.5), (1.33, 0.525), (1.67, 0.537), (2.00, 0.556), (2.33, 0.575), (2.67, 0.59), (3.00, 0.65), (3.33, 0.7), (3.67, 0.8), (4.00, 0.9), (4.33, 0.95), (4.67, 0.975), (5.00, 0.99)
DOCUMENT: A multiplier representing the relationship between the skill level of the maintenance worker and the impact to the motivation of the maintenance worker. For example, highly skilled maintenance worker (4.67 from the graph) will be a highly motivated worker (.975 or 97.5% out of a possible 100%) resulting in high productivity from the maintenance worker. The values for the above relationship are the author's "best estimate" from his experiences.

⊘ The_impact_of_operator_involvement_to_equip = GRAPH(Level_of_operator_involvement {Percent})
(1.00, 50.0), (1.33, 51.5), (1.67, 52.5), (2.00, 53.5), (2.33, 54.2), (2.67, 55.0), (3.00, 68.0), (3.33, 80.0), (3.67, 83.0), (4.00, 86.0), (4.33, 88.8), (4.67, 91.5), (5.00, 95.0)
DOCUMENT: A multiplier representing the relationship between the level of operator involvement in performing maintenance activities and the impact to the ongoing condition of the equipment. These values for this relationship are the author's "best estimate" from his experiences.

5.6 MAINTENANCE RESOURCE SECTOR

This sector represents the maintenance resources of the department. The number of hours that are available to perform preventive maintenance and maintenance requests are generated within this sector. This sector monitors the cumulative years of total experience specific to maintenance, since experience can significantly impact the overall skill level of the department. The overall skill level of the department can be significantly affected if very highly experienced employees leave the department whether it be due to attrition, termination, or leaving for better opportunities elsewhere. The departmental skill level can also be affected if very highly skilled employees are hired into the department. The issues of maintaining a certain number of employees within the department, and employees either joining or leaving the organization are simulated in this sector. Overtime is also examined within this sector since it can affect both motivation and the level of productivity of the worker. The potential hours available for overtime if required is examined since there is no guarantee that employees will work the additional hours (unionized environment - overtime is voluntary). Figure 19 below illustrates the system flow diagram of the maintenance resources sector. The equations representing the system flow diagram are listed in section 5.6.1.

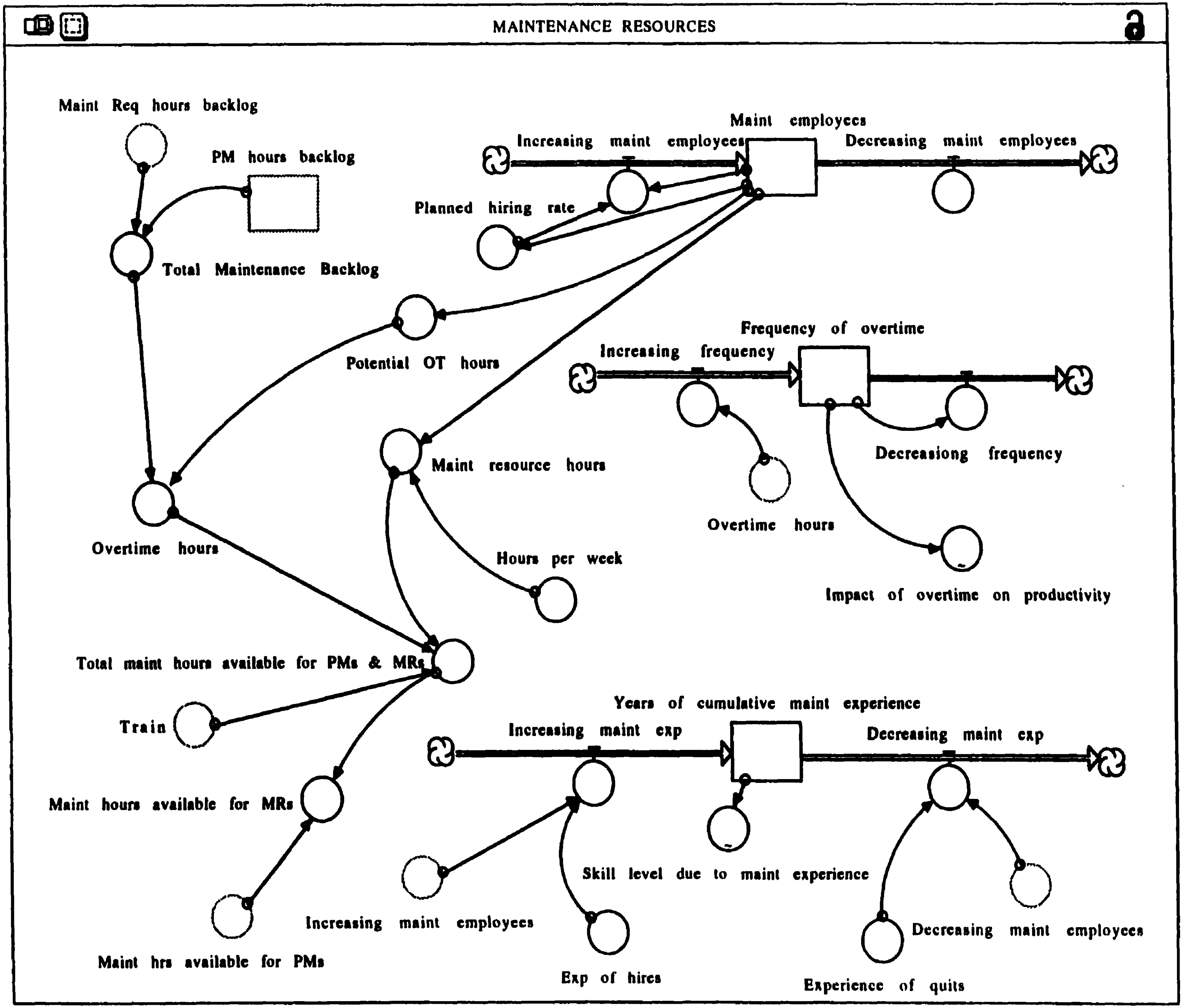

Figure 19. Systems flow diagram of maintenance resource sector

5.6.1 Equations for the Maintenance Resources Sector

☐ Frequency_of_overtime(t) = Frequency_of_overtime(t - dt) + (Increasing_frequency - Decreasiong_frequency) * dt
INIT Frequency_of_overtime = 0 {Non-dimensional}

DOCUMENT: Monitors the frequency of overtime that is worked by the maintenance department. The reason for monitoring overtime stems from the fact that too much overtime can significantly impact the effectiveness of the maintenance worker. It has been observed by the author that with each week of overtime, there seemed to be a reduction in the worker's effectiveness. Eight weeks of overtime in succession seemed to reduced the worker's effectiveness by approximately 50%. This relationship between frequency of overtime and worker's effectiveness is based on the author's "best estimate" from his experiences.

INFLOWS:

Increasing_frequency = IF(Overtime_hours > 0) THEN(1) ELSE(0) {Non-dimensional/Week}
DOCUMENT: Counts the frequency of overtime. A value of one indicates that overtime was worked during that week.

OUTFLOWS:

Decreasiong_frequency = IF(Frequency_of_overtime > 8) THEN (Frequency_of_overtime) ELSE (0) {Non-dimensional/Week}
DOCUMENT: Reset the overtime counter to zero after reaching a value of eight. That is, after measuring eight weeks of overtime worked, the monitor is reset to zero.

☐ Maint_employees(t) = Maint_employees(t - dt) + (Increasing_maint_employees - Decreasing_maint_employees) * dt
INIT Maint_employees = 20 {Maintenance workers}

DOCUMENT: Represents the number of maintenance employees in the department that are responsible for working on maintenance work requests and preventive maintenance work orders. The number of maintenance workers is used to determine the total maintenance resource hours available to work on both maintenance work requests and preventive maintenance work orders.

INFLOWS:

Increasing_maint_employees = IF(Maint_employees < 20) THEN (Planned_hiring_rate) ELSE (0) {Maintenance workers/Week}
DOCUMENT: A logic statement used to monitor the number of maintenance workers in the department. If for what ever reasons anyone or more than one worker leaves, then that required number of workers (Planned_hiring_rate) would automatically be replaced.

OUTFLOWS:

Decreasing_maint_employees = PULSE(1,20,104) {Maintenance workers/Week}
DOCUMENT: Represents the scenario of maintenance workers leaving the organization whether it is because of retirement, termination, laid off or finding a better opportunity.

☐ Years_of_cumulative_maint_experience(t) = Years_of_cumulative_maint_experience(t - dt) + (Increasing_maint_exp - Decreasing_maint_exp) * dt
INIT Years_of_cumulative_maint_experience = 200 {Years of experience}

DOCUMENT: Represents the cumulative amount of maintenance experience within the maintenance department. The cumulative experience is determined by adding up the experience of each of the maintenance employees within the department. Cumulative experience can significantly impact the average skill level within the department. For example, within the department, there maybe a couple of maintenance employees that may each have 20 years of maintenance experience specifically around the equipment within that facility. Losing those employees can significantly impact the effectiveness of the department from the perspective of being able to quickly repair unexpected machine failures minimizing production equipment downtime. Typical years of experience of maintenance workers for a large established maintenance department of a manufacturing facility is approximately ten years based on the author's experience. Hence, an approximation for a maintenance department of twenty maintenance workers would be 200 years of cumulative experience.

INFLOWS:

Increasing_maint_exp = Increasing_maint_employees*Exp_of_hires {Years of experience/Week}
DOCUMENT: Represents an increase in the cumulative experience of the maintenance department as a result of hiring an employee that may have relevant experience for the organization.

OUTFLOWS:

Decreasing_maint_exp = Decreasing_maint_employees * Experience_of_quits {Years of experience/Week}
DOCUMENT: Represents a decrease in the cumulative experience of the maintenance department as a result of experienced maintenance workers leaving the organization whether it is from being laid off, fired, or a better opportunity.

○ Experience_of_quits = 12.5 {Years of experience/Maintenance worker}
DOCUMENT: Based on the author's experience, the years of experience of those maintenance employees leaving a maintenance organization are between ten to fifteen years.

○ Exp_of_hires = 7.5 {Years of experience/Maintenance worker}
DOCUMENT: Based on the author's experiences, the years of experience of new hires ranged from five to ten years.

○ Hours_per_week = 40 {Hours/week}
DOCUMENT: Represents the number of hours available per maintenance person to work each week. This number multiplied by the number of maintenance employees in the department determines the total number of maintenance resource hours (other than the addition of overtime hours) that are available to complete all maintenance activities: i.e. Maintenance Requests (which includes Emergencies, Operations, and Scheduled), and Preventive Maintenance work orders.

○ Maint_hours_available_for_MRs = Total_maint_hours_available_for_PMs_&_MRs-Maint_hrs_available_for_PMs {Hours/week}
DOCUMENT: Represents the number of maintenance resource hours that are assigned for working on Maintenance Requests (which includes Emergency, Operations and Scheduled maintenance requests). The number of hours is usually determined by subtracting the number of hours designated for preventive maintenance from the total available maintenance resource hours.

○ Total_Maintenance_Backlog = Maint_Req_hours_backlog+PM_hours_backlog {Hours}
DOCUMENT: Represents the current number of hours of maintenance work including both maintenance requests and preventive maintenance that have not been completed. The outstanding backlog maybe as a result of poor productivity, low equipment availability, poor spare- parts inventory or a high number of unexpected machine breakdowns.

○ Maint_resource_hours = Maint_employees * Hours_per_week {Hours/week}
DOCUMENT: Represents the total number of maintenance resources hours that are available to complete maintenance work requests and preventive maintenance work orders. Based on the author's experiences, a typical split between maintenance requests and preventive maintenance is fifty percent for each. That is 50% of the total available hours are assigned for completing maintenance requests and the other 50% is assigned for completing preventive maintenance work orders.

○ Overtime_hours = IF(Total_Maintenance_Backlog > 800) THEN(RANDOM(0.75,1)*Potential_OT_hours) ELSE(0) {Hours/week}
DOCUMENT: Determines the number of overtime hours that may be worked during a week. Working overtime is based upon the current total maintenance backlog hours which includes both maintenance requests backlog hours and preventive maintenance backlog hours. Overtime is worked if the total maintenance backlog rises above 800 hours. The number of overtime hours worked will vary since overtime is done on a volunteer basis. There is no guarantee that the overtime requirements would be met. A random generator is used to simulate the variability of overtime that may be worked.

○ Planned_hiring_rate = SMTH1(20-Maint_employees,4) {Maintenance workers/Week}
DOCUMENT: Represents the number of maintenance workers that are hired to replace those employees that have left the organization. For the purposes of this simulation, the mintenance department consists of twenty maintenance workers. (20-Maint_employees) represents the number of workers that need to be replaced. The SMTH1 function represents the delay in the hiring process. The hiring process usually takes up to four weeks to be completed.

○ Potential_OT_hours = Maint_employees*16 {Hours/week}
DOCUMENT: Represents the total possible number of overtime hours that could be availabe if required. The reason for suggesting possible overtime is that as the author has experienced, overtime in an unionized maintenance department is on a volunteer basis. Typically during the summer months, the maintenance employees tend not to work as much overtime as in the winter months. The value 16 is determined from working 2 hours from Monday to Thursday and 8 hours on a Saturday.

○ Total_maint_hours_available_for_PMs_&_MRs = Maint_resource_hours + Overtime_hours-Train {Hours/week}
DOCUMENT: Represents the total number of maintenance hours that are available for completing maintenance requests and preventive maintenance activities. This number is calculated by multiplying the number of maintenance employees by 40 hours, and then subtracting any number of hours that maybe required for training and finally adding any overtime hours that maybe worked.

⊘ Impact_of_overtime_on_productivity = GRAPH(Frequency_of_overtime {Non-dimensional})
(0.00, 1.00), (1.00, 0.95), (2.00, 0.9), (3.00, 0.85), (4.00, 0.8), (5.00, 0.75), (6.00, 0.7), (7.00, 0.6), (8.00, 0.5)
DOCUMENT: A multiplier representing the relationship between the number of consecutive weeks of overtime that the maintenance employees work in a row and their level of productivity. The author has observed from his experiences that after working eight weeks in a row, the level of productivity of the maintenance employees reduces by about 50%. After working four weeks in a row, their productivity is reduced by about 20%. The above relationship is the author's best estimation based on data and experienced gained in managing maintenance departments over the last ten years.

⊘ Skill_level_due_to_maint_experience = GRAPH(Years_of_cumulative_maint_experience {Non-dimensional})
(100, 1.00), (117, 1.25), (133, 1.50), (150, 2.00), (167, 2.30), (183, 2.40), (200, 2.50), (217, 3.00), (233, 4.00), (250, 5.00)
DOCUMENT: A multiplier representing the author's best estimation of the relationship between cumulative department experience and the average maintenance worker's skill level of the department from the data and experienced gathered and gain from managing maintenance departments over the last ten years. This relationship is significant since the maintenance worker's skill level can heavily impact their productivity and also their effectiveness in repairing unexpected production equipment failures in terms of the length of downtime which of course can affect production equipment capacity.

CHAPTER 6

SIMULATIONS WITH THE MAINTENANCE SECTOR OF THE MODEL

6.1 INTRODUCTION

Using the following initial conditions, we will now run several simulations with the model. The maintenance department within a unionized environment consists of 20 maintenance workers, working one shift eight hours a day. Preventive maintenance is based on the current number of pieces of equipment in operation. There are 100 pieces of equipment including both new (less than two years old) and mature (between two to eight years old) in operation at the start of the simulation. New equipment requires one hour of preventive maintenance per piece of equipment per week, and mature equipment requires three hours of preventive maintenance per piece of equipment per week. There is a current preventive maintenance backlog of approximately 250 hours. The maintenance requests (including both emergency and operations) generated weekly is approximately between 120 to 200 hours with the current backlog being about 200 hours. The production operators' involvement in performing simple maintenance tasks vary between little or no involvement to very high involvement. Maintenance training is dependent upon the skill level of the maintenance worker and the cumulative experience of the department. The current overall operating condition of all production equipment is at 80% of its original design specifications. Overtime is dependent upon the total current backlog of the maintenance department which includes both the preventive maintenance backlog and maintenance request backlog. Overtime occurs only if the total maintenance backlog rises over 800 hours. The author assumes that all 100 pieces of production equipment are in operation. The model is simulated over ten years, divided into 520 weeks with a DT of 0.25. The purpose of the simulations is to observe how the model responds to different maintenance policies, and to to gain a better understanding of the interrelationships within the maintenance department. The first simulation run will be based upon the above-mentioned conditions emulating normal operation of the maintenance department.

6.2 RUN 1: Base Run - Normal Operation

The graph below (Figure 20) demonstrates that within the first year of the simulation, there is an increasing trend in the total maintenance backlog (curve 3). This situation is as a result of not completing all scheduled preventive maintenance and the majority of maintenance requests that are generated in the early stages of the simulation as indicated by the decrease in percentages completed for both the maintenance request (curve 2), and preventive maintenance (curve 1).

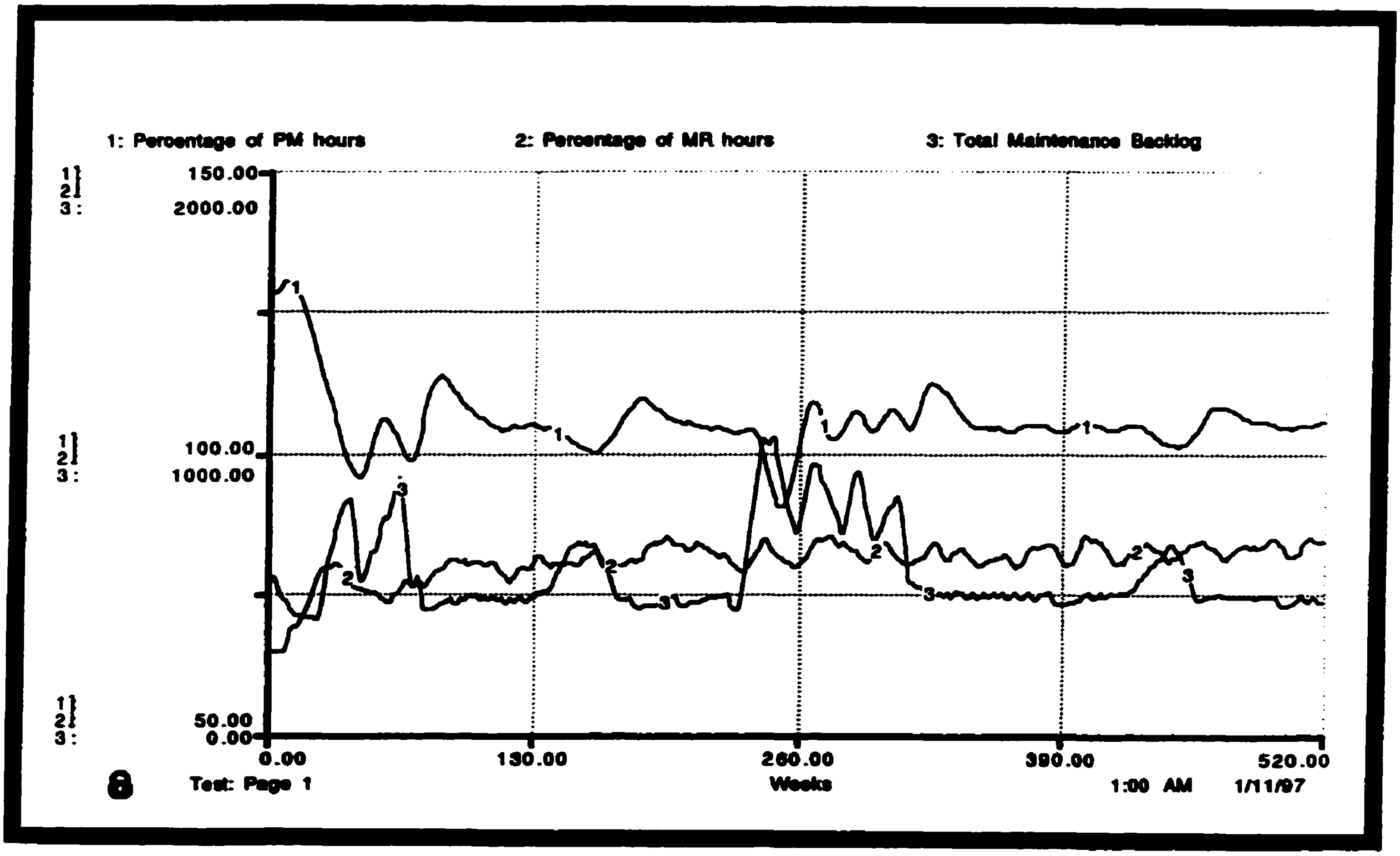

Figure 20. Base run - Preventive maintenance/Maintenance Request/Total Maintenance Backlog

However, shortly thereafter, there is an increase in the percentages of preventive maintenance completed followed by an increase in the percentages of maintenance requests completed which reduces the total maintenance backlog. There is a significant increase in the total maintenance backlog between weeks 230 to 250 followed by a decreasing trend for the remainder of the simulation. The significant increase can be attributed to the fact that both a large number of preventive maintenance tasks and maintenance requests were not being completed (to be explained later). The high total maintenance backlog is continuously reduced thereafter over the next ten to fifteen weeks due to the increasing high percentages of completions for both preventive maintenance and maintenance requests.

The graph also indicates a relationship between the percentages of preventive maintenance completed and the percentages of maintenance requests completed. Almost immediately after an increase in the percentages of preventive maintenance completed, there seems to be an increase in the percentages of maintenance requests completed which occurs periodically throughout the entire ten year period. The reason for these increases in the percentages of maintenance requests being completed is that by completing most of the scheduled weekly preventive maintenance, there is a reduction in the maintenance requests generated which results in an increase in the percentages of maintenance requests completed (since percentages of maintenance requests completed = maintenance requests completed divided by maintenance requests generated). The result of reducing the maintenance requests that would be typically be generated reinforces the importance of preventive maintenance. To further understand the initial increase at the beginning of the simulation, and the sudden increase between weeks 230 to 250 in the total maintenance backlog, let us examine the graph below (Figure

21) which illustrates the total maintenance backlog, level of operator involvement and the productivity of the maintenance worker.

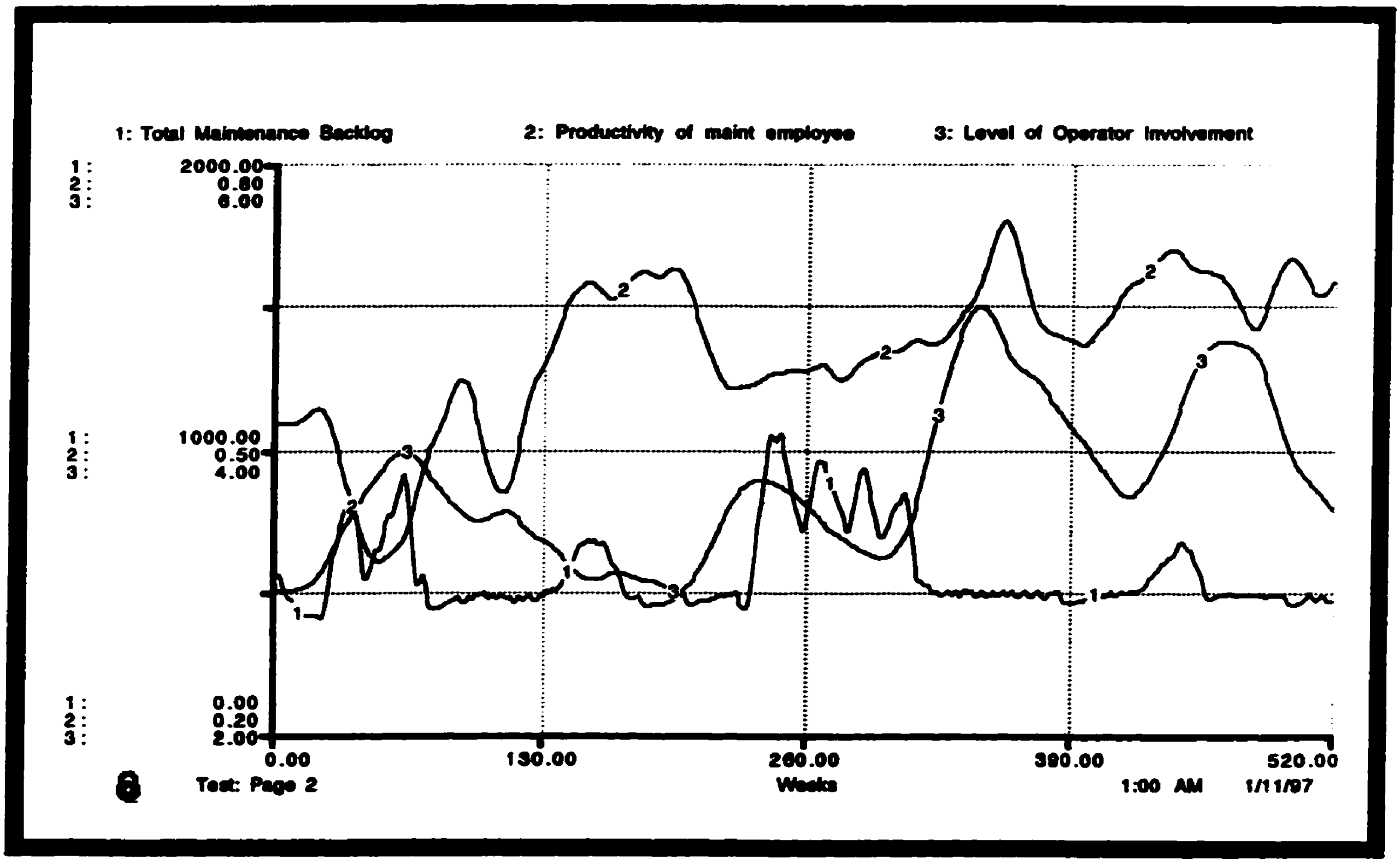

Figure 21. Base run - Total Maintenance Backlog/Productivity of Maintenance Employee/Level of Operator Involvement

As this graph indicates both at the onset of the simulation and between weeks 230 to 250, there is a significant increase in the level of operator's involvement in performing simple maintenance tasks. Along with this increase in the operator's involvement in performing simple maintenance tasks, there are productivity levels of the maintenance workers below 100% (1 representing 100%) leading into a downward trend. The below average productivity levels of the maintenance worker is due to the negative impact of the operator's involvement in performing the work belonging to maintenance (unionized environment). There is the perception that, by having the production operators perform the maintenance work, they are reducing the potential for the maintenance workers to work additional overtime, demotivating the maintenance worker resulting in poor productivity.

The decrease in the maintenance worker's productivity causes lower than normal completion rates for both preventive maintenance and maintenance requests resulting in an increase in the total maintenance backlog both within the first year of the simulation and between the weeks 230 to 250. The next two graphs, Figure 22 illustrating preventive maintenance backlog (PMs), percentages of preventive maintenance hours completed, and productivity; and Figure 23, maintenance request backlog, percentages of maintenance request hours completed and productivity; both re-emphasizing the effects of the maintenance worker's productivity on the total maintenance backlog.

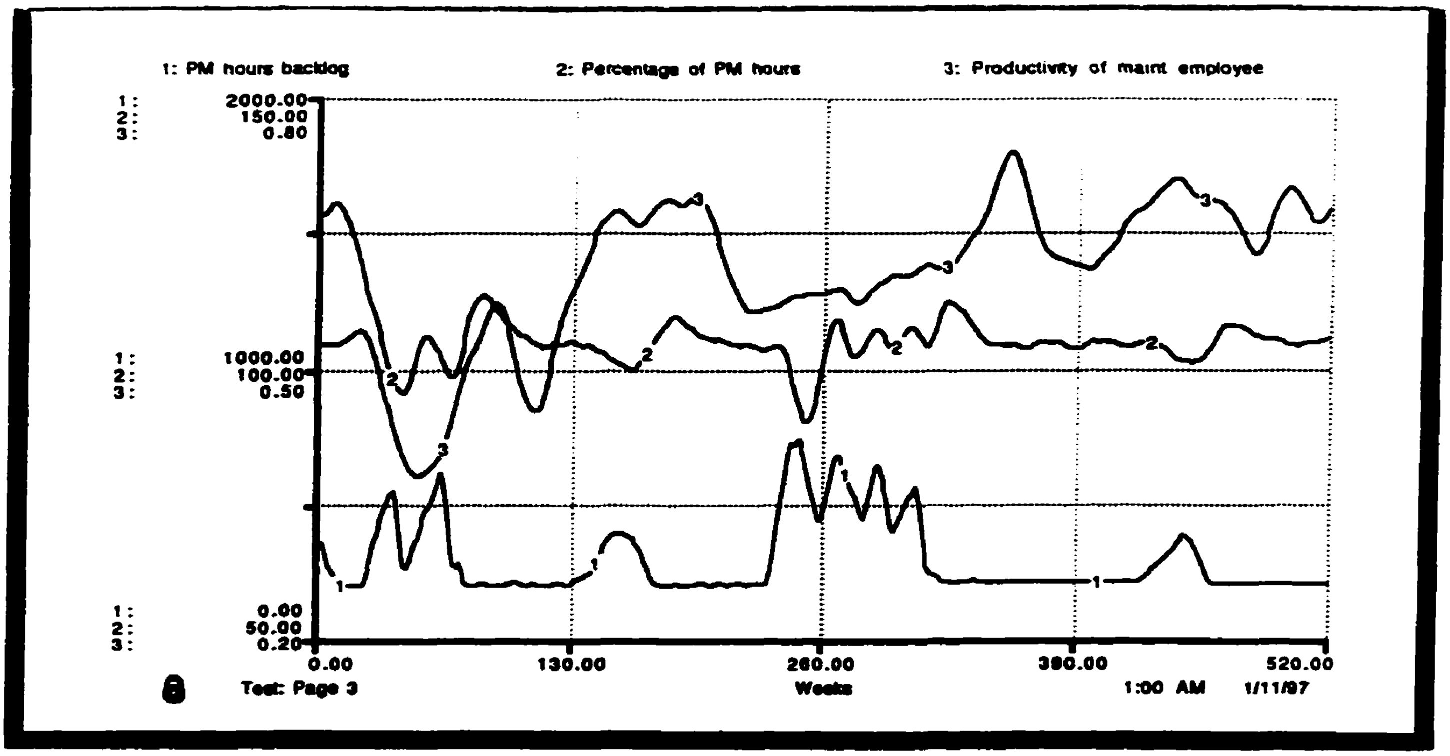

Figure 22. Base run - PM Hours Backlog/Percentage of PM Hours/ Productivity of Maintenance Employee

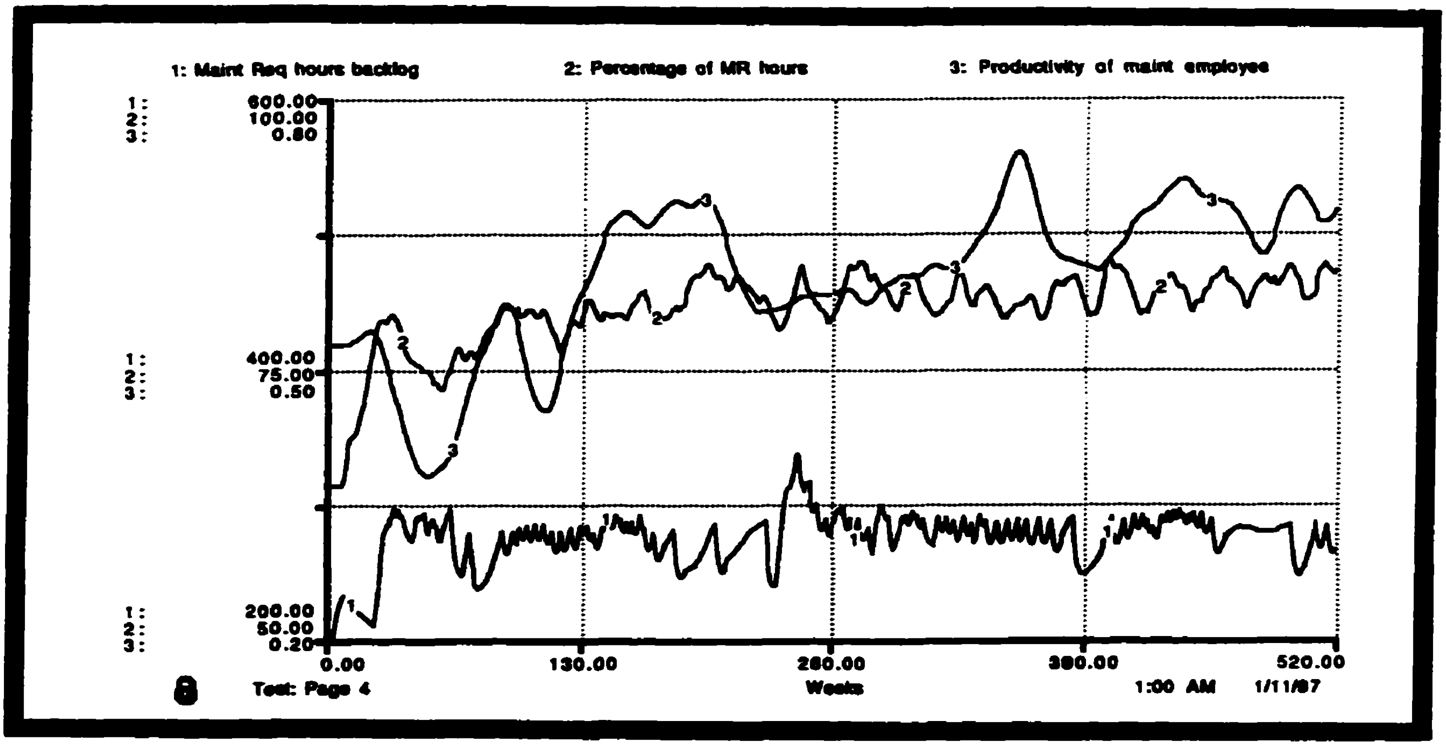

Figure 23. Base run - MR Hours Backlog/Percentage of MR Hours/ Productivity of Maintenance Employee

It is interesting to note that one could have been led to believe that the strategy of having the production operator performing the simpler maintenance tasks would free up the maintenance workers to aggressively go after reducing the overall maintenance backlog which of course is counter-intuitive as illustrated in the simulation. It appears that the extra time made available for maintenance due to operator's involvement is not greater than the time loss from the drop in productivity of the maintenance employees. It is also interesting to note that as time goes by, not only is there an increasing trend in the production operator's involvement but there is also an increasing trend in the productivity of the maintenance worker (noted beyond week 300 to the remainder of the simulation - Figure 23). These trends will be explained with the graph below (Figure 24) which illustrates the level of operator involvement, maintenance worker's productivity and skill levels.

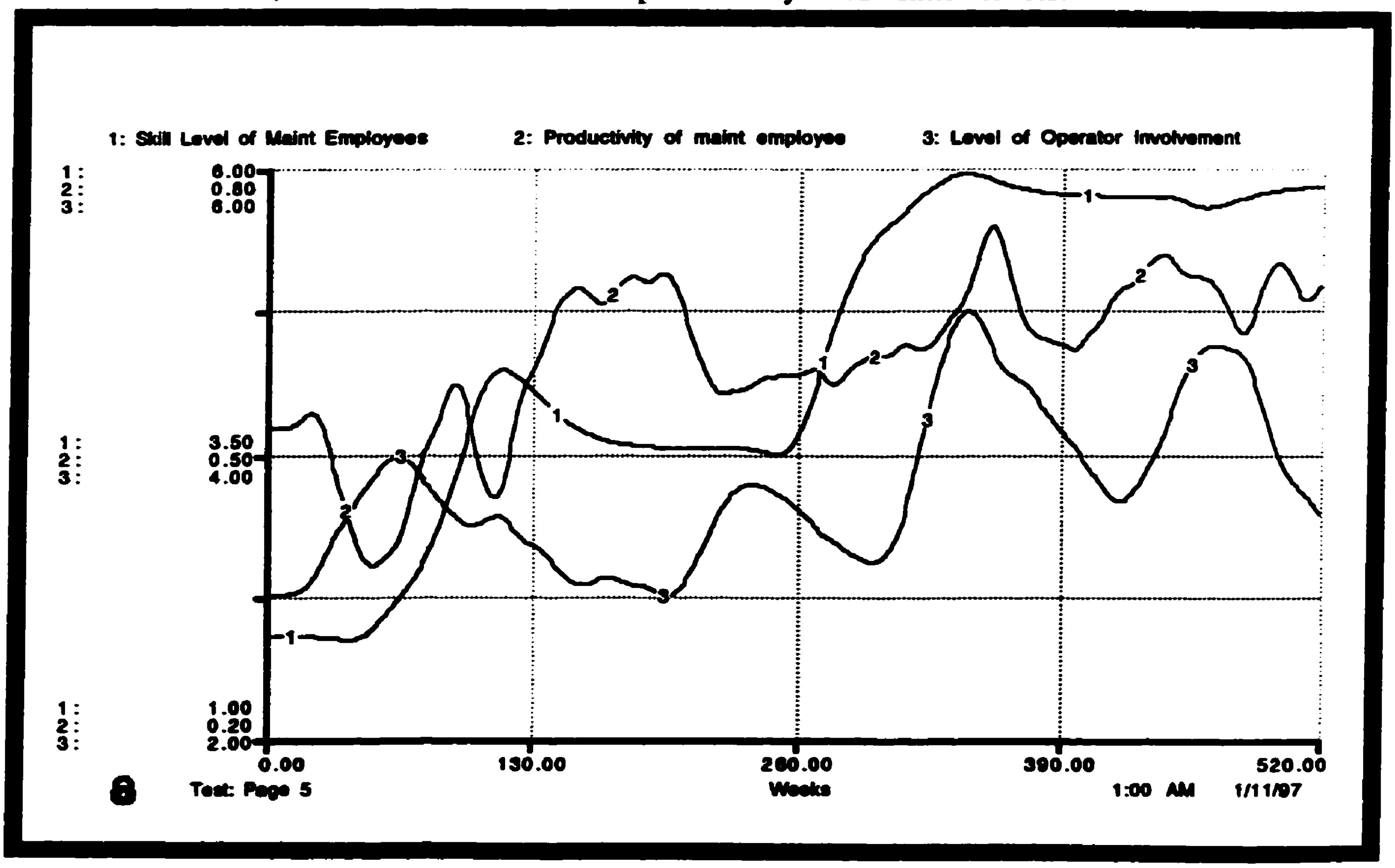

Figure 24. Base run - Skill Level of Maintenance Employee/Productivity of Maintenance Employee/Level of Operator Involvement

This graph clearly demonstrates the effects of the level of operator involvement in performing simple maintenance activities on the productivity of the maintenance worker. During the first year of the simulation, there is a definite increase in operator's involvement probably due to the fact that the maintenance activities add variety to the regular production work that the operator does daily. With this increase, there is a definite decrease in the level of productivity of the maintenance worker. However, approximately 65 weeks into the simulation, there seems to be a decrease in the degree of operator's involvement. This decrease is probably due to the large influx of grievances submitted to the union by the maintenance department, since the operators' according to the collective agreement are performing work beyond the scope of their job classifaction. With the decrease in operators' involvement, there is a definite increase in the productivity of the maintenance worker. However, there is also an increase in the skill levels of the maintenance worker. The increase in skill levels will impact the productivity of the maintenance worker favorably, but there is an interesting point worth mentioning. The fact of having the production operators get more involved with maintenance activities, made time available for the maintenance workers to be involved in other activities such as training, which was the reason for the increased skill levels within maintenance. The question now becomes which of the two actions are more strategic in long term thinking? Allowing production operators to become more involved with maintenance activities providing the opportunity for maintenance employees to be trained increasing their skill levels and becoming more productive; or minimizing production operators involvement, hence, not impacting the maintenance employees motivation and their productivity levels. For the purposes of this dissertation, an accurate answer is not as important as to note the fact that there can be underlying effects when certain decisions are made, which, if not appreciated, can result in inappropriate decision making.

As pointed out earlier, an increase in the operators' involvement caused a decrease in the productivity of the maintenance worker's productivity. However, illustrated in this graph beyond week 300 and for the remainder of the simulation, both the operators' involvement and the maintenance workers' productivity are increasing which at a glance seems to be counter-intuitive. The reasons for this counter-intuitive behavior are as follows. First, the organization adopting a policy to minimize overtime which was a point of contention for the maintenance workers. Second, decreasing the production operators' involvement with maintenance reduced the possibilities to further increasing their skills due to the lack of time for training. Third, maintenance workers had to do all maintenance activities with respect to maintaining the equipment which even included cleaning the equipment. After relentless efforts at educating the maintenance workers about the benefits of operator involvement in participating on the maintenance of equipment, the maintenance workers changed their perceptions of operator involvement. Hence, the re-implementation of the operator involvement strategy, resulted in increasing both maintenance skill levels and productivity.

The next graph below in Figure 25 illustrates the impact of percentages of preventive maintenance hours completed and the level of operator involvement on the operating conditions of the production equipment. Operating condition of the equipment refers to the current condition of the equipment with respect to speed and accuracy. For example, an operating condition of 80% would indicate that the equipment is operating 20% slower

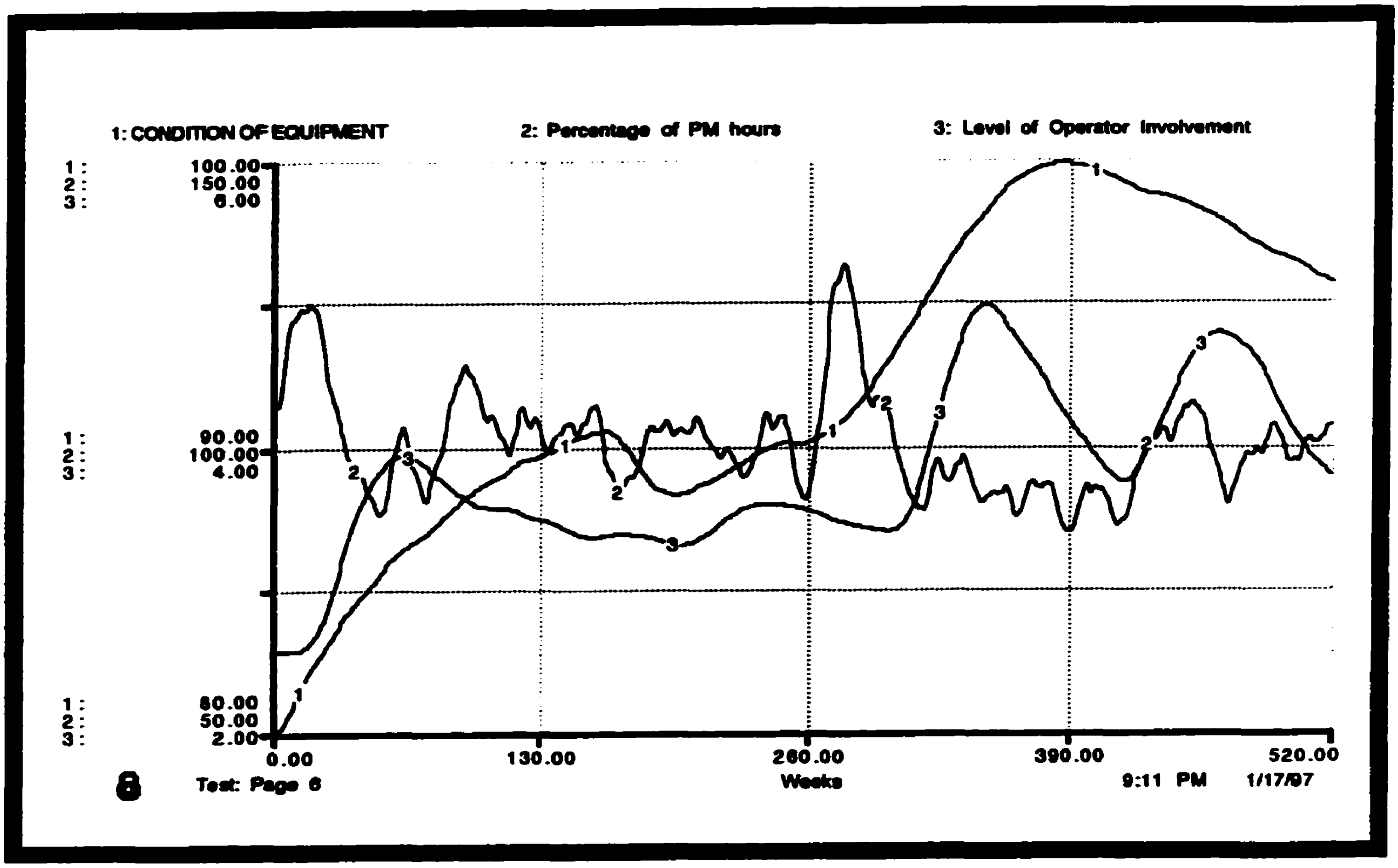

Figure 25. Base run - Condition of Equipment/Percentage of PM Hours/Level of Operator Involvement

than its original condition, and/or 20% of the product produced by the equipment is defective. Even though there is high consistency in completing all weekly scheduled preventive maintenance activities throughout the simulation, there seems to be deterioration in the equipment's operating condition between weeks 150 to weeks 220 (i.e. from approximately 90% to 87%). For some period of time prior to the start of the deterioration of the equipment's operating condition, there is a steady decline in the level of operator involvement (i.e. from a level 4 to approximately 3.2) with respect to performing the minor equipment maintenance activities which is the catalyst for starting the deterioration. In addition, there is a reduction in the percentage of preventive maintenance hours that were completed between weeks 150 to 220. Another factor that worsens this issue is the fact that the skill level of the maintenance worker starts to decrease just before week 130 (see figure 24) suggesting that the maintenance workers were not performing high quality preventive maintenance on the equipment.

Figure 24, also indicates a significant improvement in the skill level of the maintenance worker between weeks 260 to 320 which positively impacts the operating condition of the equipment. Beyond week 320 (figure 25), the operating condition of the equipment begins to deteriorate once again which is a result of the decrease in both the percentage of preventive maintenance that is being completed (due to lower productivity of the maintenance worker), and the degree of involvement of the production operator. The high percentage of completed preventive maintenance just beyond week 260, and the high degree of operator involvement around weeks 300 and beyond, created the opportunity to continuously improve the maintenance of the equipment resulting in a general upward trend regarding the equipment's operating condition beyond week 260. Other factors that attributed to the upward trend in improving the operating condition of the production equipment beyond weeks 260 were the increased skill levels and productivity of the maintenance worker as illustated in Figure 24. The graph below in figure 26, illustrates the impact of the maintenance worker's skill level on the operating condition of production equipment and the implications of continuously operating poorly maintained equipment with respect to the aging of equipment. The significance of the aging of equipment is that once the equipment has been operated for a period of time under a specific preventive maintenance plan, it becomes old and inefficient and needs to be replaced. However, there are number of factors that may influence the aging rate of equipment which could therefore, affect the number of pieces of equipment that would need to be replaced.

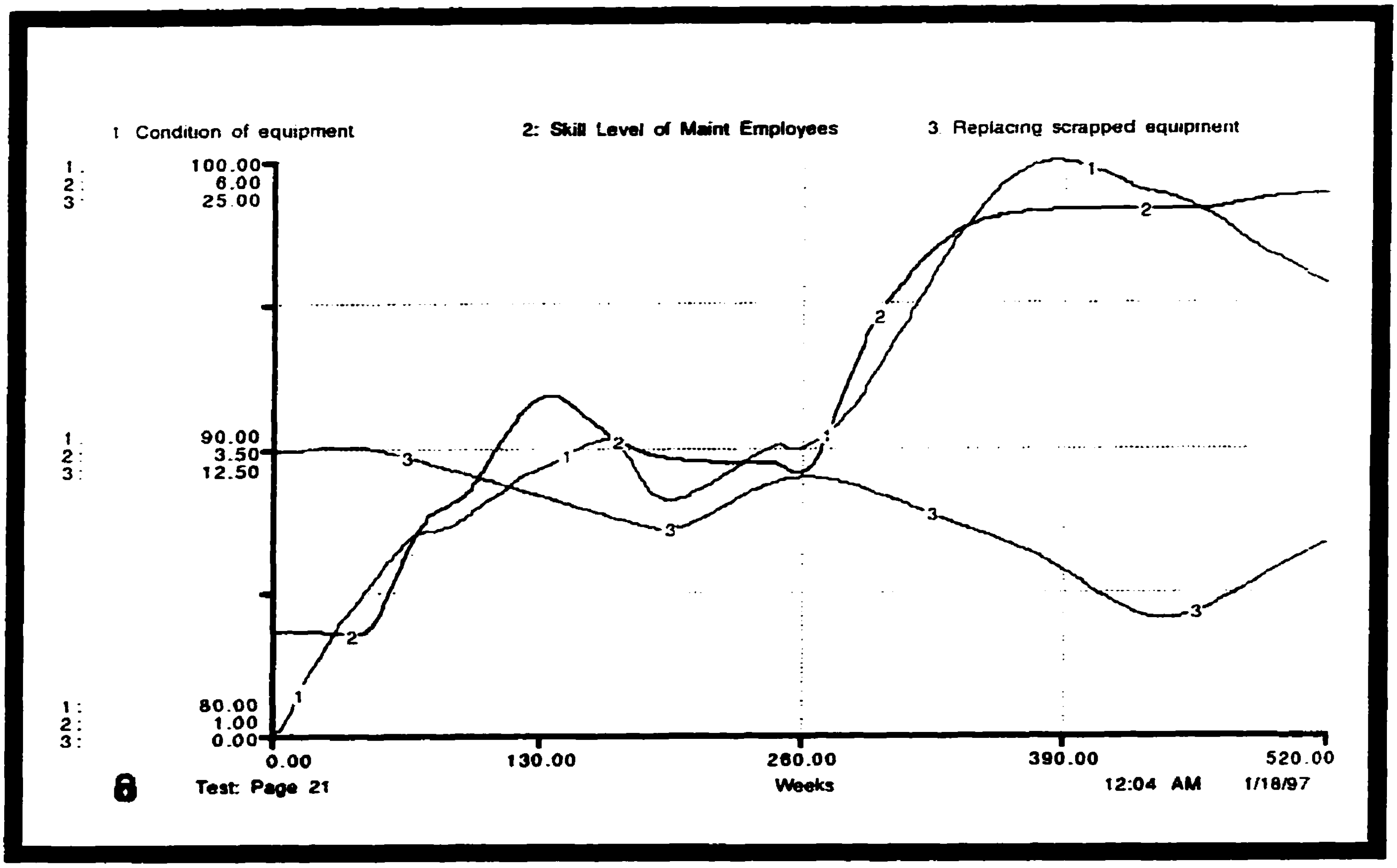

Figure 26. Base run - Condition of Equipment/Skill Level of Maintenance Employee/Replacing Scrapped Equipment

The graph indicates that during the first few years of the simulation, the operating condition of the equipment (this, as previously mentioned, refers to the speed and accuracy at which the equipment currently functions) steadily improves, reducing the aging rate for both new equipment (less than 2 years old) and mature equipment (more than two years old but less then eight years) resulting in a decreasing trend of the number of pieces of equipment that need replacing. As pointed out earlier, between weeks 150 to weeks 220, the equipment operating condition deteriorates to some extent, speeding up the aging rate for both new and mature equipment resulting in an increase in the number of pieces of equipment that need replacing. However, beyond week 260, the trend for replacing equipment that is being scrapped becomes one of a decreasing nature. A major factor attributed to this downward trend is probably due to the continuous improvements of the maintenance worker's skill which are significantly higher during the last five years of the simulation as indicated in figure 26. Over the first two years of the simulation, the skill level of the maintenance worker increases which in turn positively influences the operating conditions of the equipment. However, at approximately week 130, there is a drop in the skill level of the maintenance workers which was due to a couple of highly experienced and specialized maintenance workers leaving the organization. The drop in the skill level of the maintenance workers affects the operating condition of the equipment (i.e. between weeks 150 to approximately weeks 230). However, after week 260, the operating condition of the equipment starts to improve and continues this trend for the remainder of the simulation. As indicated in figure 26, it appears that the improvement to the operating condition of the equipment may be directly related to significant rise in the skill level of the maintenance workers.

The next graph below (Figure 27) demonstrates both the importance of training, and the effectiveness of the training which together can increase the maintenance worker's skill level that could lead to continuous improvements of the operating conditions of equipment.

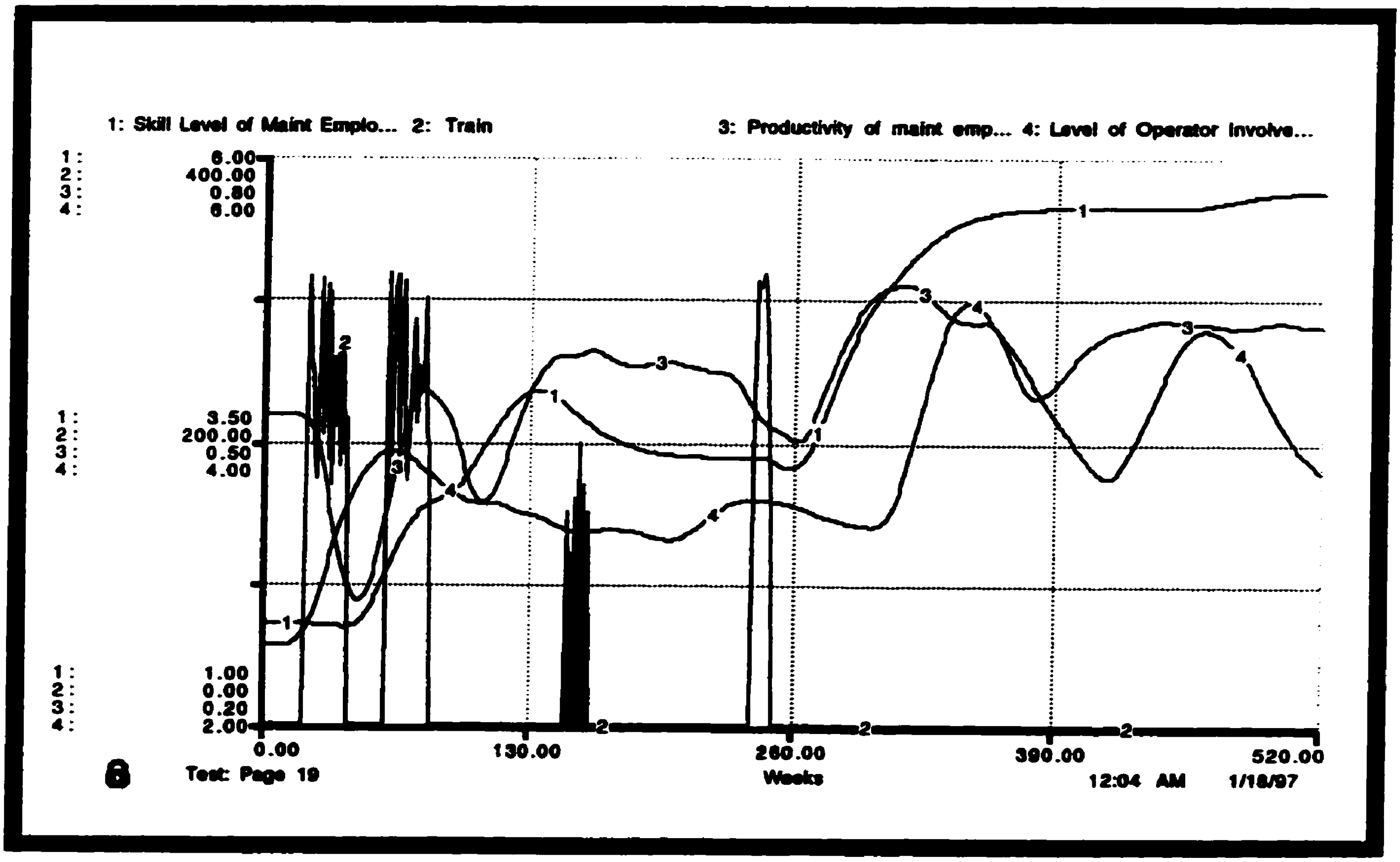

Figure 27. Base run - Skill Level of Maintenance Employee/Productivity of Maintenance Employee/Level of Operator Involvement

An interesting point to note here, is that there were some situations that, even when training was provided, did not result in an increase in the maintenance workers' skill levels (around weeks 150 to 160) of the simulation. The reason for this is that some of the training that was provided may not have been effective whether it was from poor delivery of the training or that the timing for the training was inappropriate. Also indicated on the graph are the following. When training was provided within the first year of the simulation, there was a reduction in the productivity of the maintenance worker. The reason for this drop in productivity was due to a learning curve that the maintenance workers experienced; in addition there was also significant amounts of involvement by the equipment operators in performing the simple maintenance activities. As previously mentioned, the involvement of the operators in performing maintenance activities demotivated the maintenance workers even though the time that was made available (due to an increase in the level of operator's involvement) was utilized for training the maintenance workers

The graph in Figure 28 takes a further look at the maintenance workers' productivity, and how it is affected by overtime, and motivation. The graph illustrates that motivation significantly impacts productivity. The variation of the impact of overtime throughout the simulation is minimal; whereas the impact of motivation varied between 0.5 and 0.8 which would indicate that productivity could drop as much as 50%.

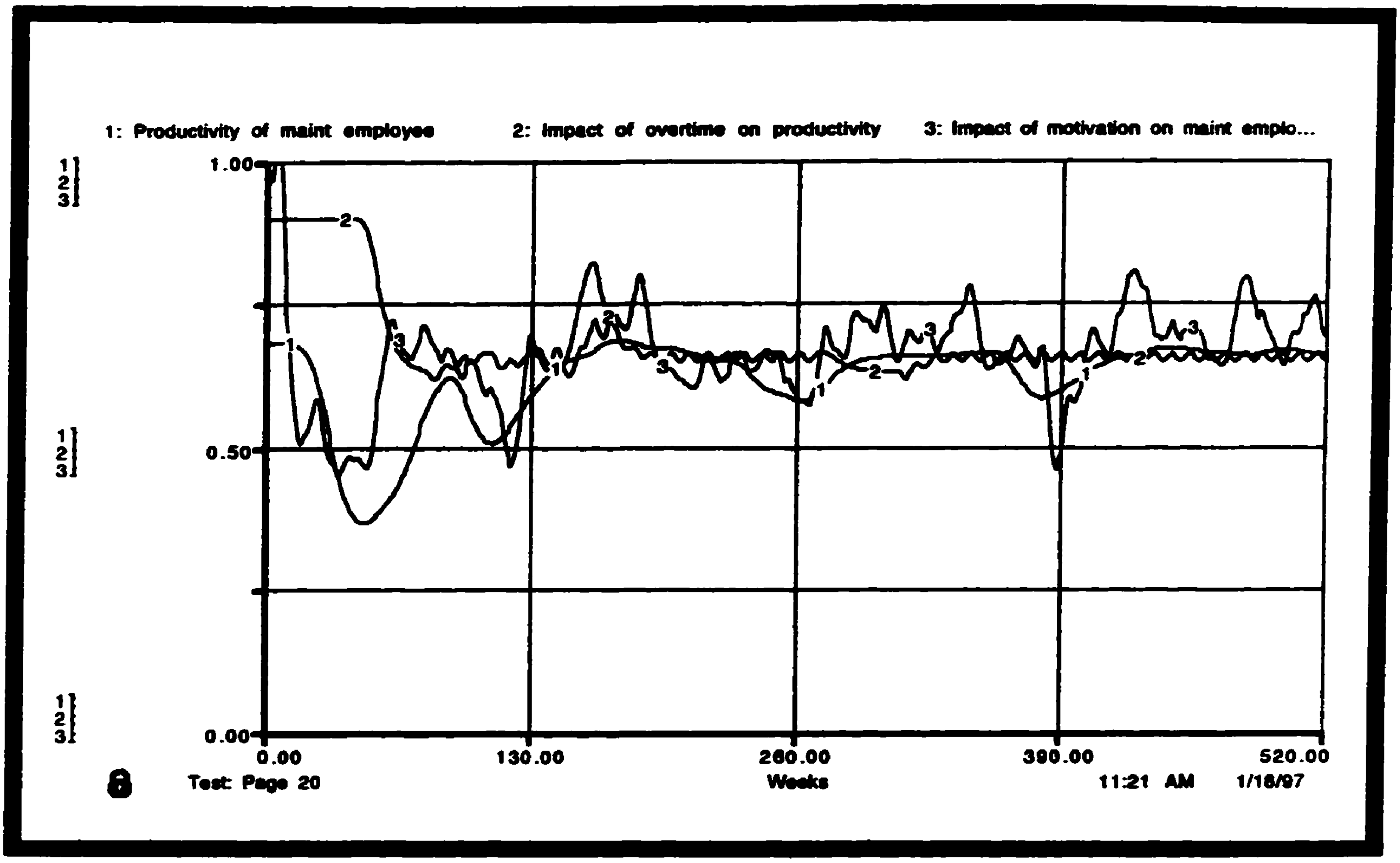

Figure 28. Base run - Productivity of Maintenance Employee/Impact of Overtime on Productivity/Impact of Motivation on Maintenance Employee

Previously mentioned was the impact of the operating condition of equipment on the aging rate and the number of pieces of equipment that would need to be replaced. The production equipment capacity within the facility is another factor that the operating condition of the equipment can impact. Production equipment capacity represents the number of pieces of equipment both new and mature that are currently available for manufacturing. The graph in Figure 29 illustrates the impact of the operating condition of the equipment on production equipment capacity. Approximately three years (150 weeks) into the simulation, the operating condition of the equipment deteriorates (previously explained) causing a drop in the production equipment capacity. However, the production equipment capacity increases thereafter with the continuously improving operating conditions of the equipment. Poorly operating equipment conditions increases both the aging rate of new equipment and scrapping rate of mature equipment resulting in a decrease in the number of pieces of equipment that are available for production. A decrease in the number of pieces of equipment available for production causes a drop in the production equipment capacity.

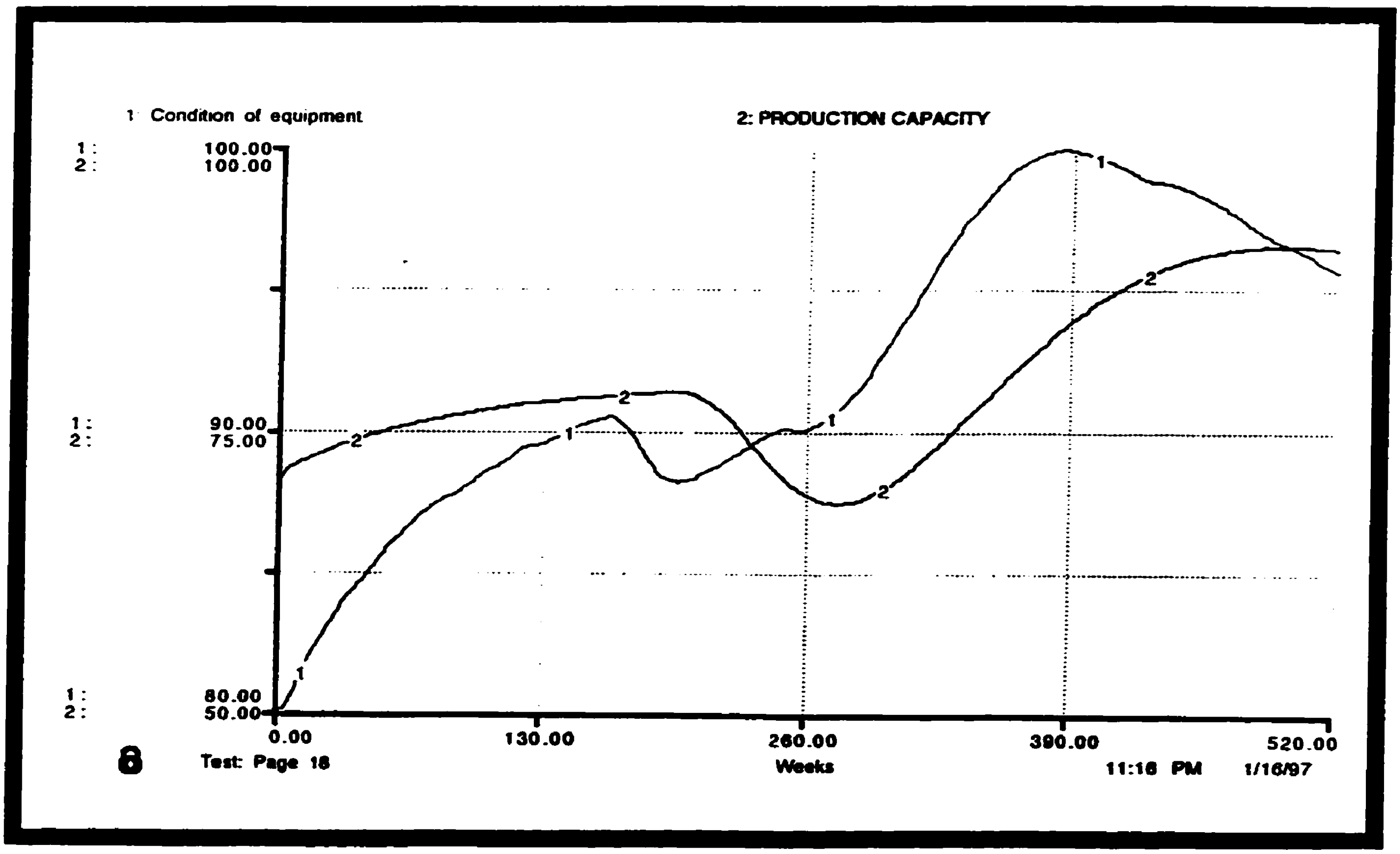

Figure 29. Base run - Condition of Equipment/Production Capacity

The above information represents the base run with the previously mentioned initial conditions. The simulation runs below represents a number of different scenarios that the maintenance department could be exposed to. The following performance measures are examined under the different scenarios: The percentages of preventive maintenance completed, the percentages of maintenance request completed, the total maintenance backlog, the condition of the equipment, and the production equipment capacity. Scenarios used are as follows:

RUN #1 Base run - normal operation (described in the above section)

RUN #2 Equipment availability reduced by 50%

RUN #3 Production operator's involvement increased by 25%

RUN #4 Reduce preventive maintenance by 50%

RUN #5 Reduce overtime by 75%

6.3 PERCENTAGES OF PREVENTIVE MAINTENANCE COMPLETED

The graph in Figure 30 illustrates a sensitivity analysis on the percentages of preventive maintenance completed with respect to the five different scenarios.

The percentage of preventive maintenance completed represents the number of preventive maintenance hours that were completed in comparison to the number that were scheduled. The percentage of preventive maintenance completed seems to be negatively impacted by both reducing equipment availability and reducing the emphasis to do preventive maintenance. Increasing operator involvement does not appear to influence the percentages of preventive maintenance completed. Reducing overtime slightly increases the percentage of preventive maintenance completed.

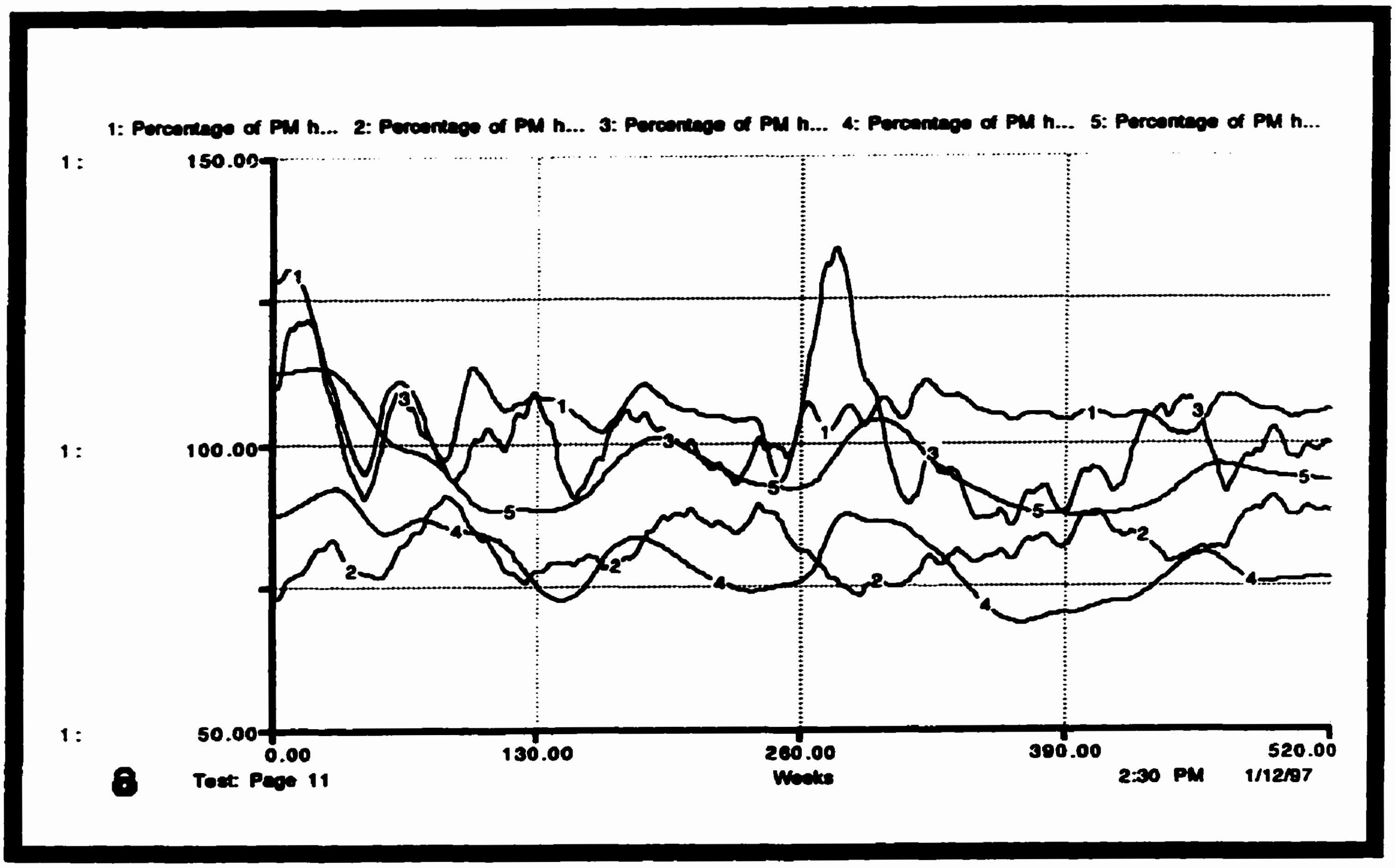

Figure 30. Percentages of preventive maintenance completed

Reducing equipment availability significantly reduces the percentage of preventive maintenance completed (curve 2). This can be counter-intuitive from the perspective that not freeing up equipment for preventive maintenance (which maybe as a result of production being behind schedule) may result in unexpected equipment breakdowns which may occur at the most inappropriate time from a production point of view, causing serious problems for production. Hence, having production understand the implications of high equipment unavailability, may force production to re-evaluate the short term strategy of not allowing the equipment to be made available for preventive maintenance.

The decision to minimize the emphasis on doing preventive maintenance may result in an unexpected rise in maintenance requests as a result of unscheduled machine breakdowns. The initial strategy may have been to change the emphasis on doing preventive maintenance inorder to mitigate the high backlog of maintenance requests. However, the simulation (curve 4) indicates that the percentage of preventive maintenance completed is significantly reduced and may result in additional maintenance requests which is counter-productive.

One might assume that reducing overtime may significantly decrease the percentage of preventive maintenance completed. However, the sensitivity analysis, indicates that reducing overtime does not significantly affect the percentage of the preventive maintenance completed. An explanation for this counter-intuitive behaviour is that working less overtime implies that a smaller number of preventive maintenance hours would be completed, hence, decreasing the percentage of preventive maintenance completed. However, working overtime can also impact the maintenance worker's productivity from the perspective that the more overtime worked, the lower the productivity which would result in completing a smaller amount of preventive maintenance than what may have been assumed to be completed by working additional hours. Therefore by reducing the overtime, the negative impact that it has on productivity is eliminated; and the gain in productivity (i.e. preventive maintenance hours completed) is greater than the productivity that may have been realized (actual preventive maintenance hours completed during overtime) if overtime was worked.

6.4 PERCENTAGES OF MAINTENANCE REQUEST COMPLETED

The graph in Figure 31, illustrates a sensitivity analysis on the percentages of maintenance request completed with respect to the five different scenarios. The percentages of the maintenance request being completed seems to be affected most negatively by the action of reducing overtime (curve 5). This result can be explained as follows. With overtime reduced, and the focus being concentrated on doing preventive maintenance and repairing unscheduled breakdowns, there is little time left to work on other maintenance requests such as those that are generated daily (Operations maintenance request) or those that are scheduled (Scheduled maintenance requests) to be done sometime in the future. Hence, completion rates decrease causing a reduction in the percentages of maintenance requests being completed. The fluctuation in the percentages of completed maintenance requests results from the strategy to work on maintenance requests as a low priority. Therefore, if there are many equipment breakdowns and a high number of preventive maintenance hours, then the percentage of maintenance requests completed will decrease. On the other hand, if there are few breakdowns and a small amount of preventive maintenance, then a high number of maintenance requests would be completed increasing the percentage of completed maintenance requests.

Reducing both equipment availability and preventive maintenance increases the percentages of maintenance requests being completed. The

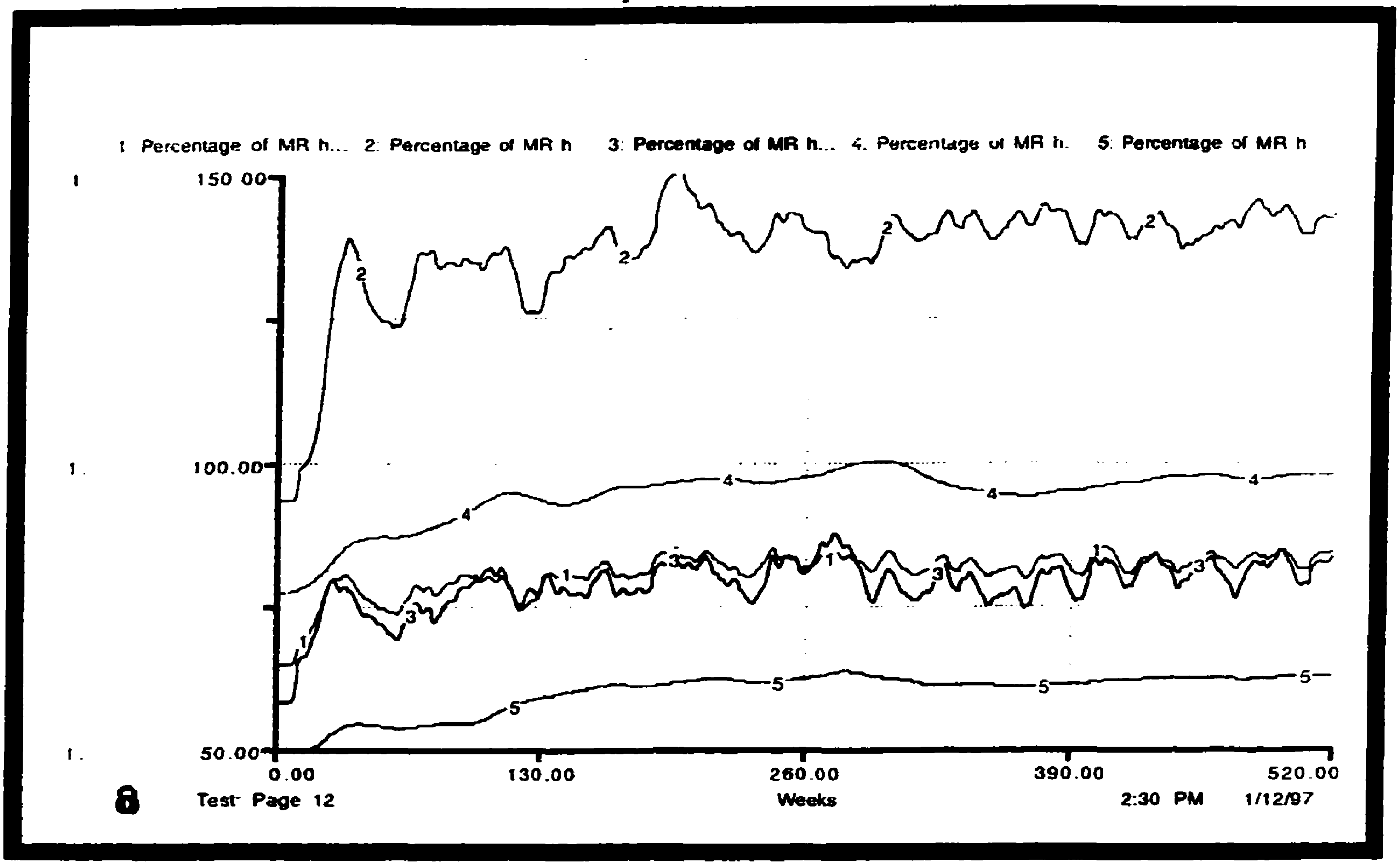

Figure 31. Percentages of maintenance request completed

percentages of maintenance requests completed were at their highest levels with the reduction of equipment availability (curve 2). Reducing both equipment availabilty and the emphasis on preventive maintenance frees up maintenance resources to work on maintenance requests increasing the maintenance request completion rates resulting in a rise in the percentages of maintenance requests being completed

The impact of increasing the production operator's involvement in performing maintenance tasks appear to be minimal throughout the simulation (curve 3).

6.5 TOTAL MAINTENANCE BACKLOG

The graph in Figure 32 illustrates a sensitivity analysis on the total maintenance backlog (includes both the preventive maintenance and maintenance request backlogs) with respect to the five different scenarios. Reducing equipment availability and preventive maintenance significantly increases the total maintenance backlog for the maintenance department.

Reducing the emphasis on preventive maintenance (curve 4) is self-explanatory. Minimizing maintenance resources for preventive maintenance will reduce the completion rates for preventive maintenance, hence, greatly reducing the percentages of preventive maintenance that would be completed, increasing the preventive maintenance backlog and concurrently increasing the total maintenance backlog.

Curve 2, representing the scenario of a reduction in equipment availability indicates a steep rise in the total maintenance backlog. A number of situations arise when production does not free up the equipment for preventive maintenance. The completion rate for preventive maintenance decreases, increasing the preventive maintenance backlog which increases the total maintenance backlog. When preventive maintenance is not performed on the equipment as scheduled, the condition of the equipment deteriorates which leads to unexpected breakdowns. Unexpected breakdowns create disruptions within the maintenance department. For example, scheduled maintenance work and or preventive maintenance does not get completed, since maintenance resources are shifted to repair the unexpected machine breakdowns. The shifting of the focus of the maintenance resources results in further reduction of percentages completed for both preventive maintenance and maintenance requests compounding the already increasing total maintenance backlog.

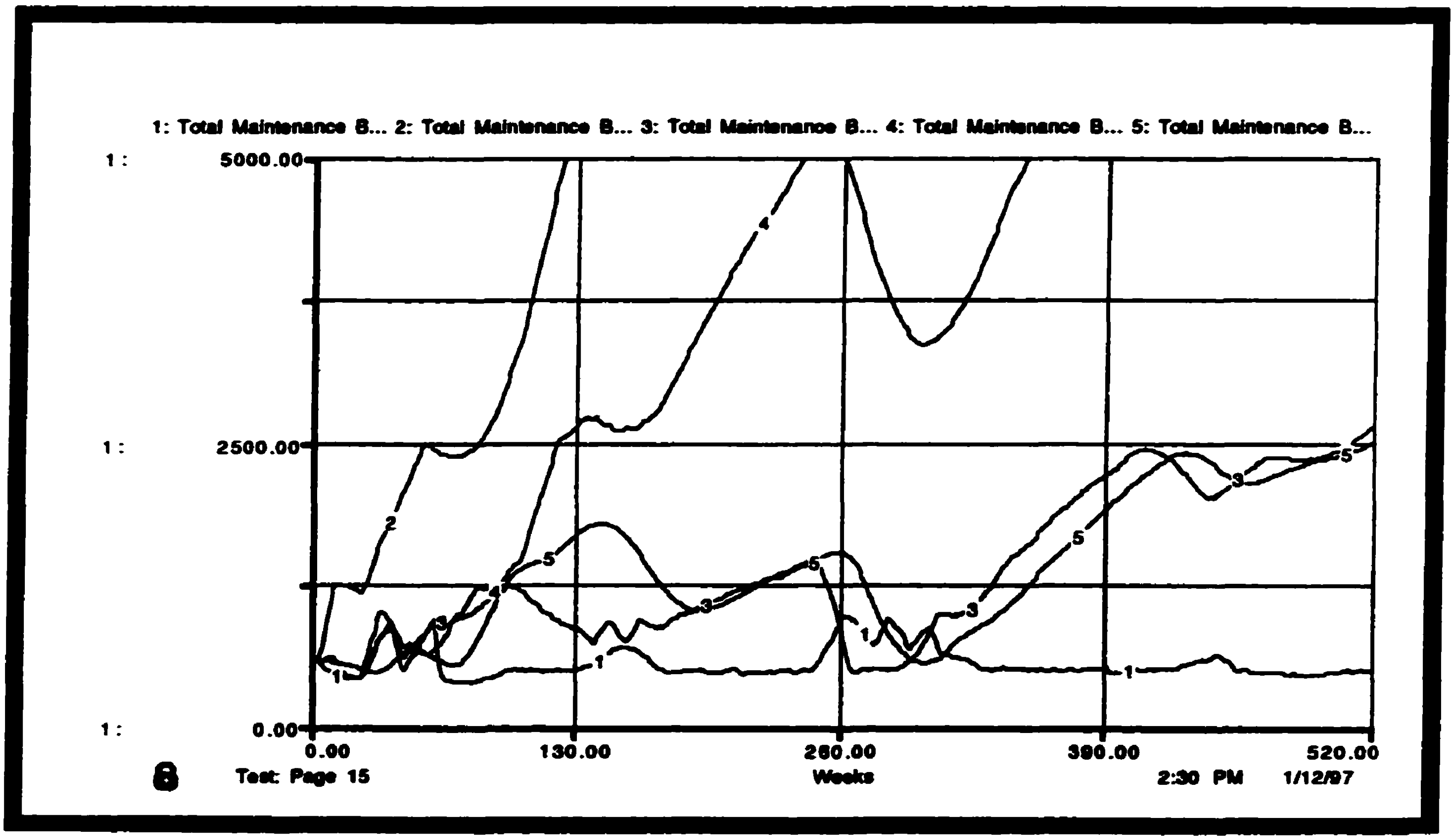

Figure 32. Total maintenance backlog

6.6 CONDITION OF EQUIPMENT

The graph in Figure 33 illustrates a sensitivity analysis on the condition of the production equipment with respect to the five different scenarios. The graph demonstrates that reducing equipment availability (curve 2), reducing preventive maintenance (curve 4), and increasing the production equipment operator's involvement (curve 3) significantly influences the production equipment's condition.

Curve 1 representing the base run indicates that over the ten year period, the condition of the equipment had deteriorated somewhat but over time was restored and maintained at approximately 90% of its original condition. At approximately three years into the simulation, the condition of the equipment had deteriorated due to a drop in the skill level of the maintenance workers as a result of a couple of highly skilled and experienced maintenance workers leaving the organization. However, over time, the condition of the equipment was restored to almost original condition (detailed explanation provided in the section on the base run).

Reducing equipment availability has the greatest negative impact on the operating condition of the equipment as illustrated in curve 2. Reducing equipment availability means not freeing up the equipment for maintenance to carry out the scheduled preventive maintenance on the equipment. Continuous operating of the production equipment with little or no preventive maintenance leads to deficiencies in the equipment causing the equipment to deteriorate.

Reducing the emphasis on doing preventive maintenance (curve 4) worsens the equipment conditions but not to the extent as in the scenario of reduced equipment availability. Although the emphasis on doing preventive maintenance on equipment is reduced, the maintenance department is still able to complete some preventive maintenance and therefore, the condition of the equipment does not deteriorate quite as badly as in the scenario where equipment availability was reduced.

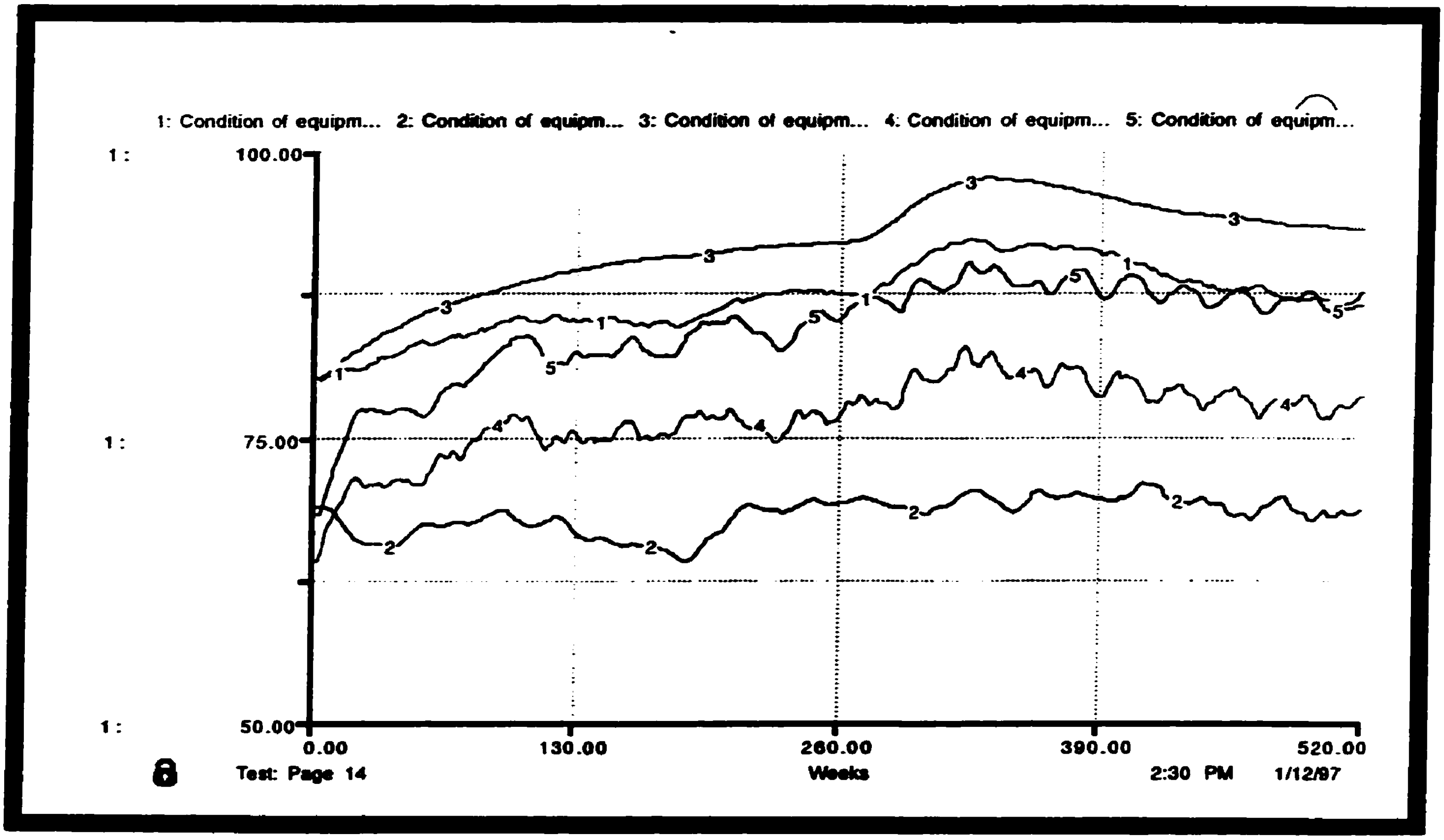

Figure 33. Condition of equipment

The impact of increasing operator involvement with respect to the condition of the equipment is extremely positive. Over the five year period, the condition of equipment rarely falls below 90% of its original condition. By allowing the operators to become more involved with the maintenance of the equipment they operate, creates a feeling of ownership for the operators which can only enhance the ongoing efforts to ensure the equipment is maintained to as close to its original condition as possible.

6.7 PRODUCTION EQUIPMENT CAPACITY

The graph in Figure 34 illustrates a sensitivity analysis on production equipment capacity with respect to the five different scenarios. The strategy of reducing equipment availability for preventive maintenance seems to have had the greatest negative impact on production equipment capacity (curve 2). Production equipment capacity as defined in this dissertation represents the number of pieces of equipment both new and mature that are currently available for manufacturing.

As mentioned earlier, the impact of reducing equipment availability can be counter-intuitive. Take for example, a situation where production has been under a lot of pressure for some period of time to produce more than normal requirements due to an unexpected rise in customer demands. It would therefore seem unreasonable to give up the equipment for preventive maintenance, especially if there appears to be nothing wrong with the equipment (i.e. not broken), since any time that the equipment is not producing causes production to fall further behind in meeting their customer requirements.

However, not performing preventive maintenance as scheduled eventually leads to unexpected machine breakdowns. The implications of the unexpected breakdowns are as follows. Breakdowns never occur at a right time, and would therefore cause major disruptions within production since downtime means that the equipment is not producing product which means that customer requirements are not being met. Hence, the initial strategy of keeping the equipment running (i.e. not making available for preventive maintenance) in an effort to meet production requirements result in a decrease in production equipment capacity as a result of unexpected and more frequent machine breakdowns due to a lack of preventive maintenance.

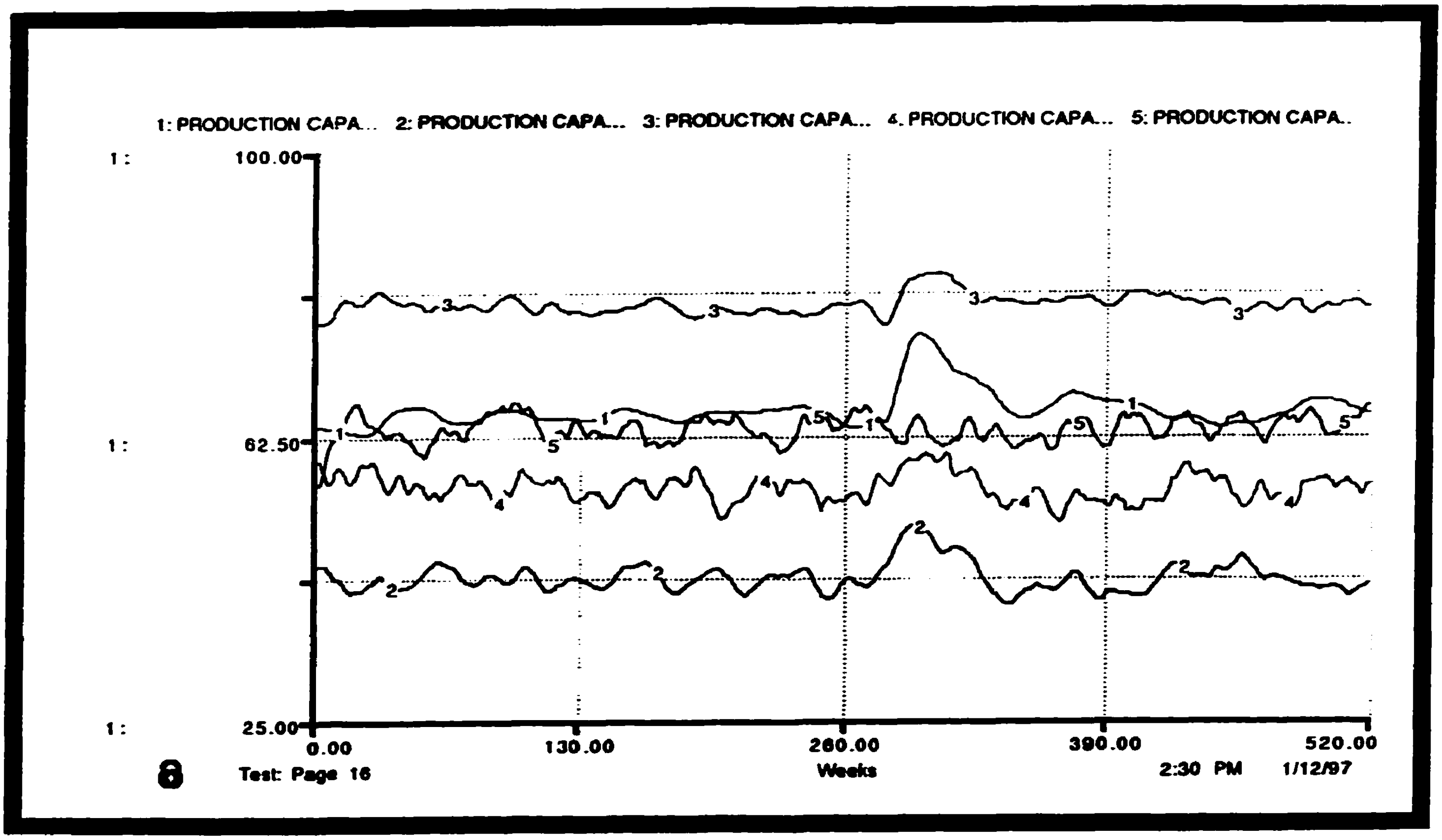

Figure 34. Production equipment capacity

Curve 3 representing the operators' involvement in performing minor maintenance activities seems to have the most positive influence on production equipment capacity. Allowing production operators to become more involved in maintaining the equipment they operate has many advantages. Their increased involvement creates a sense of ownership that tends to make the operators more concerned of the condition of their equipment. The operator probably knows more about the idiosyncrasies of the equipment than the maintenance workers due to the amount of time that the operators spend with their equipment. With this knowledge, the operators are probably the first to become aware of any malfunctions as minor as they may be; and would probably contact maintenance immediately to correct the deficiency rather than waiting for maintenance to find and correct when they perform their weekly or monthly preventive maintenance. Catching minor deficiencies before they become problems can significantly impact the ongoing operating conditions of the equipment. Having the operators do minor maintenance on the equipment can decrease unnecessary downtime and help to maintain the condition of the equipment to its original condition. For example, minor greasing, as required, can save on unexpected bearing failures. Regular cleaning of the equipment makes minor oil leaks noticeable immediately which can quickly be repaired before becoming major problems. Having the operators develop a sense of ownership will tend to make the operators very conscious of the way they operate and care for the equipment which will help to maintain the optimum equipment condition.

It is interesting to observe that reducing the emphasis on doing preventive maintenance (curve 4) does not significantly impact production equipment capacity; especially since it was noted earlier that reducing equipment availability to allow for preventive maintenance did have a significant negative impact on production equipment capacity. There is however, a subtle difference between not freeing up equipment for the maintenance workers to do scheduled preventive maintenance versus reducing the emphasis on doing preventive maintenance. Preventive maintenance is essential to ensuring maximum equipment efficiency and to minimize unexpected breakdowns. But the frequency of preventive maintenance is not an exact science. The amount, type and frequency of preventive maintenance depends upon the environment that the equipment is operating within. For example, equipment operating in a wet or dusty environment would require different preventive maintenance than equipment that was operating in a humidity controlled environment. Equipment operating with very low tolerances may require a higher frequency of adjustments than one that is operating with high tolerances. High speed equipment requires different preventive maintenance checks than low speed operating equipment. Equipment operating seven days a week, twenty four hours a day will require more preventive maintenance than equipment that is only operating eight hours a day, five days a week. Therefore, reducing the emphasis on preventive maintenance, whether it is as a result of a change in requirements for preventive maintenance or scheduling the preventive maintenance as a low priority, will not necessarily impact the equipment and production equipment capacity in the negative fashion similiar to that caused by reducing equipment availability. On the contrary, reducing the preventive maintenance where appropriate, will increase production equipment capacity, since the equipment is not being taken out of production unnecessarily.

Another interesting behavior observed in the above sensitivity analysis was the impact of reducing overtime (curve 5). The graph indicates that the reduction of overtime resulted in slightly less production equipment capacity than the base run representing normal operations which consists of working overtime as required. This indication is suprising because one would assume that working overtime helps the maintenance department to keep up with maintenance requirements of the facility. It was however, noted earlier that working overtime may not necessarily be beneficial due to the impact that overtime for prolong periods has on the level of productivity of the maintenance worker. Working overtime can be counter-productive because of the decrease in productivity of the maintenance worker working the longer hours. Hence, working sixty hour weeks for any prolonged period of time will probably be as productive as working a regular forty hour week. Therefore, reducing overtime mitigates the decrease in the productivity levels of the maintenance workers resulting in effective maintenance which would minimize downtime, hence improving production equipment capacity.

6.8 TESTING BEST CASE/WORST CASE SCENARIOS OF THE MODEL

It is clear that there are certain parameters to which the model is very sensitive, most notably: production operator involvement, emphasis on preventive maintenance and equipment availability. The graph in Figure 35, represents the simulated results of three different scenarios. Total maintenance backlog is measured since it is indicative of how well the maintenance department is functioning. The first scenario represents normal base run operation (curve 1). Curve 2 represents a scenario where the sensitive parameters are set to be optimum (i.e. a very high involvement from production operators, the appropriate amount of preventive maintenance that minimizes equipment breakdowns, and a high percentage of equipment availability. Curve 3 represents a worst case scenario where operator involvement is extremely low to non-existant, minimal preventive maintenance, and low equipment availability. The results are illustrated below in terms of total maintenance backlog.

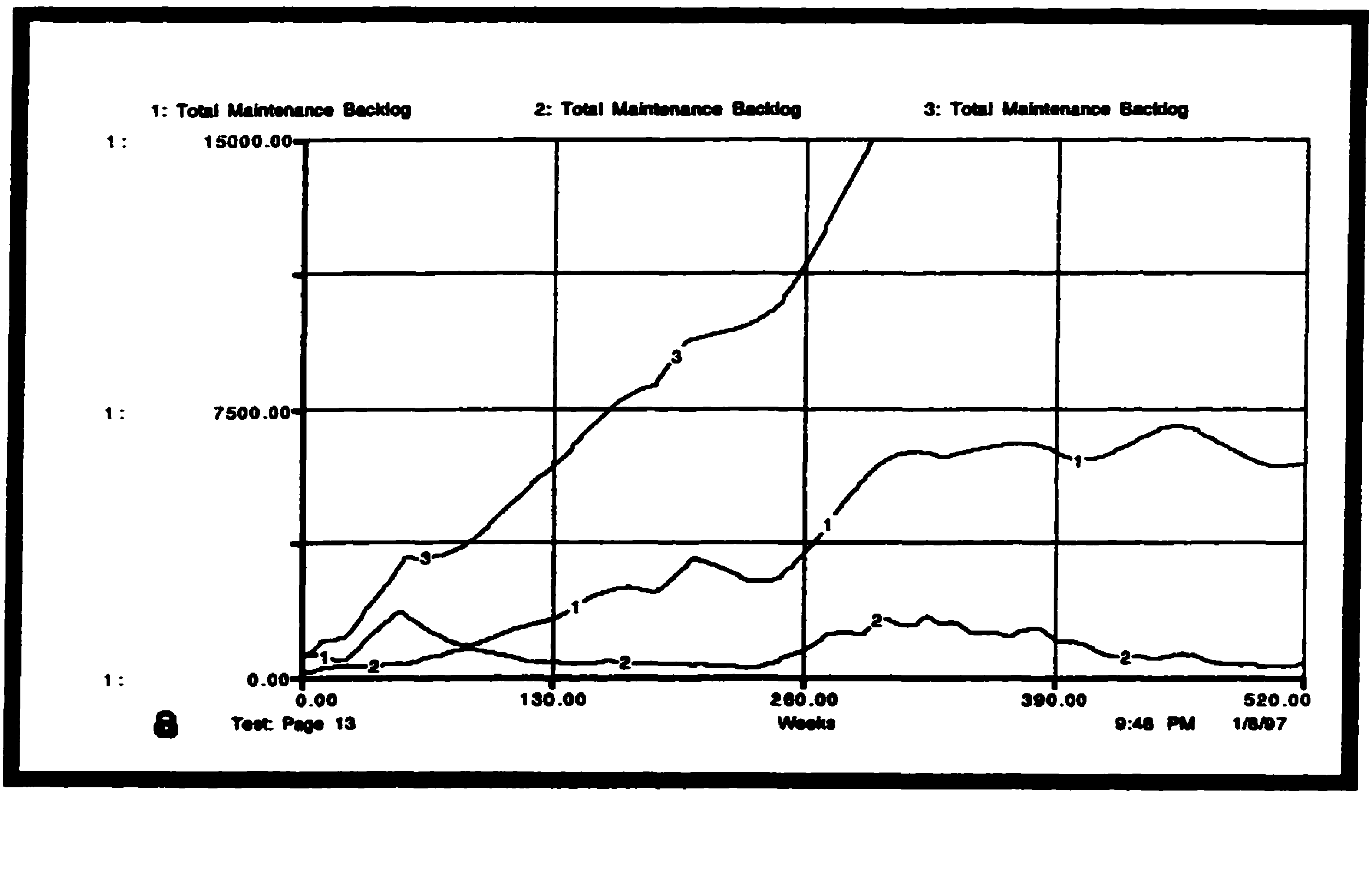

Figure 35. Total maintenance backlog

Curve 1, normal operation, indicates a total maintenance backlog of approximately 7000 hours over a ten year period, which in the author's opinion, is normal for a maintenance department, depending on the maintenance worker's productivity. Curve 2, which represents optimum conditions indicates less than 500 hours backlog over the ten year period. Curve 3, representing worst case indicates an extremely high backlog even after the first year. These results are representative of reality confirmed by the author based on first hand experience that the author has gained from managing maintenance departments over the last ten years.

6.9 SUMMARY

Based on the scenario analyses; within the limitations of the model to represent a real situation, the model shows the following.

Preventive maintenance is fundamental to an effective production system. By carrying out an effective preventive maintenance program, maintenance requests that are normally generated are minimized and unexpected equipment breakdowns can be prevented. Training can play an important role even though it may cause a short term rise in maintenance backlog, since available time used for training could have been used to work on reducing the overall maintenance backlog.

The involvement of production operators can significantly influence the production equipment's condition. Although the initial impact of the operator's involvement is perceived as being negative due to maintenance workers reducing their productivity, it is an effective long term strategy for improving overall equipment condition.

A common theme of the model simulations is that the system can behave in unexpected ways. This shows that it is not enough to assume one knows how the system will respond; it is necessary to think carefully about how the strategies one sets influence other parts of the system. <u>**The System Dynamics methodology illustrated here could provide understanding and insights of strategic importance to managers of Production and Maintenance operations.**</u>

CHAPTER 7

CONCLUSION AND FUTURE RESEARCH DIRECTIONS

Manufacturing strategy has been promoted as a concept that can eliminate the competitive malaise that manufacturing companies have faced. The main purpose of manufacturing strategy is to develop capabilities in manufacturing with which the business can outperform its competitors. That means that decisions made in operations must support each other in emphasizing the capabilities that a business deems necessary to gain advantages over its competitors. The message behind manufacturing strategy is very simple - perform actions in operations that help the business perform better. This is a message that early researchers (Skinner 1969; Wheelwright 1978; Hayes and Schmenner 1978) of manufacturing strategy have stated. Since then other researchers (Buffa 1980; Hayes and Wheelwright 1984; Hill 1985; Skinner 1985) have continued to emphasize that manufacturing strategy is an approach for making manufacturing into a competitive weapon. Most researchers (Skinner 1969; Wheelwright 1978; Hayes and Schmenner 1978; Buffa 1980; Hill 1985) concur with the perspective that the purpose of manufacturing strategy is to link decisions in operations with each other and with business strategy. Researchers have proposed ideas in linking decisions in operations but only from a disjunctive point of view, and, to date, relationships and linkages between only a few decisions have been studied.

This dissertation's main contribution is the conceptualizing of a systems dynamic modelling framework for studying manufacturing strategy from a more holistic point of view to further understanding of relationships and linkages among the various decision areas. In addition, this work identifies maintenance as a key area that has not been previously linked to manufacturing strategy.

Systems Dynamics was chosen as the approach to study manufacturing strategy because of the dynamic nature of manufacturing. The relationships within and between decision areas are nonlinear and very complex; and current optimizing methods would not have been able to effectively represent the operating characteristics of a manufacturing environment. In addition, optimizing methods are not conducive to studying systems from a holistic point of view.

This chapter summarizes the research conducted in this thesis. The first section briefly overviews the content, focus and findings of the study. Section two summarizes some contributions of this thesis research on manufacturing strategy. Finally, the third section identifies some future research directions.

7.1 RESEARCH OVERVIEW

This section briefly describes the content and findings of each chapter. The literature review (Chapter 2) is discussed in the next section, followed by a brief discussion of the qualitative analysis (Chapter 4), quantitative analysis (Chapter 5), and finally the results of the simulations of the maintenance sector of the manufacturing strategy model are summarized (Chapter 6) .

7.1.1 Literature Review Summary

The literature on manufacturing strategy is categorized based on a taxonomy proposed in the thesis. The taxonomy categorizes the literature into five major aspects of managing manufacturing strategy: planning (decisions, linkages, and segmentation), control and process. The review attempts to connect the literature on manufacturing strategy with strategy management literature.

The objective of the review was not to describe and summarize the current knowledge base but to use the taxonomy to identify issues and gaps in current research. Until recently, the majority of research on manufacturing strategy has mainly relied on case studies. Recently, there have been empirical studies and analytical analyses to attempt to gain insights into the linkages of decision areas in manufacturing strategy. Weaknesses identified with most of the current research is that the research has been conducted from a disjunctive point of view rather than from a holistic one. Much of the existing research focuses on a single content area such as quality or production systems. Little research has been aimed at understanding the relationships that exist among content areas or how decisions in one content area affect decisions in other areas. Manufacturing strategy is a very complex issue. A dynamic approach is required in order to better understand the complex interrelationships among the decision areas of manufacturing.

7.1.2 Qualitative Analysis

The qualitative analysis consisted of conceptualizing a systems model to represent some of the operations management decision areas of manufacturing strategy with maintenance being introduced as a new specific key decision area. The decision areas selected for this research were quality, workforce management, materials management, process versus product and maintenance. In developing the model, two distinct avenues were pursued in the process of selecting key variables that could significantly influence the behavior of the decision areas under examination.

Variables for the decision areas of process versus product, quality, materials management, and workforce management were deductively derived from the author's existing knowledge base. Interviews were then conducted with manufacturers in industry ranging from senior manufacturing managers to front line manufacturing supervisors to validate the selection of the key variables. The influence diagrams as described in this dissertation have evolved as a result of numerous discussions with individuals that have had direct involvement in developing manufacturing strategy in industry.

Since there seems to have been little, if any, published effort to date to relate maintenance to manufacturing strategy, the variables identified for this decision area in the model are of an exploratory nature by the author as a result of his own experiences and insights gained from being directly involved in the process of developing maintenance strategies within two very large manufacturing organizations in North America.

Cycle time which is defined in this dissertation, as the time required to manufacture a product unit was selected as the measure to examine relationships among and within the decision areas of processes, quality, materials management, workforce management and maintenance.

The qualitative analysis has illustrated a new approach to understanding manufacturing strategy. The qualitative analysis has demonstrated that there are numerous influences among the variables within the decision areas and between the decision areas, most of which were not explicit; and that the process of constructing influence diagrams leads those involved in the analysis to gain a better understanding of how the overall system works including "soft" variables such as worker's morale, skill levels and productivity.

7.1.3 Quantitative Analysis

The qualitative analysis has demonstrated that by requiring the key elements of a system to be understood and put into proper relationship with each other, managers are forced to think about how the individual parts fit together to form the entire system. Clearly, having an overall picture of the system is key to understanding it. However, in a society where we have become increasingly specialized, having this kind of holistic view is not common. Even after diagramming the system and striving to capture what is most important, what we are left with can still be quite complicated. It is often not clear how systems with many influences, and feedbacks behave, which is the reason people often cannot agree on whether a particular policy will be beneficial or detrimental. It seems, then, that if it is difficult for most of us to envision how a multitude of relationships and influences act together to produce the behavior of a system, then it would be useful to have some way of being able to simulate how a system evolves over time. Quantitative simulation modelling is such a method.

A quantitative analysis was conducted on one sector of the manufacturing strategy model (the maintenance decision area), for the purposes of illustrating how a systems dynamic approach can offer a means for people to visualize how a system in its entirety operates. The analysis demonstrates that by better understanding relationships among systems and within a system, policies can be evaluated in a more concrete and decisive manner, thus leading to better decision making. The key variables studied within the maintenance decision area were the percentages completed for both preventive maintenance and the maintenance requests, the level of the machine operator's involvement in performing maintenance activities, maintenance resources in terms of number of employees and hours available to do maintenance work, and the operating conditions of the production equipment. The next section provides a brief summary of the simulations.

7.1.4 Summary of Simulations

The following assumptions were undertaken in an effort to examine the interrelations of variables within maintenance and to also better understand how decision areas relate to each other when meshed together.

The maintenance department is part of a unionized environment consisting of 20 maintenance workers, working one shift eight hours a day. Preventive maintenance is based on the current number of pieces of equipment in operation. The number of pieces of equipment including both new (less than two years old) and mature (between two to eight years old) in operation at the start of the simulation is 100 pieces. New equipment requires one hour per piece of equipment per week, and mature equipment requires three hours per piece of equipment per week of preventive maintenance. There is a current preventive maintenance backlog of approximately 250 hours. The maintenance requests (including both emergency and operations) generated weekly is approximately between 120 to 200 hours with the current backlog being about 200 hours. The production operators' involvement in performing simple maintenance tasks vary between little or no involvement to very high involvement. Maintenance training is dependent upon the skill level of the maintenance worker and the cumulative experience of the department. The current overall operating condition of all production equipment is at 80% of its original design specifications. Overtime is dependent upon the total current backlog of the maintenance department which includes both the preventive maintenance backlog and maintenance request backlog. Overtime occurs only if the total maintenance backlog rises over 800 hours. Current production equipment capacity is at 100% (i.e. the author assumes that all 100 pieces of production equipment are in operation). The model is simulated over ten years, divided into 520 weeks with a DT of 0.25. The purpose of the simulations is to observe how the model responds to different maintenance policies, and to to gain a better understanding of the interrelationships within the maintenance department. The first simulation run was based upon the above-mentioned conditions emulating normal operation of the maintenance department.

Within the limitations of the model to represent a real situation, results from the simulation indicate that there are certain relationships (listed below) that are important to effective production operations in the kind of firm modeled.

Preventive maintenance is fundamental to an effective production system. By carrying out an effective preventive maintenance program, maintenance requests that are normally generated are minimized and unexpected equipment breakdowns can be prevented.

Training can play an important role even though it may cause a short term rise in maintenance backlog, since available time used for training could have been used to work on reducing the overall maintenance backlog.

Production operator's involvement can significantly influence the production equipment's condition. Although the initial impact of the operator's involvement is perceived as being negative because of maintenance workers reducing their productivity, it is an effective long term strategy for improving overall equipment condition.

A common theme of the model simulations is that the system can behave in unexpected ways. This shows that it is not enough to assume one knows how the system will respond; it is necessary to think carefully about how the strategies one sets influences other parts of the system. This is an important finding, since if one does not believe that a system can behave in expected ways, one will not be on guard to think carefully about the ramifications of one's strategic and policy decisions.

Maintenance is suggested as a strategic decision area to manufacturing. The simulations executed in this thesis show that maintenance can indeed influence manufacturing strategy. There are a number of interrelating variables within the decision area of maintenance which, if effectively meshed, can cause maintenance to be a significant factor in making operations management a competitive weapon.

7.2 RESEARCH CONTRIBUTIONS

The research contributions of this thesis are discussed under two areas: definitions and simulation analysis.

7.2.1 Definitions

Definitions of manufacturing strategy in the literature (Skinner 1969; Wheelwright 1978; Hayes and Schmenner 1978; Buffa 1980; Miller et al. 1981; Hill 1985; Hayes and Wheelwright 1984; DeMeyer et al. 1987; Roth 1987; Krajewski and Ritzman 1987) emphasize the notion of consistency and linkage among decisions in operations. Researchers use the terms (consistency or linkage) to denote many things, and as a result the terms create ambiguity. In this thesis, the term linkage is defined in Chapter 1. The definition makes the term more meaningful, hopefully reducing ambiguity associated with its use.

A paradigm for managing manufacturing strategy is proposed in Chapter 2. The paradigm synthesizes the work of other researchers. The paradigm takes a comprehensive look at what constitutes manufacturing strategy and what is involved in planning strategy. Most researchers focus on the purpose of manufacturing strategy, rather than defining the content of manufacturing strategy or the process of managing it. The paradigm delineates the different components of manufacturing strategy. The paradigm offers a focus for categorizing past work in manufacturing strategy and identifying issues that need to be addressed in the future.

7.2.2 Simulation Analysis

This thesis has demonstrated an innovative approach to studing linkages among and within decision areas of manufacturing strategy.

First, this research has developed a systems dynamic model of manufacturing strategy where manufacturing strategists can visualize and understand the parameters influencing strategic management decisions, the relationships among them, and how they affect each other.

Secondly, maintenance is introduced as a key operations management decision area within manufacturing.

Thirdly, a quantitative analysis of the maintenance decision area was carried out to demonstrate that systems can behave in unexpected ways. This reinforces the point that it is not enough to assume one knows how the system will respond; it is necessary to think carefully about how the strategies one sets influence other parts of the system. This is an extremely important finding, since if one does not believe that a system can behave in unexpected ways, one will not be on guard against the unintended side effects of one's strategic and policy decisions.

Using systems dynamics to gain a better understanding of manufacturing strategy is to the best of the author's knowledge not available any where in literature to date. The author is convinced from this research that a systems dynamic approach to studying manufacturing strategy will help managers in industry to better understand the complex nature of operations management and that operations management can become a competitive weapon if relationships among and within decision areas are well understood and effectively linked.

7.3 FUTURE RESEARCH DIRECTION

Manufacturing strategy research is still in its infancy. There is much to be learned about the content and process of managing strategy. The knowledge of linkages between operations management decisions and competitive priorities is crucial to managing strategy. More research is needed from a holistic perspective to understand and verify how decisions relate with each other and with the competitive priorities for manufacturing to strive to achieve.

More research can be done within the context of the model conceptualized in this thesis. This thesis examined the linkages among and within the decision areas of processes, materials management, quality, workforce management and maintenance in relation to one of the competitive priorities: delivery time - measured by cycle time. The model can be expanded to include other competitive priorities such as cost, quality, dependability and flexibility. Additional decision areas that could be included are production planning and scheduling, product and corporate strategy.

The objective in this area of research should be the development of a grand model of the relationships among and within all decision areas of manufacturing strategy. This dissertation is just the beginning.

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